State-of-the-Art: Sweden

Quality Management in Design, Construction and Operation of Borehole Systems

2018

A work document prepared within IEA ECES Annex 27
"Quality Management in Design, Construction and Operation of Borehole Systems"

Prepared by

Olof Andersson, Geostrata

Signhild Gehlin, Swedish Geoenergy Center

Geostrata HB

PREFACE

This State-of-the-art report is a work document compiled within the framework of the 2016-2018 IEA ECES Annex 27 “Quality management of design, construction and maintenance of Borehole thermal energy systems”. The report is a summary of the Swedish state of the art concerning, market, design, construction and operation of borehole thermal energy systems (GSHP and BTES systems) at the time for the annex work in 2018.

The authors gratefully acknowledge the financial support for their work from the Swedish Energy Agency and from their employers, and for valuable comments and inputs from the many people working with GSHP and BTES systems in Sweden.

SUMMARY

Shallow geothermal boreholes are used worldwide in order to make heating and cooling of buildings more efficient than conventional systems and cut the emission of environmentally harmful gases and substances to the atmosphere. However, failures in design, construction and operation of these systems may cause damage to buildings and the environment. Hence, the objective with this IEA ECES Annex is to work out preventive measures and recommendations for national and international guidelines and standards, not only to avoid problems, but also to offer solutions and remediation of faults.

Sweden is a world leading country using the underground as a heat source for space heating, typically with heat pumps. The Swedish geology with mainly crystalline bedrock, abundant groundwater and a climate with a large temperature difference between summer and winter, are all favorable factors for GSHPs and BTES.

Boreholes for GSHP systems have been drilled and used for more than 40 years in Sweden. Despite the long experience from BTES and GSHP technology and practice in Sweden, there are few regulations concerning this technology. Procedures and common practice for BTES and GSHPs have developed over time to a technically proper level without formal standards and guidelines. Legislations and regulations related to BTES and GSHP installations are found in the environmental and health codes, building codes, local regulations, technical guidelines for testing and materials and installation procedures.

There are at least 500 000 GSHP and BTES installations in Sweden so far, of which approximately 400 000 are vertical boreholes in hard rock. The majority of these systems are installed in single-family houses with one or occasionally two boreholes. In later years there has been an increase in the market also for larger system. While there is statistic material available on numbers and depths of drilled boreholes from the Geological Survey of Sweden, and sales figures on heat pumps, there is no specific statistics collected on problems and failures of GSHP systems. Some information is available from insurance companies; however that information mainly concerns heat pumps and installation. On the whole the frequency of known damages and failures is very low, considering the large amount of produced GSHP boreholes.

CONTENTS

IEA ECES ANNEX 27 DESCRIPTION

The project is one of several other international projects that are executed within the framework of IEA (International Energy Agency) with its head quarter placed in Paris. It belongs to the Technical Collaboration Program named Energy Conservation through Energy Storage (ECES) to which it is reported twice a year to the ECES Executive Committee (ExCo).

The leading country is Germany, whose operating agent has the responsibility to manage the Annex and report the status to the ExCo.

Shallow geothermal boreholes are used worldwide in order to make heating and cooling of buildings more efficient than conventional systems and cut the emission of environmentally harmful gases and substances to the atmosphere. However, failures in design, construction and operation of these systems may cause damage to buildings and the environment. Hence, the objective with the project is to work out preventive measures and recommendations for national and international guidelines and standards, not only to avoid problems, but also offer solutions and remediation of faults.

The project covers all stages of realization of borehole systems. It covers borehole systems of all sizes, and the process from planning and design, to the long-term operation; covered in five different subtasks as follows:

1. Planning and design (Leading country Sweden)
2. Construction (Leading country Denmark)
3. Operational monitoring (Leading country Japan)
4. Problems and solutions (Leading country Germany)
5. Environmental assessment (Potential subtask)

The appointed subtask leaders (in brackets) will put together information from all other countries in subtask reports in which recommendations for standards and guidelines are given. In addition to the subtask leading countries, also Belgium, Canada, China, Finland, Korea, Turkey and The Netherlands are participating in the Annex.

This report describes the Swedish State-of-the-Art to serve as an input to all subtasks. It has initially been compiled as a draft, which will be sent out to drillers and installers of shallow borehole systems in Sweden for review and comments. After revision, the final version will be used as input to further discussion at upcoming expert meetings.

VERTICAL GSHP AND BTES IN SWEDEN

Definitions and boundaries

The annex is focused on borehole systems but may in certain parts also consider the HVAC system to which it is attached as source for heating and/or cooling.

The borehole system will typically be one or several *closed loop* boreholes that serve as heat source or cold source for a building, with or without heat pump aid.

By *closed loop* is understood an installed piping filled with brine that transfers thermal energy into and out of the underground through the boreholes. This thermal energy is transferred to other HVAC loops by various types of heat exchangers. In this annex only the brine loop is considered.

In Sweden, these borehole systems are typically used in the following types of applications:

- **Ground Source Heat Pump (GSHP) systems** for heat extraction only. The heat is extracted from the underground during the winter season and is recovered naturally during the summer season.
- **Ground Source Cooling (GSC) systems** for extraction of cold only. The cold is most often extracted throughout the year, but to a larger part during the summer season. Recovers naturally during the winter season
- **Borehole Thermal Energy Storage (BTES) systems** for extraction of heat and/or cold through boreholes in the ground. Recovery by seasonal storage of waste heat from the cooling system (summer season) and waste cold from heat pump evaporators (winter season).

Market development

Ground source heat pump systems (GSHP)

Sweden is a world leading country using the underground as a heat source for space heating, typically with heat pumps. The most common type of installation is what in Sweden is called “Bergvärme” (rock heat), i.e. a small-scale vertical GSHP system in hard rock for heat extraction only. The installations of these systems started with small-scale applications at the end of the 1970’s and have since grown in numbers. The first market boom occurred in the mid 1980´s due to high oil prices. A second boom started in the mid 1990´s and is still going on, this time more for environmental and economic reasons.

There are at least 500 000 GSHP installations in Sweden so far, of which approximately 400 000 are vertical boreholes in hard rock. The majority of these systems are installed in single-family houses with one or occasionally two boreholes. In later years there has been an increase in the market for larger system also, see figure 1. Many of these larger systems are mainly applied for residential multi-family buildings and housing associations and have typically 10-20 boreholes connected to one or several heat pumps.

Figure 1. Market development of GSHP in Sweden the last six years as shown by sales of heat pumps

The potential for these systems is very large, but will in many cases compete with existing district heating systems in urban areas.

Ground source cooling systems (GSC)

Ground source systems for cooling are typically used by the telecom sector for process cooling of electronic equipment. The majority of these systems are applied for cooling of central telecom stations and digital television broadcasting equipment, especially in the northern part of the country.

A huge potential future market would be approximately 100 000 base stations for the mobile telecom systems, especially those situated at remote areas. With an increased power demand for these stations this sector could save a considerable amount of electricity by using the ground source cooling instead of chillers. There is also a huge potential within the industrial sector for GSC systems.

Borehole thermal energy storage systems (BTES)

Unfortunately we are lacking detailed statistics on BTES systems. However, by collecting information from a number of different sources we know that there are approximately 80-90 systems with a total borehole length of 10 000 m or more in Sweden. These are mainly BTES systems used for both heating and cooling. By studying the number of boreholes reported to the Swedish Geological Survey (SGU), there seems to be a growth of some 30 plants/year with 20 boreholes or more. All together it seems as if there are at least 500 BTES system with 20 or more boreholes in operation in Sweden today. The market seems to grow steadily. These systems are preferably used for commercial and institutional buildings.

There are also a few systems for high temperature storage, HT-BTES, for seasonal storage of solar heat or waste heat in the industrial sector. In later years the there is growing interest for this type of storages, especially combined with cogeneration plants.

Geological and climatic conditions

In Sweden the major part of the rock consists of old crystalline rock types such as granites and gneisses. Occasionally there are dykes of intrusive rocks, mainly diabase. There are also minor areas with volcanic rock. Only some 10 % of the surface has sedimentary rock layers, including the metamorphic sedimentary rock in the mountain areas by the Norwegian border, see figure 2.

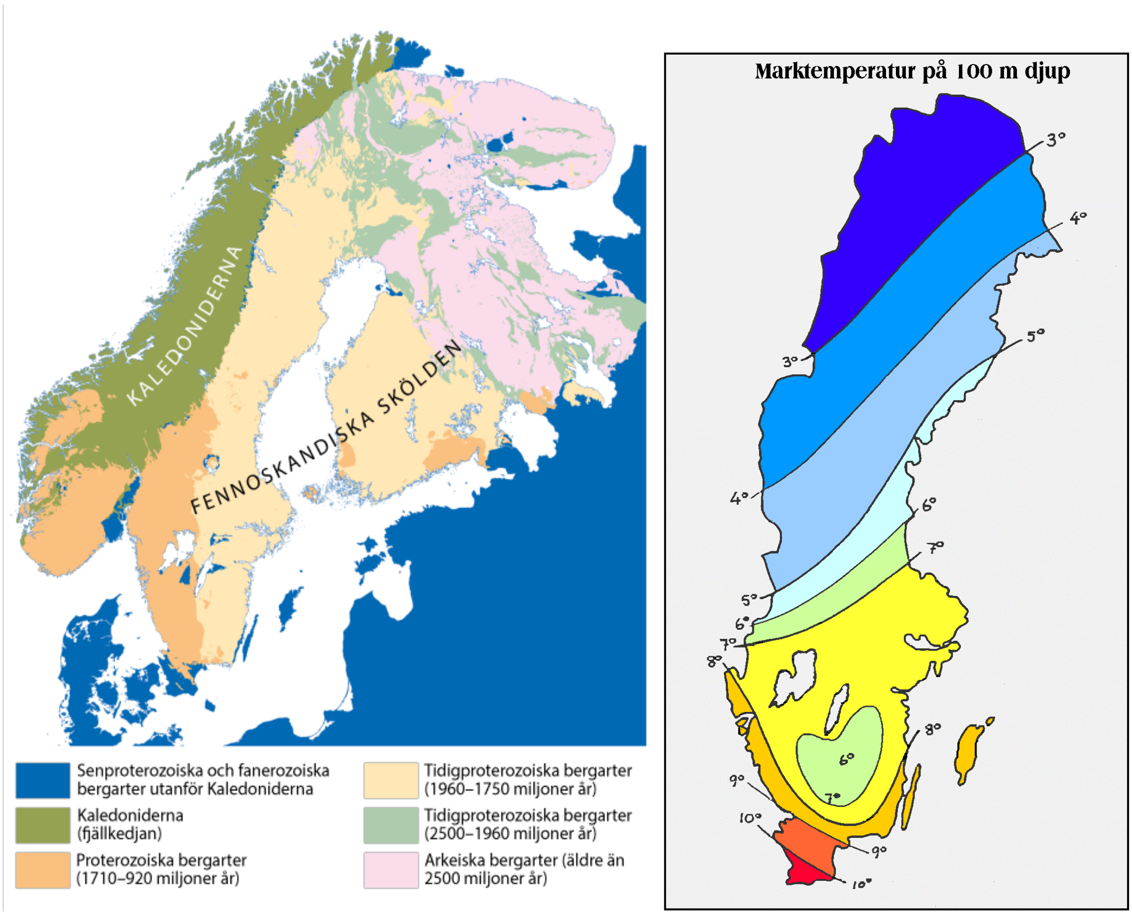


Figure 2. (Left) Sweden is a part of the Fennoscandia Shield with mainly crystalline rock types that increase in age towards NE. Only in the south there are undisturbed sedimentary rocks. (Right) The temperature at a depth of 100 m reflects the average ambient air temperature except in the north where snow insulates during the winter.

The geology with hard crystalline rocks is the main reason to allow for open-hole, groundwater-filled boreholes, as well as the development of efficient drilling technologies. These boreholes are protected from contamination of the groundwater by using steel casing drilled into the rock and grouted in order to create a sealing from water in the overburden. There is also an environmental acceptance to use the harmless bioethanol as antifreeze in heat carrier fluids in order to avoid contamination of the groundwater in case of leakage. However, in groundwater protected areas, backfilling with a water tight grout may be required by local authorities.

The southern half of Sweden has a temperate continental climate, while the northern half has a more continental type of climate. The temperature varies considerably from north to south, especially during the winter. Average high temperatures in summer are 21°C in the south and 20°C in the north, while average low temperatures in winter are -3°C in the south and -14°C in the north. This is clearly reflected in the underground temperature, see figure 2.

The climate difference is the obvious reason why the frequency of vertical GSHP systems is much lower in the northern part of the country. However, this does not affect the potential of using BTES for seasonal storage of heat and cold. On the contrary, these systems are even more suitable in the more continental type of climate.

LAWS, GUIDELINES AND STANDARDS

Despite our long experience from BTES and GSHP technology and practice in Sweden, there are surprisingly few regulations concerning this technology. However, procedures and common practice for BTES and GSHPs have been developed over the years to a technically proper level without formal standards and guidelines. This section gives a brief overview of existing Swedish legislations and regulations that concern BTES and GSHPs.

Legislation

Environmental codes

The Swedish Environmental Code (Miljöbalken, MB, SFS 1998:808) regulates in general terms the legislative demands for any type of construction that involves installation in groundwater and surface water, and hence regulates the legislative demands on those who intend to install BTES or GSHPs. Any type of construction that will deviate groundwater require permits through water-rights judgement according to MB chapter 11, unless the facility is meant for a single-family or dual-family house. However for BTES and vertical borehole GSHP systems, water is not extracted – hence permit through water-rights judgement is not required.

The Environmental and Health Code (Miljö- och hälsoskyddslagen, SFS:1998:899) specifically states that any GSHP system with boreholes or wells, regardless size, must be registered at the Local Environmental Authority (LEA) prior to installation. It is the heat pump installation that requires registration. The LEA may deny installation for environmental or health reasons or state certain terms in the permit. Typical terms could be that the driller be certified and that the drilling shall be executed according to the well construction guideline Normbrunn-16 (see below).

Water protection areas

The Swedish Environmental Protection Agency (Naturvårdsverket) has issued regulations for water protection areas (NFS 2003:16), based on the Environmental Code (MB, chapter 7). Both groundwater and surface water are included.

Special requirements are given by the Regional Environmental Authority (REA) for installations in water protection areas. In the inner and secondary zones of the protected area BTES and GSHPs are forbidden. In the tertiary (outer) zones BTES and GSHPs may be allowed, but special requirements on grouting and monitoring may be required.

Well registration

Since 1976 all professional well drillers are required by law (SFS 1975:424, SFS 1985:245) to register all drilled wells and boreholes to the Swedish Geological Survey (SGU). SGU keeps the open access Well Database where all registered wells are listed. There are today around 600 000 wells registered in the database. Of these around 320 000 boreholes are vertical boreholes for ATES, BTES or GSHPs.

Work environment protection

The Swedish Work Environment Authority’s (Arbetsmiljöverket) Statute Book (AFS) contains a number of provisions with AFS designations. AFS 2006:4 regulates the use of work equipment, such as for drilling.

Consumers rights

Consumers’ right (Konsumenttjänstlagen, 1985:716) regulates the rights of private persons buying services from a company, such as a GSHP installation.

Building code

The Building Code (BBR 18, chapter 9) regulates how much energy a building may use for heating and cooling. GSHPs are considered as “electric heating”, which is stricter regulated than other heating alternatives (such as biomass, district heating etc.). It is only the electricity used for the heat pump that is counted. The renewable energy from the ground is not considered in the amount of energy used by the building.

Refrigerants

The Refrigerant decree (Köldmedieförordningen, SFS 2007:846/2009:382) regulates who may install and handle refrigerants, for example for heat pump installations such as GSHPs, how and how often these installations must be inspected.

Regulations

Local regulations

Local and regional environmental authorities may issue local safety regulations mainly for protection groundwater, health considerations and damages of any kinds. Common requirements are grouting of boreholes as well as special terms for handling drilling fluids and cuttings. These requirements will in practice vary a lot between municipalities and regions.

Well construction guidelines for groundwater protection

The ”Normbrunn procedure” (Normbrunn-16, SGU 2016) is a guideline for design and installation of groundwater wells and vertical ground heat exchangers with the aim of protecting groundwater.

Normbrunn-16 recommends the following procedure for completion of boreholes for closed loop systems:

1. A permanent steel casing is drilled down through the overburden and at least 2 m into hard bedrock
2. The annular space between the casing and the lower part of the borehole is sealed by using grout.
3. An open hole is drilled to the designed depth and the hole is cleaned by air flushing (air-lift if water)
4. Before insertion the BHE should be filled with the heat carrier fluid and after that a hydrostatic test is performed (minimum pressure 3 bar during minimum 30 minutes) to check for any leakage. Pressure testing must never be performed with air.
5. Pressure test is performed after installation of the BHE and installation of a tight lid on top of casing, **or** occasionally installation of BHE and grouting from bottom to top (thermal grout), **or** alternative sealing methods (green collector or section plugs/packers)

Normbrunn-16 also gives recommendations on what fluids to use in the system, and recommended minimum distance between two boreholes on neighbouring properties. It also gives recommendations on material use and construction of borehole heat exchangers.

Technical guidelines

The 2015 ISO/CEN standard on ”geothermal response testing” (EN ISO 17628:2015) is not accepted and used in Sweden. For this reason the Swedish Centre of Geoenergy (Svenskt Geoenergicentrum) issued guidelines on equipment, performance, analysis and reporting of Thermal Response Tests (TRT) to be applied in Sweden (Svenskt Geoenergicentrum, 2015).

The Swedish Centre of Geoenergy is currently working on two more guidelines; one for measurement and monitoring of shallow geothermal systems, and one on a revision of previous guidelines for

horizontal piping for closed loop systems (GSHP and BTES).
The Swedish Heat Pump and refrigeration association (SKVP) together with real estate owners and organizations have issued a common guideline for contracting of heat pumps for residential and commercial buildings (GTVF 14).

Quality certification of ground heat exchanger pipes

The geoenergy sector has agreed on using the so-called P-Mark as a quality label for ground heat exchanger pipes. The P-Mark means that the product (in this case the ground heat exchanger pipes) meets legal or regulatory requirements and also more stringent requirements demanded by the market. P-marking means that the product is type-tested. Normbrunn-16 recommends P-marked ground heat exchangers.

Contract by tender rules

The Common Regulations AB04 and ABT06 (Allmänna Bestämmelser, Svensk Byggtjänst, 2004/2006) set general contractual rules for construction and installations. According to these rules quality control and environmental control are required.

General rules for contracting

Administrative rules (AF) and General materials and job description for civil works (AMA Anläggning 13) provide some general rules for contracting of underground construction installation works.

Conclusions

Sweden has a long tradition of installing GSHPs and BTES systems, yet there are few designated standards or guidelines for these systems. There are however a number of legislations and regulations that to some extent relate to BTES and GSHP installations, such as Environmental and health codes, Building codes, Local regulations, Technical guidelines for testing and materials and installation procedures etc.

Procedures and common practice for BTES and GSHPs have been developed over the years to a technically proper level without standards and guidelines. However, there is a need to consolidate and confirm the procedures and common practice in guidelines in order to harmonize the technology and to create a general quality code. Furthermore, it would also create more equal conditions of competition among drillers and installers.

A guideline would also be of importance at all stages of a project development and serve as a reference in forming technical specifications in tender documents. As such it may be of great importance to prevent potential problems and damages during construction and operation of borehole systems.

DESIGN OF GSHP AND BTES

Definition

In Sweden borehole thermal energy storage (BTES) systems are defined and designed with the purpose to actively store thermal energy (heat and cold) in the underground, while ground source heat pump (GSHP) systems are defined and designed to extract heat or cold from the underground, while the underground recovers in a passive way by heat transfer in the underground surroundings. Larger GSHP systems are mainly applied within the residential sector. The main market for BTES applications is commercial and institutional buildings.

Design approach

Design parameters and tools

The main design parameters would be: the ambient underground temperature (^{o}C), the ground thermal conductivity (W/m,K) and monthly heat or cooling load (kWh) as well as temperature limits, type and size of BHE, flow rate and duration time. The number, depth and distance between boreholes is then preferably defined by a simulation/design model (most often the design program Earth Energy Designer EED), or for smaller systems by experience. Numerical models are rarely used, other than for R/D projects.

Heat and cold sources for storage

The most common sources for storage of heat are waste heat from the cooling system in summer mode operation, and waste cold from the heat pump evaporator in winter mode operation.

Other sources of heat are sometimes used for storage during the summer season, mainly for residential buildings: Outdoor air by using a condenser cooler or a cooling tower, waste heat from centralized ventilation systems by using an air-water heat exchanger, and warm surface water from nearby lakes, streams or dams by using a water/water heat exchanger.

Load characteristics

The design of a BTES system as well as GSHP system would typically cover 60-80% of the maximum heat load of the building, producing 80-95% of the heat demand. The heating peak load is typically supplied by district heating or an electric boiler, and less commonly by oil or gas boilers. For newly constructed single-family houses the design load is typically 100%.

The BTES system would typically cover 100% of the cooling load and cold production. Free cooling from the BTES application would typically be at least 50% of the maximum load and up to 75% (occasionally 100%) of the cooling demand over a year. The remaining peak cooling load is produced with heat pumps running as chillers. The excess heat is disposed by using condenser coolers or cooling towers. Smaller chillers known as “window shakers” may be an option for residential buildings. For residential buildings peak shaving of cooling is of little interest. Free cooling from the underground provides a base load that is better than no cooling at all.

Pre-feasibility studies

A pre-feasibility report will commonly be a desktop study where the BTES or GSHP options are compared to other forms of heating and cooling, by example district heating/cooling. The main sources of information in a pre-feasibility are given by situation, topographic and geological maps, and geological data basis. Based on energy consumption over a year, load and temperature demands, a system is principally pre-designed and investment and operational costs are roughly calculated and compared to other forms of energy supply.

Sources of information include:

- Geological maps are available all over the country (Swedish Geological Survey) most often in the scale 1:50 000
- A geological data base is available all over the country (Swedish Geological Survey). Information of existing boreholes and geological and hydrogeological features can be found at the homepage of SGU.
- Hydrogeological information is available all over the country (Swedish Geological Survey). Information of existing boreholes and geological and hydrogeological features can be found at the homepage of SGU
- Underground obstacles and limitations are not commonly considered at this stage, except for tunnels in urban areas, groundwater protected areas and less commonly, mining areas. Consultancy with water and mining authorities is not considered in this phase.
- Geotechnical aspects are mainly considered in areas with sedimentary clay deposits (risk for settlement)
- Legal aspects with respect to property ownership are always considered. The user of the system must own the property for borehole installations. However, an option is to use other properties by borehole easements.
- Environmental aspects are always considered with general environmental and legal aspects. Commonly environmental benefits of using BTES/GSHP are put forward. Risk for salt groundwater intrusion and occurrence of water protections areas and polluted ground are taken into consideration.
- Survey on underground installations, like pipes and cables, is very important to find out at an early state. Information can normally be found as a free service through internet (ledningskollen.se)
- A rough estimate on investment cost, energy savings and profitability are always main items in economic considerations within pre-feasibility studies in Sweden.

Feasibility phase

The pre-feasibility study will be developed further. Typically one or several test-holes are drilled and documented and tested. Furthermore, detailed data (occasionally specially logged) on heat and cold load characteristic are obtained and used as basis for design, as well as temperature profiles. Environmental and legal aspects are also more thoroughly considered than in the prefeasibility stage.

Test drilling

Location of test drillings is mainly based on geological conditions, land availability for placing the boreholes, and survey of underground installations (water or gas pipes, electric and tele/fiber cables, etc.). Depending on the system size (predicted number of boreholes) one or several holes are chosen. No permit is needed for test drilling if the drilling takes place on your own property. Test holes are normally used as production holes later on.

The depth of a test hole should be the same as the expected production holes. The depth is mainly dependent on geological conditions at site.

As a rule of thumb, the number of test holes in Sweden is related to the expected size of the borehole field:

- Up to 10 boreholes: Normally no test holes are drilled. The underground geological, thermal and hydrogeological conditions are based on pre-feasibility data.
- 10-30 boreholes: One test hole is drilled and documented, often followed by a TRT.
- 30-120 boreholes: At least two test holes are drilled and documented, occasionally three. Commonly followed by at least one TRT, occasionally two.
- >120 boreholes: At least two test holes are drilled and documented, most commonly three or more, followed by at least two TRT:s.

Documentation at test drilling

Stratigraphy (geological layers) is documented by the drillers log, and occasionally by sampling. Occurrence of permeable zones is identified as airlift capacity at hammer-drilling with compressed air, occasionally loss of circulation if drilled by water or mud.

Groundwater level should be measured before start of drilling each morning.

Structural drilling problems such as fracture zones, unstable hole, swelling clay, large yield of water, etc. are noted in the driller's log.

Documentation and measurement of drilling parameters such as ROP (Rate of Penetration) as a function of WOB (Weight on Bit), Torque, etc. are only done in scientific projects.

TRT service is supplied by 4-5 companies. One or several TRT measurements are performed after drilling and insertion of borehole heat exchanger. There is a manual for performance worked out by the Swedish Centre of Geoenergy (Svenskt Geoenergicentrum 2015). The duration of a TRT is commonly 50-70 hours. In special cases more. Typically evaluation is performed based on the Line source method, with or without parameter estimation.

On site geophysical investigations are seldom used. However, occasionally VLF (very low frequency radio waves) is used to detect vertical fracture zones in Archean rocks, and radar for mapping the soil depth. Furthermore, the deviation of boreholes is sometimes measured, especially in urban areas (often as a term for permit).

Environmental concerns

The environmental concern is mainly related to protection of groundwater. In groundwater protected areas a permit is given only if it can be shown that the boreholes will not hazard the groundwater quality. If a risk, grouting or other forms of borehole sealing will be a term for the permit.

There may be risk for settling of nearby buildings by consolidation of finely grained sediments, mainly clay and silt. Such settling can be caused by freezing of clay outside the casing, drainage of groundwater in the soil into the rock trough badly sealed casing, and creation of cavities during drilling that later lead to collapsed surface.

Predesign of the system

Predesign procedure of the system is based on the results from test drillings, evaluated thermal parameters (from TRT) and energy load profile, the borehole system is predesigned by using the design program Earth Energy Designer (EED). A borehole field (occasionally more than one) is placed and the configuration, depths and deviation of boreholes (if restricted surface area) are established.

Economic considerations

Investment cost is normally based by experience from other similar and newly constructed plants. Maintenance cost is estimated to practically zero for a closed loop borehole thermal energy system.

Calculation of energy savings is done from the expected SPF of thermal energy production. The outcome is then compared to one or several alternative systems producing the same amount of thermal energy. The difference is defined as energy savings.

Profitability is often calculated as a straight pay-back time with investment cost divided by the value of energy savings/year. Occasionally it is also presented as a return rate of investment (%).

The use of Life Cycle Cost analyses is commonly done for a period of 20 years (technical life time of mechanical units) with a rest value for the borehole system that has at least 40 years lifetime.

Detailed design

Contract forms

The customer normally has two options to realize the plant. These options would be by a *turnkey contract* (design by the contractor) or a *performance contract* (design by the client).

The turnkey contract normally has two separate set of documents, Administrative Regulations and a Technical Frame Description. In the latter, the technical terms and specification are given on which the final design of the system must be executed. These documents are sent out to potential contractors with call for tenders. In Sweden this type of contract, with the functional responsibility of the system resting upon the contractor is the most frequent one. However, the client has the option to review and make comments on the design before it is stamped as construction documents. This is a way for the client to have a quality control of the design, but not always used.

In a performance contract the responsibility for the design lays on the customer, commonly by using consultants and experts for the actual design work. This type of contract is worked out with a similar procedure as a turnkey project. The main difference is that in the turnkey project, the client is responsible for the design and function of the system. The contractor is only constructing the plant according to the design but can of course suggest adjustments that may be accepted by the client. In Sweden this option is much less frequent than the turnkey option.

Modelling

The design is normally performed and specified by a consultant company. As a tool for design the consultant might use modeling tools other than EED (Earth Energy Designer), for example DST (Duct Storage Model). In the modelling procedure a number of parameters are considered, see the list below and a number of other items considered further down.

- Load profile over an average year - Normally monthly loads. Maximum loads for heating and cooling.
- Temperature demands over the year- Normally related to outdoor temperature variations.
- Heat load coverage - Varies, but often 60-80 % of maximum heat load.
- Cooling load coverage in BTES systems - Normally 30-50 % of maximum load as free cooling and the rest covered by the heat pump. Occasionally all cooling is supplied by the heat pump with waste condenser heat seasonally stored in the BTES system.
- Modelling of borehole fields - Studied and optimized with the model.
- Influence of groundwater level - Defines the active borehole length (if not grouted holes).
- Influence of natural ground water flow - May affect storage system performance in a negative way, but dissipative borehole systems in a positive way. Not modeled, just considered in the design.

Borehole heat exchangers (BHE)

Single U-pipe dominates (cheapest option). Double U-pipe is quite common in larger systems with restricted free cooling temperature limit (more costly, but also more effective). Occasionally coaxial BHE is used, so far mainly for R/D projects.

Plastic pipes, PE100 (replaced PE80 in later years), are used and joints are welded with special electro-joints for connection to the surface pipe system. The U-bend at the bottom of the BHE is specially welded by manufacturer.

Most commonly DN40/2.4 SDR 17 (PN10) for single U-pipes and DN32/2.0 SDR17 (PN10) for double U-pipes are used. In recent time also DN50 and DN45 are being used, especially for deeper boreholes (> 250 m). Quality criteria for BHE are bursting pressure, collapsing pressure, extension coefficient and change of strength with increased temperature. BHEs should be type tested and certified by third party and BHE properties are tested and traced accordingly by the manufacturer.

Manufacturing of BHE is done in larger workshops, in production lines with material mixing, melting, pressure molding, water basin cooling and finally winding. There are 2-3 large suppliers. Before delivery, a pressure test is done. The BHE manufacturer should be accredited and certified by third party to produce pressure pipes.

BHEs are connected to the surface pipe system by specially designed 90 degree electro-joints according to specifications from the joint manufacturer. Special tools are used. Adjoining pipes must be perfectly cleaned and wet weather conditions should be avoided.

In groundwater filled boreholes, spacers make no significant difference on the borehole resistance. Therefore spacers are not commonly used.

A variety of underground field manifolds have been developed by the BHE manufacturers. These are normally designed for 10-20 boreholes and prefabricated. Less common is special designs that are constructed on-site. Occasionally the manifolds are placed indoor in the energy central. In later years it has become increasingly frequent to place manifolds in custom made boxes on the ground surface.

Most commonly the boreholes and field manifolds are connected in parallel. The main reason is to minimize the flow resistance in the system.

In larger systems the circulation pump is often frequency controlled which allows the flow rate through the system to be adapted to the energy demand from system. Each connection to boreholes has a simple flow meter and a valve for adjustment of flow. In practice these are adjusted only once, but the valve can be used to shut down single boreholes if required.

Only in special cases, grouting is used in Sweden. However, there is a tendency to increased use due to permits terms, see above. There is no standard or common practice for how to grout the boreholes. There is a discussion going on how to grout deep boreholes in hard rock types. Thermal grouts are mainly imported from Germany or Denmark, but since recently thermal grout is also produced in Sweden. There are alternative borehole-sealing systems available. These are not using grout for groundwater protection and consist of a plug that separates different water-holding fractures in the rock. Another method is to use or a hydrostatically controlled capsule along the entire borehole length. None of these alternatives have so far been fully approved by the authorities.

Horizontal pipe system

The pipe material used for the horizontal system between the borehole heat exchangers and manifold is PE100. Dimension and strength of horizontal pipe system is most commonly DN40/2.4, SDR 17 (PN10). Occasionally DN50/2.9 SDR17 (PN10) is used to decrease the fluid resistance losses.

Insulation of horizontal pipe systems is only done for parts that are exposed to air or placed at shallow depths. The horizontal pipe system is commonly placed some 0.8-1.2 m below ground surface (non-freezing depth). Pipes should be placed at 20 cm spacing. The bottom bed material is typically a sand bed, and must be free of stones with sharp edges. Backfilling of pipe trenches is commonly done with a layer of sand and on top of that a permeable geotextile. The filling ends with soil material from digging the shaft. A warning tape is often placed at the top of the trench below the surface.

The boreholes

The distance between two independent boreholes (two boreholes that should not thermally interact with each other within reasonable time) in GSHP systems is stipulated to be >20 m. The space between the boreholes in BTES systems normally varies between 5-10 m.

Borehole spacing and configuration are mainly dependent on the thermal properties of the rock, available surface space and thermal balance between heat and cold extraction/injection. In urban areas with limited or restricted space to place boreholes, there is a tendency to drill boreholes with increasing depth to compensate for thermal interaction. Also use of deviated (angled) boreholes is common in densely urbanized areas, in order to have enough space between the holes.

Heat carrier fluid

Commonly bioethanol as antifreeze component to water is used. The content of ethanol shall be less than 27% (flammable at higher concentration). The ethanol used has two slightly toxic additives, n-Butanol (45 gr/m^3) and Isopropanol (350 gr/m^3). These additives make the ethanol undrinkable. Pure water is occasionally used in systems with storage of heat only.

A typical working temperature of the brine loop (heat carrier) in a BTES system connected to a heat pump would be -3/-4^{o}C as lowest (normally in February) and +14/+16^{o}C as highest (normally in August). With groundwater filled boreholes, it has been shown that running the heat carrier with an average temperature below -5°C during a longer period of time will cause the groundwater in the borehole to start freezing that may in worst case cause damages.

Risk analysis

Environmental risk analyses are commonly made in the feasibility stage after test drilling. The main subject is then to show the risks for groundwater contamination by leakage of the heat carrier fluid.

Another risk is that the boreholes penetrate several permeable zones (fracture systems in hard rocks) and cause an uplift of deep brackish water to higher levels with fresh groundwater.

A third risk considered is drainage of groundwater in clayey soil layers with a risk for settling.

Technical and economic risk analyses are considered in the feasibility stage by using risk scenarios of different kinds. Risk analysis is normally asked for in the contracting documents for larger projects.

Approval procedures

Regardless of system size an application/notification is sent to the local environmental authority (municipality level). Here the project is reviewed with respect to local environmental regulations. The application format can be found online. Information on property owner, placement of boreholes and borehole configuration shall be attached to the application as well as size and type of heat pump, volume and type of refrigerant. Furthermore, name of drilling company and heat pump installer must be written. For larger systems the drilling company and heat pump installer should be certified, but this is not always the case at present. The authority evaluates the project from an environmental point of view only.

If no risks, the project is normally approved within a few weeks. However, the approval is commonly given with certain terms that the applicant must follow. Examples are that drilling excess water must be handled according to local regulations and that the sealing of casing towards the rock shall be done according to norms stated in Normbrunn-16.

If there is risk for contamination of groundwater the authority can either deny the application, or subscribe terms to avoid that risk. Sealing of boreholes by grouting is an example of such terms.

Call for tenders

Form of contracts for construction of borehole systems is mainly Turnkey or Performance contracts based on General Regulations for Constructions (ABT06 and AB04).

In the specification, the tenderers must deliver documents showing Quality Control certification as well as Environmental Control certification. Bidders are also asked for organization scheme including CV:s on key personnel and name a number of reference projects to show their skill.

For damages, linked to the functional design and construction of the plant, the contractor will be held responsible if it is a turnkey project. This responsibility is normally limited to 5 years. For a performance contract, responsibility for functional design is put on the client. Yet, the contractor can be held responsible for damages caused by bad performance in construction.

CONSTRUCTION OF GSHP AND BTES

Site Preparation

If drilling is done on the customers own property no drilling permit is needed other than the approval from the local environmental authority (LEA).

If water and electricity is needed for the drilling, it is commonly provided by the customer. Potential underground obstacles (pipes for water, gas, electric cables and, fiber cables, etc.) must be surveyed before placing the boreholes.

Permit for disposal of "drilling excess water" in the storm drain system is required in some municipalities, in others it is not a requirement. A few municipalities have requirements for treatment of drilling excess water that are very hard to meet.

For safety reasons the working area is commonly marked by lines or by a temporary fences.

The drilling with compressed air does not require any excavated pit for handling water or mud. Instead cuttings and "drilling excess water" is handled by using containers.

If there is a risk for soil contamination, samples of cuttings are taken during drilling. If contamination in the soil is found, the drilling must be stopped and the findings must be reported to the local environmental authority. Occasionally, a full soil contamination survey has to be executed prior to start drilling.

Drilling methods

Practically all GSHP and BTES boreholes in Sweden are drilled with the DTH-method (Down-The Hole-Hammer) and compressed air (occasionally a water-driven hammer is used). The drilling and the BHE installation is commonly done in the following steps:

1. A steel casing is drilled through the overburden and at least two meters into stable rock. This is done by a reamer or an enlarged ring bit leaving a space between the borehole wall and the casing.
2. The annular space between the wall and the casing is sealed off by placing a grout in the bottom, then lifting and replacement of the casing and finally press or hit the casing towards the bottom.
3. An open hole is drilled to the designed depth and the hole is cleaned by air flushing (air-lift if water)
4. The driller notes the type and colure of samples taken at the outlet pipe, fractures or fracture zones, and air lifting yield of water. Also the salinity of water is measured, as well as the ground water level after finishing the borehole. These data are later reported to SGU.
5. A pre-filled (with water) borehole heat exchanger (BHE) is installed, normally a single U-pipe 2 x 40 mm and with a bottom weight at the U-bend. Occasionally 4 x 32 mm (double U-pipe) is used. For really deep holes, a single U-pipe 2 x 45 or 2 x 50 m may be used.
6. Pressure test of the BHE and installation of a tight lid on top of the steel casing, **or** occasionally installation of BHE and grouting from bottom to top (thermal grout), **or** in rare cases alternative sealing methods (green collector or section plugs/packers)

This procedure is commonly referred to as "The Normbrunn procedure", see figure 3

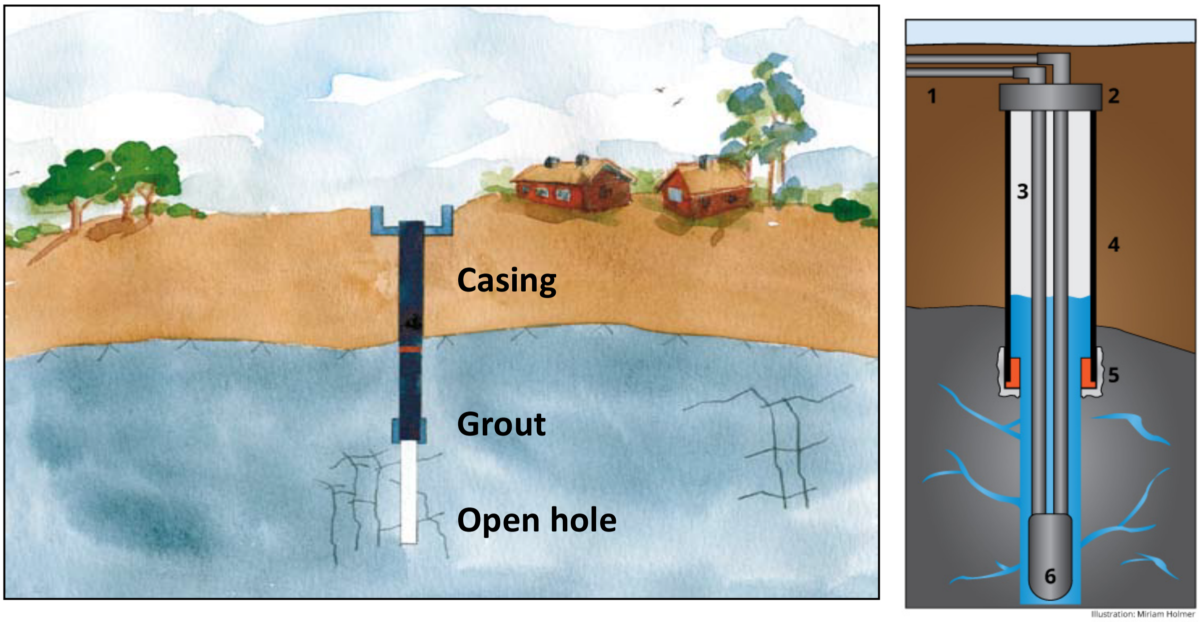


Figure 3. Borehole completions according to the “Normbrunn procedure” (left) and the principal outcome of a vertical energy borehole filled with groundwater (right). (1) Connecting pipe (2) The lid (3) The collector (4) The casing with the casing shoe (orange) (5) Grout for sealing (6) Bottom weight

Later on, the boreholes are connected to make a borehole system. Finally the rest of the system is filled up with a heat carrier (water mixed with ethanol), degassed and finally pressure tested and often tested for flow resistance.

The dominating flushing medium is compressed air. The main site equipment needed is a drilling rig, a compressor and a container for handling the separation of cuttings, see figure 4.

Figure 4. Left, a normally sized drilling rig and a 30 bar compressor. Right, set up for drilling showing the compressor and container for separation of cuttings. The hose hanging down from the container is connected to the rig out-blow.

The drilling through the overburden is performed with a casing drilling equipment, see figure 5, normally with a rotating ring-bit. Independently of method the casing is drilled down in 3 m lengths that are welded together. Occasionally, with large size rigs, 6 m lengths are used.

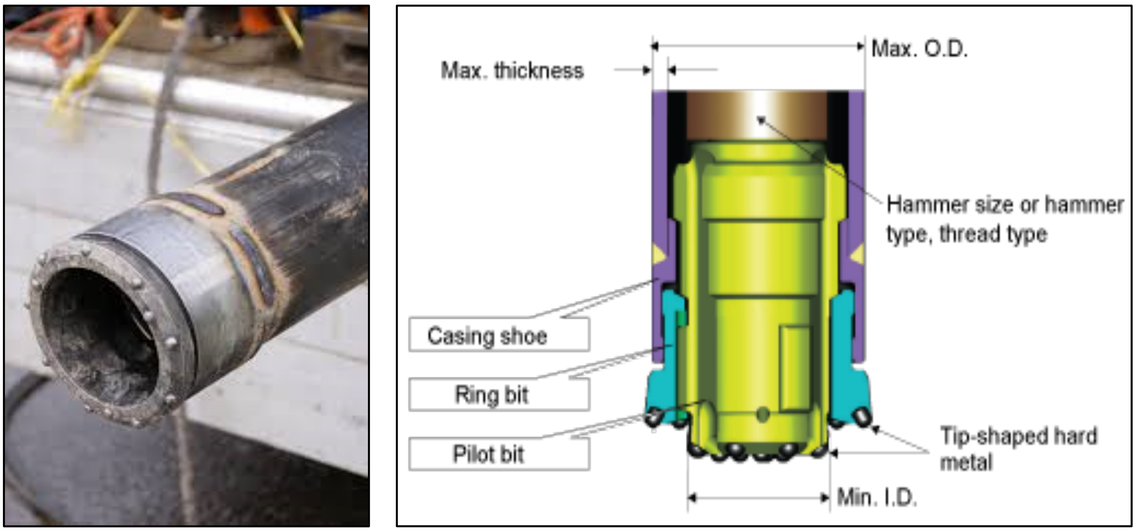


Figure 5. A rotating disposable ring bit attached to the bottom of the non-rotating casing has become the dominating method for drilling down the casing. After reaching firm rock conditions the casing is withdrawn a meter or so. The bottom of the borehole is then filled with grout, through which the casing is reset leaving grout to harden in the annular space between borehole wall and the casing. Finally, the grout inside the casing is drilled out. There is today no method to establish that the grout actually seals off the later drilled open-hole below the casing from groundwater in the soils

There are two standard size casings, 139,7 and 168 mm. The majority of boreholes are drilled with 139,7 mm steel casing and with 115 mm open hole. The diameter in the open hole with 168 mm casing is 140 mm. The larger diameter is preferably used for double U-pipe BHE installations and for deeper boreholes in which single U-pipe with a diameter of DN45 or DN50 is installed.

The open-hole drilling is performed with a button bit. Drilling in granite or gneiss, a 115 mm drill-bit will last for 400-500 m of drilling, depending of quartz content in the bedrock. An abrasion of the drill bit with 4-5 mm of the diameter is the maximum.

The high speed of compressed air together with sharp edge cuttings will also erode the drilling pipes However, the rods are made of special steel alloys that will make them last for many thousands meter of drilling.

The rate of penetration at open-hole drilling is approximately 1-1, 5 minutes when drilling in hard crystalline rocks. A pressure of 30-35 bars is commonly used and these highly effective compressors allow drilling to depths down to 300 m or more. As can be seen in figure 6 the deepest GSHP borehole drilled with air is around 500 m, and the average borehole depth is steadily increasing with time.

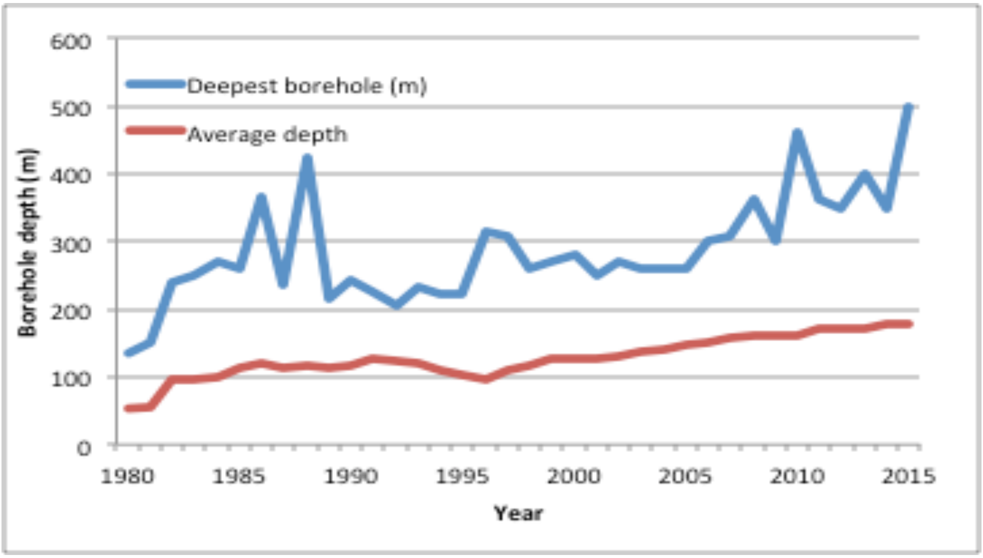


Figure 6 Trends of borehole depths at DTH drilling. The deepest boreholes in 1980-90 are due to the introduction of a booster drilling technology (several compressors in series) where a large size drilling rig was used. The increase of average depth the last 20 years is also dependent on a decreased portion of more shallow water wells compared to energy boreholes.

Deep energy boreholes are most common in dense urban areas with a limited space for several boreholes. Under such conditions it is also common to drill deviated boreholes in order to involve enough rock mass for the designed thermal exchange. Still, both vertical and deviated boreholes are not always as straight as designed. Measurements in drilled boreholes have shown a considerable drift of the target spot that sometimes is 20 m or more. This is a potential problem, especially in urban areas with a number of adjacent installations.

The yield of water during drilling is a limiting factor when using compressed air for drilling deep bore holes. If the rock is dry, or contains only minor water holding fractures, a depth of 300 m or more is easily reached. On the other hand, a large yield of water can drastically shorten the target depth. In such a case additional boreholes may have to be drilled.

Another method for deep drilling is to use the water driven hammer. This technology is more or less limited by the lifting capacity of the drilling rig and the borehole diameter, but with a medium sized rig a depth of 300-400 m with 115 mm can be drilled. However, loss of fluid through fractures in the rock may be a limiting factor.

The water driven hammer method works with highly pressurized water. The high pressure, ca 200 bars, requires thicker drill pipes, but apart from that the same rig as for drilling with air can be used. The method can only be applied with clean water as flushing medium. Hence, the water coming up from the borehole must be disposed after the cuttings have been separated. The water consumption, approximately 4 l/s while drilling is a considerable cost factor as well as cleaning the water from cuttings before disposal. Still, this drilling method has become more frequently used the last 5-10 years since it is more energy efficient than using compressed air and under certain geological conditions it may be the only option.

The driller must in general follow what is regulated in AFS 2006:4 in order to protect the personal as well as any third part. There are special rules for hot works (by example welding). Many drilling contractors are using a Safety Check List prior to drilling. At large construction sites the drillers have a “safety education”.

The drillers try to classify the stratigraphy at their best knowledge based on cutting samples and changes in lithology. Stratigraphy is reported to the Swedish Geological Survey (SGU) by completing a documentation form. The form also contains information on level of fractures and air-lift yield, salinity, and the ground water level. In rare cases the borehole deviation is measured, but else no geophysical logs are run.

The temperature is always recorded as a part of TRT: s. Initial circulation of fluid in boreholes also gives a clue on the geothermal gradient. The drilling process creates a temperature increase along the borehole length. For this reason the TRT cannot be performed until the normal borehole temperature has been reestablished. This takes normally from a few days, up to a week.

Backfilling

Only a fraction of the boreholes in Sweden must be grouted (or sealed off one way or another). Thermal enhanced grout is commonly used if full-hole grouting is required, more seldom alternative sealing methods.

At least 90 % of all boreholes are drilled into crystalline rocks, most commonly granite and gneiss. The overburden is drilled by a steel casing at least 2 meters into the crystalline rock. Before drilling the open hole the casing is sealed off by grout, see former figure 5.

The same method is used in areas with sedimentary rocks (commonly limestones, shale and consolidated sandstones). In rare cases the rocks contains more than one aquifer. In these cases the borehole must sealed in a way that mixing of water from different aquifers is avoided.

Alternative sealing by different forms of sealing plugs that are attached to the BHE are mainly used to prevent salt or brackish water from entering higher levels in the boreholes, but may potentially also be used to seal off potential leakage between aquifers.

For full hole grouting a tremie pipe is used to pump down the grout from bottom to top. For deep holes the grouting must be performed in two or even three steps. There is no manual available in Sweden and the knowledge about grouts, its properties and grouting procedures is generally low among designers, drillers and installers.

Research and development is going on by using a full hole capsule, which is hydraulically pressed towards the borehole wall. This system has not yet been approved by the authorities.

There are several thermal grouts on the Swedish market. The suppliers provide information on thermal conductivity, density (at certain water contents) strength and permeability after hardening. This data is given as defined at laboratory tests. The thermally enhanced components are mainly finely grained quarts sand and/or graphite.

There are no special mixers for grout, other than the ones used for grout injection at construction of tunnels etc.

Installation of Borehole Heat Exchangers (BHE) and horizontal pipe systems

Installation of the borehole heat exchangers is done with specially made reel equipment's, often with an electric motor as an aid. The BHE is pressure tested and filled with water prior to insertion, and balanced by a bottom weight. A slight over-weight will straighten the shanks of the BHE. The bottom weight is left hanging a few decimeters above the bottom of the hole to give room for thermal expansion during operation. However, there is no standardized procedure for BHE insertion in Sweden.

Leakage test is done before and after insertion, commonly by using 5 bars until a stable pressure drop is reached. The duration is typically 30-60 minutes. The loss of pressure due to expansion depends on the BHE length and type of PE, but is by experience 0, 5-1 bar. The pressure test is then repeated when the total system is installed, commonly after the system has been filled with the heat carrier (water and ethanol) and the primary degassing of the fluid has been executed. There is yet no standard procedure for how to perform pressure test in Sweden.

Normally the pressure tests are documented in a protocol over self-controls by the contractor and as part of the documentation (only larger systems).

Occasionally a flow test is required in order to find out the flow resistance at different flow rates. More commonly the flow resistance is only calculated.

For the horizontal connections and pipe installation, welding of joints/gaskets should be performed by a certified plastic welder. Unfortunately this is not always the case at present, but the importance of this issue must be emphasized.

Thermal extension of plastic pipes is not always considered, but normally coped with by placing the pipes with a slight sinus curve when it comes to horizontal pipe systems.

The pipes are resting on and in best case surrounded by a layer of sand. Sharp edged particles are not allowed. Often the shafts with horizontal pipes are documented by photographs for larger systems.

Test protocols as self-control by the contractor is part of the final documentation (only larger systems).

Functional control of the system is required to have the system approved at the final inspection (only applies for larger systems and not for small systems with one or two boreholes).

Quality control at the start up

In general, all large projects are subject to a final inspection as soon as the plant has been put into operation. This inspection is done according to the general rules in ABT06 or AB04 and serves as a first quality and functional control of the total system.

In short, the contractor delivers a set of documents that show how the system is constructed, the main components and the function of the system. These documents must be delivered prior to the final inspection. Prior to the inspection also functional controls must be made and documented by the contractor. Finally, also operational instructions will be a part of the documentation supplied by the contractor.

The documentation is delivered as paper files as well as in digital form. The inspector or set of inspectors will carefully review all documents and protocols and note whatever quality faults and weaknesses he finds. The inspector may or may not approve the status of the installation. If not the inspection is repeated until the faults have been corrected.

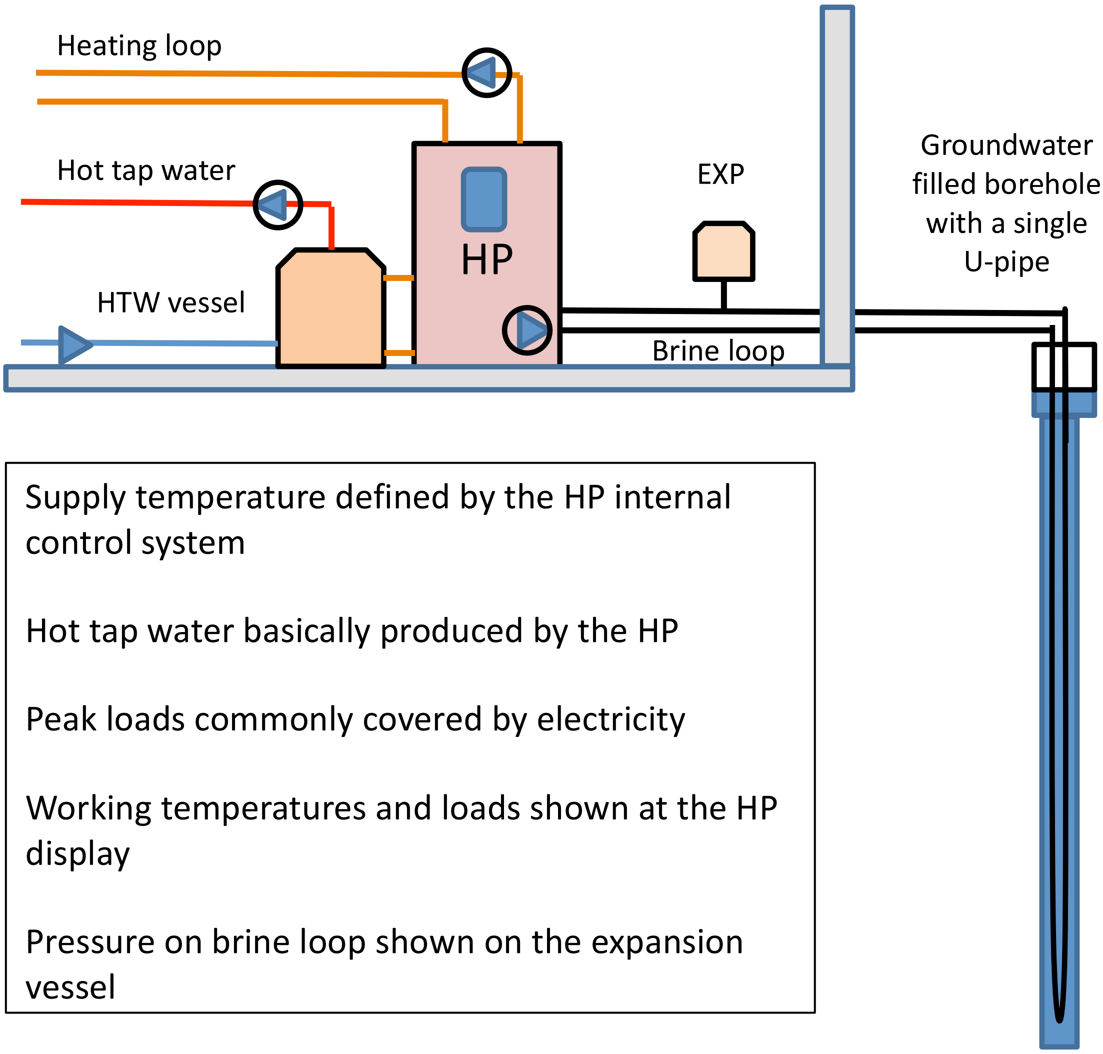
CONTROL AND MONITORING SYSTEMS

Smaller systems

By small systems is understood one or a few boreholes that serve as a heat source to a single heat pump. The heat pump size would typically be in the order of 5-10 kW, occasionally up to 20 kW, serving single-family houses or minor multifamily buildings with space heating.

The number of boreholes varies depending on geology and target depth. Commonly simplified table values are used in the design. Nowadays a certain “safety marginal” is applied to avoid under-design of the thermal active borehole length. The borehole depth in standard design is commonly around 200 m, and the borehole is groundwater-filled.

The heat pump and a second source for peak loads produce all heat to radiators or floor heating and hot tap water. The design is more or less standard and can be found at the homepages of heat pump suppliers. A typical principal flow chart is shown in figure 7.



Supply temperature defined by the HP internal control system

Hot tap water basically produced by the HP

Peak loads commonly covered by electricity

Working temperatures and loads shown at the HP display

Pressure on brine loop shown on the expansion vessel

Figure 7 Principal flow chart for a smaller GSHP installation

The modern heat pumps with scroll compressors can work with variable loads. They contain an in-built circulation pump for the brine loop as well as in-built peak load coverage (electric canister). Optionally, the water heater can be a single unit as side equipment as shown in the figure. Some heat pumps produce hot water above +60°C by using a "hot gas heat exchanger". This temperature is mandatory for elimination of Legionella bacteria.

The heat pumps have an internal control system that regulates the supply temperature with respect to the outdoor temperature. The heat load curve is adjustable.

The heat carrier fluid is typically circulated at the same flow rate. This means that delta T over the evaporator varies depending on the heat pump load. The heat carrier temperature values, as well as the heating loop values and current electricity load, are visible on the heat pump display.

If the inlet brine temperature gets too low, the heat pump will at first show an alarm on the display. If the temperature continues to drop the heat pump will automatically stop at a certain (adjustable) value.

There are normally no special monitoring meters attached to the brine loop. However, sometimes there are at least a thermometer on the loop and a manometer for visual inspection of the system pressure on the expansion vessel.

Functional control of the boreholes is not an issue, except for checking that the brine loop is keeping its working pressure.

Larger systems

By large systems means multi-borehole installations for large residential buildings and BTES systems for commercial and institutional buildings.

The borehole system serves as an energy source for heating with one or several heat pumps, or to produce free cooling for air-condition and sometimes also process cooling.

Depending on the size of application the borehole system is either designed by experiences (typically 5-10 boreholes), or by using the EED (Earth Energy Designer) model as a tool (typically > 10 boreholes).

The borehole depth in larger systems will often be "as deep as possible" due to limited space in an urban environment. For the same reason the boreholes are sometimes deviated. Typical borehole depths under these conditions are often 200-250 m, but occasionally 300 m or more.

The heat pump output capacity varies from 20 kW up to 1 MW, with the majority around 100-300 kW.

For systems up to 200-300 kW it is common to use several "small" standard heat pump sizes (20-60 kW) to cover the design load. For larger systems (>300 kW) single "industrial heat pumps" with variable speed screw compressors, or in late years scroll compressors are commonly used.

The heat pumps are always equipped with internal control and monitoring systems. The main difference, compared to small heat pumps, is that the brine circulation pump will be specifically designed and placed on the brine loop. This pump is then controlled and monitored by the external control and monitoring system. The pump is often frequency controlled (inbuilt or attached).

The external control system must for many reasons be able to communicate with the internal heat pump control system in order to have a functional production of heat and cold (often by MODBUS).

The external system will control and monitor a number of regulating valves, temperatures, pressures, flow rates, use of electricity, and produced heat and cold. A typical design is shown in Figure 8.

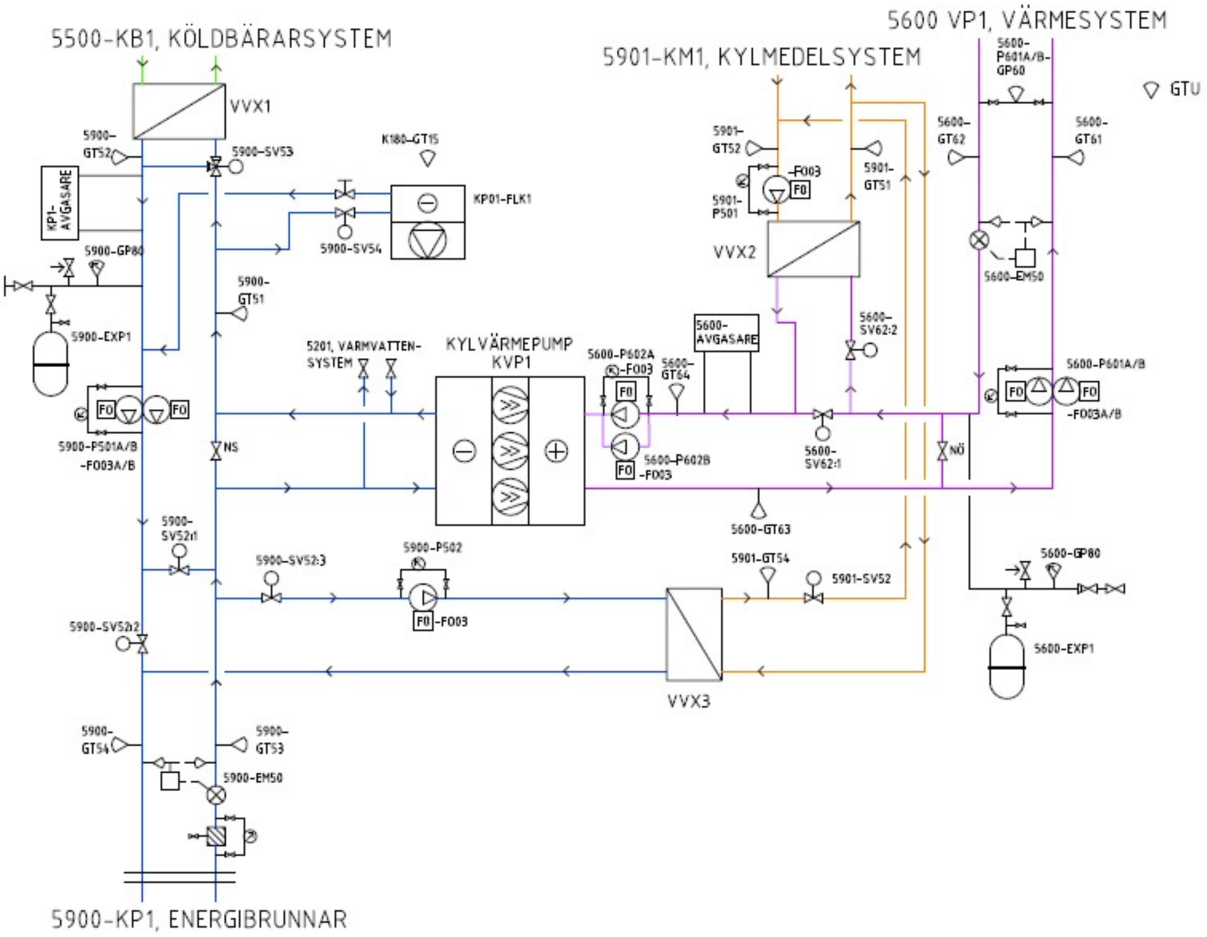


Figure 8 Example of control and monitoring system for a BTES application (Kristallen in Lund). The heat carrier loop (blue color) is only shown as indoor installations which is typical since the boreholes have no controllable function

Exclusively for the heat carrier loop only temperature in and out is monitored. Only occasionally the electricity used for circulation of the brine loop is measured as well as thermal energy produced from the boreholes.

Measuring of borehole temperatures is rarely done. Still, there are some examples of recordings that have been applied for legal reasons. One such example is shown in figure 9, where the temperature variation in a BTES borehole is shown.

The figure shows a typical seasonal variation of the temperature over a full year in a borehole placed at the center of a borehole field with 100 boreholes, 180 m deep. Another graph shows that the salinity front is lifted upwards, caused by an increased temperature in the boreholes during heat injection in the summer season. This data was used to prove that salty water from the bottom of the borehole field did not enter the fracture system on the top.

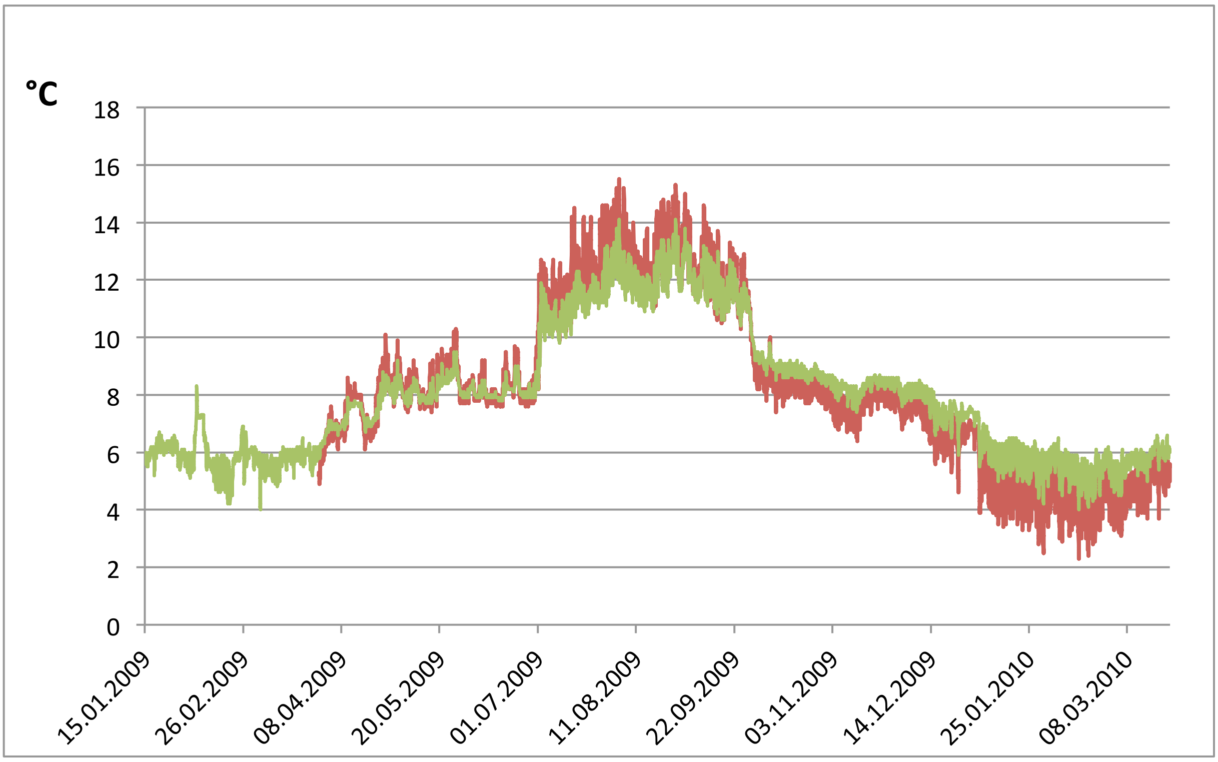


Figure 9 Borehole temperatures in BH 4 at 50 m (green) and 100 m depth at the IKEA BTES plant in Uppsala.

Maintenance

"No maintenance required" would be a trade mark for boreholes used in GSHP and BTES systems. Hence there is hardly any maintenance program applied, neither in general terms nor as contractual terms. The common approach is that there are no "mobile parts" in need of maintenance and that the system is properly designed and constructed.

One sensible and visible part of a borehole system is the field manifold. These are often dug down underground and exposed for moisture and sometimes water. For this reason metal parts (mostly brass valves) may be corroded and not functional.

In some contracts a periodic supervision is prescribed as a maintenance point in a program that else is concentrated to indoor equipment's.

On the other hand the indoor maintenance program may give indications that something is wrong with the borehole system. In this way the boreholes can be considered as an indirect part of the main maintenance program.

System efficiency

Smaller systems

For smaller systems COP is given by the heat pump contractor based on information from the heat pump manufacturer.

The COP values are commonly to be found on the homepages of the manufacturer, but perhaps not always truly clear for the customer. The COP varies a lot with inlet temperature to the evaporator and the outlet temperature from the condenser, see figure 10.

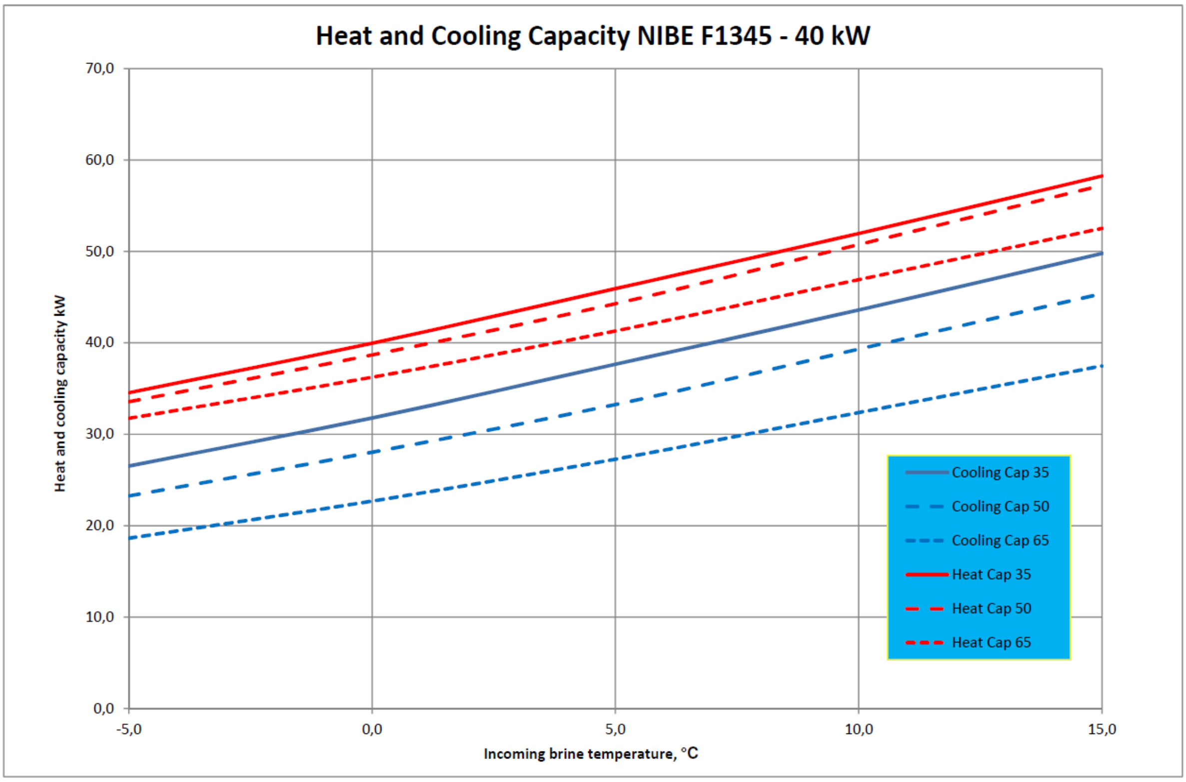


Figure 10 Condenser capacity as a function of operating temperatures. Nominal value is 40 kW at 0^{o}C brine temp in and 35^{o}C heating supply temp (Nibe 2016)

COP values at different temperatures, calculated from the graph in fig. 10, are shown in Table 1

Table 1 COP as a function of different working temperatures for Nibe F1345-40 kW.

Condenser outlet temp (^{o}C)	Brine inlet temp (^{o}C)	Condenser effect (kW)	Compressor effect (KW)	COP (kW/kW)
35	-5	34,5	7,9	**4,4**
	0	40,0	8,1	**4,9**
	+5	45,9	8,3	**5,5**
50	-5	33,5	9,7	**3,4**
	0	38,5	10,5	**3,7**
	+5	44,2	10,9	**4,0**
65	-5	31,8	13,0	**2,4**
	0	36,2	13,4	**2,7**
	+5	41,3	14,0	**3,0**

Comparing the diagram in Figure 10 with the values in Table 1 it can be shown that the inlet temperature from the boreholes substantially affects the COP, as well as the thermal capacity of the condenser. For this reason it is of great importance that the borehole system is not undersized. Instead, it would be favorable to slightly oversize the borehole length.

Larger systems

For larger systems certain COP or SPF values is theoretically calculated in the design phase (if not earlier). In practice it has been shown that the theoretical values seldom correspond to the actual measured ones. Often the design values are overestimated. Evaluation based on detailed monitoring over a longer period of time is unfortunately so far rarely performed, which means that system may run under non-optimal conditions.

There are some exceptions where monitoring and calculation of system efficiency is a contractual term of condition. This is often the case if the owner is expecting to have the building classified according to environmental classification systems, such as Green Building, LEED or BREEAM. In such cases highly efficient GSHP or BTES systems would be gold worth, at least potentially.

To fulfill any requirements given for certification the prime energy consumption must be measured carefully and efficiency monitored. An example of such a case is Kristallen in Lund, a densely populated administrative building owned by the municipality. It was constructed in 2013 and for heating and cooling a BTES system was applied in order to have the building certified according to the Green Building system.

A borehole field with some 4 000 m borehole lengths is connected to the indoor system shown in the former Figure 9. In the contract it was stated that the SPF for production of heat, hot water and cold should not be less than 5,0. This means that the use of electricity has to be less than 20 % of the thermal energy produced by the system.

In the Lund case it was shown that the system did not fulfill the demands the first years of operation. However, after a number of system adjustments the SPF now seems to be in the same order as the design values (Guide för Geoenergi, Gehlin 2017).

PROBLEMS AND SOLUTIONS

Boreholes for GSHP systems have been drilled and used for more than 40 years in Sweden. More than 400 000 boreholes for energy use have been drilled over the years, with approximately 20 000 new boreholes for GSHP systems drilled every year this last decade. While there is statistic material available on numbers and depths of drilled boreholes from the Geological Survey of Sweden, and sales figures on heat pumps, there is no specific statistics collected on problems and failures of GSHP systems. Some information is available from insurance companies; however that information mainly concerns heat pumps and installation. On the whole the frequency of known damages and failures is very low, considering the large amount of produced GSHP boreholes.

Occurring problems and failures may be categorized based on when and where they occur:

- Drill site issues
- Impacts of drilling
- Issues related to borehole heat exchanger and piping
- Damage occurring after installation
- Problems occurring after start of operation

Occurring problems could further be classified as human safety risks, risks for the environment or for economic consequences. In the following, examples are given of failures and problems that have occurred in GSHP systems the last 40 years, with focus on the ground part of the GSHP systems.

Drill-site issues

Issues occurring at the drill-site could either be related to work safety regulations or to the disposal of excess water from the drilling process.

Work safety regulations

Swedish drillers are well aware of safety risks at the drill-site. Work safety and work related health issues at Swedish drill-sites are well regulated through the Working Environment Regulation Law (AFS 2006:4). AFS 2006:4 is typically referred to in drilling contracts. Also some guidelines are available concerning safety at drill-sites (Borrningssäkerhet, Prevent 2008).

The AFS regulation stipulates that the site supervisor is responsible for checking and securing the work place in order to minimize risks for health and accidents. Accidents occur, but fatal accidents are fortunately very rare. The most common injuries reported are crushing, tool handling, heavy lifting, etc. According to the AFS statistics one single fatal accident is reported as “a driller” over the last 15 years (the person got stuck under a falling rig).

Improving safety in the use of very high air pressure would be particularly desirable. Modern compressors work with pressure levels up to 35 bars. Obviously, being hit by a broken hose coupling may be fatal. The Swedish drillers’ organizations are continually working with education and procedures to minimize risks for drill-sites accidents.

Disposal of drilling excess water

An acknowledged problem for drillers is how to handle the excess water from the drilling procedure in a way that meets the prerequisites from local authorities. In some Swedish municipalities, this causes significant difficulties, while in others not.

Practically all boreholes for BTES and GSHP systems in Sweden are drilled with down-the-hole hammer drilling, where the compressed air removes cuttings from the drilling process and water from the bedrock, from the borehole to the ground surface. This exhaust from the borehole consists of a mix of water, air and drill cuttings of various sizes. The disposal of this borehole residue has in recent years become an issue, particularly in urban areas.

Finely grained particles (silt and clay) in the drilling exhaust water stay in suspension for a very long time, even if the water is calm. A common method to separate the coarsely grained particles is by using a container (typically 10 m^3). Finely grained particles in suspension may still pass with the excess water pumped to a recipient (lake, pond or stream). If further reduction of the amount of particles in suspension is required, the water is pumped to one or several larger containers (often 30 m^3) for sedimentation. This will typically settle fine sand and silt, but clay will remain in suspension. The problem is most significant for drilling in sedimentary rocks producing large quantities of fines. It is less significant when drilling in crystalline rock where the content of fine particles (<0.06 mm) is typically much lower compared to most sedimentary rock types.

Insufficiently settled drilling exhaust water disposed to storm water systems or to a lake or stream, may settle in the piping system and/or in the end recipient, causing negative effects under some circumstances. Only one such event has been reported over the years; a let-out in a minor stream that caused limited fish death. This incident was combined with construction of a large tunnel project in which bentonite was used.

Impacts of drilling

Many Swedish BTES and GSHP systems are located in dense urban areas, where the drill-site be surrounded by buildings and infrastructure. There are reported examples of drilling related ground uplifts, settlement and cavities causing physical damage to surrounding buildings and infrastructure, in particular when boreholes are located very close to buildings.

Uplift and bursting

Under certain geological conditions, drilling with highly compressed air could cause an uplift of the ground, resulting in damage to buildings and roads. This could occur in geological formations where bedrock is covered by a layer of permeable sand with a top layer of clay. When drilling through the clay and reaching the permeable sand layer, it is possible that exhaust air is trapped between the bedrock and the impermeable clay layer, causing an uplift of the clay cover with resulting damage on surrounding buildings and pavement.

The drillers’ organization Geotec in Sweden has estimated that such uplift damage occurs with an approximate frequency of once every 10 000-12 000 drilled boreholes (approx. 2 times/year).

Settlement and cavities

Over the years there have been a few examples where unwanted cavities have formed in the ground and have caused building settlement and subsequent damage. Certain geological conditions, with thick overburden of saturated fine sand and silt (“quicksand”), in combination with high friction and drilling ejector capacity, could cause over-production from these layers. Cavities may also form after drilling and borehole heat exchanger installation if the geological conditions allow for running sand resting directly on top of the bedrock to find its way down to the borehole below the upper borehole steel casing, and the casing is not properly sealed. There are a few known examples of such cases, where insurance companies have been involved, but in general the experienced and cautious driller would be well aware of these risk factors.

An estimation based on reported cases in newspapers and consultancy reports indicates a frequency <1 incident/year.

Issues related to borehole heat exchanger and piping

The three most common types of problems related to the BHE installation process are underground obstacles, borehole shortcutting and problems with pipe welding and connections.

Down-the-hole obstacles

In crystalline rock with fracture zones, swelling clay and bends in the borehole, obstacles may occur along the borehole, which will prevent the borehole heat exchanger from being installed at its full length. In sedimentary rocks the most common down-the-hole obstacle is layers of poorly consolidated sand beds. These issues are regarded as purely technical/economic problems and are commonly solved by additional boreholes.

A study based on borehole protocols from 8 larger GSHP and BTES projects indicates a frequency of approximately 5% in crystalline rocks. The study covers 762 boreholes with a total length of 140 000 meters in projects performed over the last 10 years. A similar study with six projects in sedimentary rock (limestones, shales and sandstones) indicates a frequency of approximately 10 %. In this case the number of boreholes were 262 representing a total of 52 450 meters of drilling.

In general, the main causes for down-the-hole obstacles are related to unstable fracture zones and large water quantities in crystalline rocks. In sedimentary rock, the higher frequency mainly depends on loose unstable sandstone layers that cause problems at insertion of borehole heat exchangers, and also problems reaching the target depths.

Borehole shortcutting

In borehole fields with a few meters spacing between the boreholes, occasionally one borehole is drilled into another borehole. It occasionally also happens that a borehole on one property is drilled into a borehole on a neighboring property. This kind of damage is regarded as a purely economic problem, without environmental consequences. The frequency of such incidents is estimated to be 1-2 % or less.

When drilling in rock with water-holding fracture zones, compressed air may occasionally find a path through fractures to enter a borehole where a borehole heat exchanger is already installed. This is called “air shortcuts” and may in its worst scenario lead to a blow-out of the borehole heat exchanger. Apart from damage to the borehole heat exchanger, such incidents are also a safety risk. Therefore borehole heat exchangers are secured with a locked and reinforced borehole cap as prevention for blow-out. The frequency of such incidents is estimated to be less than 1%.

Pipe welding and connections

Welding of connections between borehole heat exchanger pipes and horizontal piping should always be performed by a certified welder. This is normally the case, especially for larger projects. Mistakes in the welding procedure sometimes occur, and if so, the pressure tests performed prior to the backfilling of the trenches will help to find the leaking joint.

Leakage may in rare occasions appear long after the installation. These types of leakages may occur due to multiple extension and extraction of the piping over time, initial microscopic fractures, wearing by sharp edged stones, etc. These potential risks are minimized by careful design and construction. These types of problems were more frequent in the early days of GSHP history but have now become very rare, estimated to be less than 0.5 %.

Borehole sealing and backfilling

Swedish drillers follow the guidelines issued by the Geological Survey of Sweden (SGU), stipulating steel casing of the borehole drilled through the overburden and at least 2 meters into hard rock. The steel casing must be properly welded and sealed with concrete where it meets the bedrock. This is done to protect surface water from leaking into the groundwater. Few examples of surface water leakage exist from properly installed borehole heat exchangers following these guidelines.

Since most Swedish borehole heat exchangers are installed in groundwater-filled boreholes without the requirement for backfilling, there is limited experience from grout and backfilling. Inexperienced drillers may make mistakes in choice of grout and backfilling methods that could lead to squeezing of the piping or insufficiently sealed boreholes. There are few reports on damage caused by backfilling.

Damage occurring after installation

Drainage and artesian ground water flow may cause problems and damage occurring after installation of the borehole heat exchanger.

Settling due to drainage

In the middle Swedish lowland with massive postglacial clay deposits, the geological conditions are such that there exist locations where the static head in the rock is lower than the groundwater level in the soil, and the soil layers of water saturated clay are sensible for settlement. If these criteria are met and the borehole steel casing is improperly sealed, there may be a flow of groundwater into the rock through the boreholes, resulting of settling of the ground and subsequent damage to buildings.

There is one reported case of such settlement damage from the 1990's from this area, but no more recent reports of such incidents.

Artesian flow

Fractures with artesian water may be hit by boreholes drilled at locations surrounded by hills, in valleys, and along hillsides, etc. Boreholes must then be carefully sealed with grout or by using packers, there is risk for an increase in groundwater level in the surrounding soil. It its worst case this may flooding of nearby houses and gardens, etc. Artesian groundwater is quite common in places surrounded by hills. Most boreholes are however located in flat urbanized areas. It is estimated that <2 % of all energy boreholes are drilled in artesian groundwater areas.

Problems occurring after start of operation

When damage or operational problems occur within the first few years of operation, the most probable cause would be that the system was improperly designed. This may result in issues such as damage due to freezing in boreholes, ground uplift due to freezing and ground settlement. There are also issues related to brine leakage and de-gassing.

Freezing of boreholes

Common practice in Sweden is to design GSHP systems with groundwater-filled boreholes so that the average temperature of the heat carrier fluid never decreases below -3°C. This will prevent the groundwater in the borehole to freeze completely. Under some circumstances water in the borehole could be trapped between two ice plugs, and in such case there is a risk that the borehole heat exchanger pipes are squeezed as the water freezes and expands. In the worst case the pipes are damaged, resulting in heat carrier leakage.

A study from early 2000 (Nordell and Ahlström, 2006) indicates that approximately 1 out of 10 000 GSHP boreholes for single family buildings in Sweden were damaged by freezing, with the highest frequency occurring in the northern part of Sweden.

For larger GSHP systems, there are some examples of severe freezing of the entire borehole field, due to too closely spaced boreholes, or insufficient borehole depth. In these cases heat significantly exceeded the natural heat recovery in the ground, and no active heat recovery was installed. There are only a couple of such incidents reported over the years. With approximately 2 000 systems with more than 10 boreholes each, the estimated frequency of such frozen systems would be around 0.1%.

Formation of cavities

Annual freezing and thawing of the soil around a borehole may under certain geological conditions cause settlement or cavities around boreholes. Damage investigations have concluded that a combination of insufficient borehole spacing, improper borehole sealing and unfavorable geological conditions is the most probable cause. Only a few such damages have been reported. An estimate of the frequency is <0.1%.

Frost heaving

The horizontal piping connecting the borehole heat exchanger with manifolds and building is placed in trenches, typically at a depth of 0,8-1,0 m. If the trenches are excavated in impermeable soil there is risk that the trenches serve as a drainage system for the surrounding ground. When this drain water freezes, it results in ground surface heaving.

Damage of this kind is prevented by drainage of trenches, insulation of sensitive places such as under buildings, and by avoiding too low heat carrier fluid temperatures. Few examples are known or reported. The frequency is estimated to not exceed 0.1 %.

Loss of heat carrier fluid

A large leakage of heat carrier fluid is easy to detect and locate, while a minor leakage may be much more difficult to locate. From an environmental point of view leakage of heat carrier fluid on the ground surface and in the boreholes may affect the quality of groundwater and possibly also affect micro fauna and flora. This type of incidents has been very rare over time and has decreased even further in later years. The cases known from later years are practically all caused by incidental digging into the horizontal pipe system. The frequency is <0.1%.

Air in the heat carrier fluid

After installation, the borehole heat exchangers of a GSHP system are filled with a heat carrier fluid, by replacing the water that the borehole heat exchangers were filled with during insertion. For larger

GSHP systems this re-filling of heat carrier fluid is done either through the manifolds or at the main pipes at the energy central.

The manifolds are commonly equipped with air valves. The main re-filling and de-gassing of the heat carrier fluid is however done by circulating the fluid through an open container until air bubbles can no longer be observed. A large number of microscopic air bubbles are still left in the fluid after the first de-gassing procedure. Over time these micro-bubbles will merge into larger bubbles, increasing the flow resistance and decreasing the thermal efficiency.

Air in the system was formerly a frequent problem, but in recent years this problem has been overcome by installation of vacuum de-gassers that continuously treat a minor fraction of the flow mass, see Figure 11.

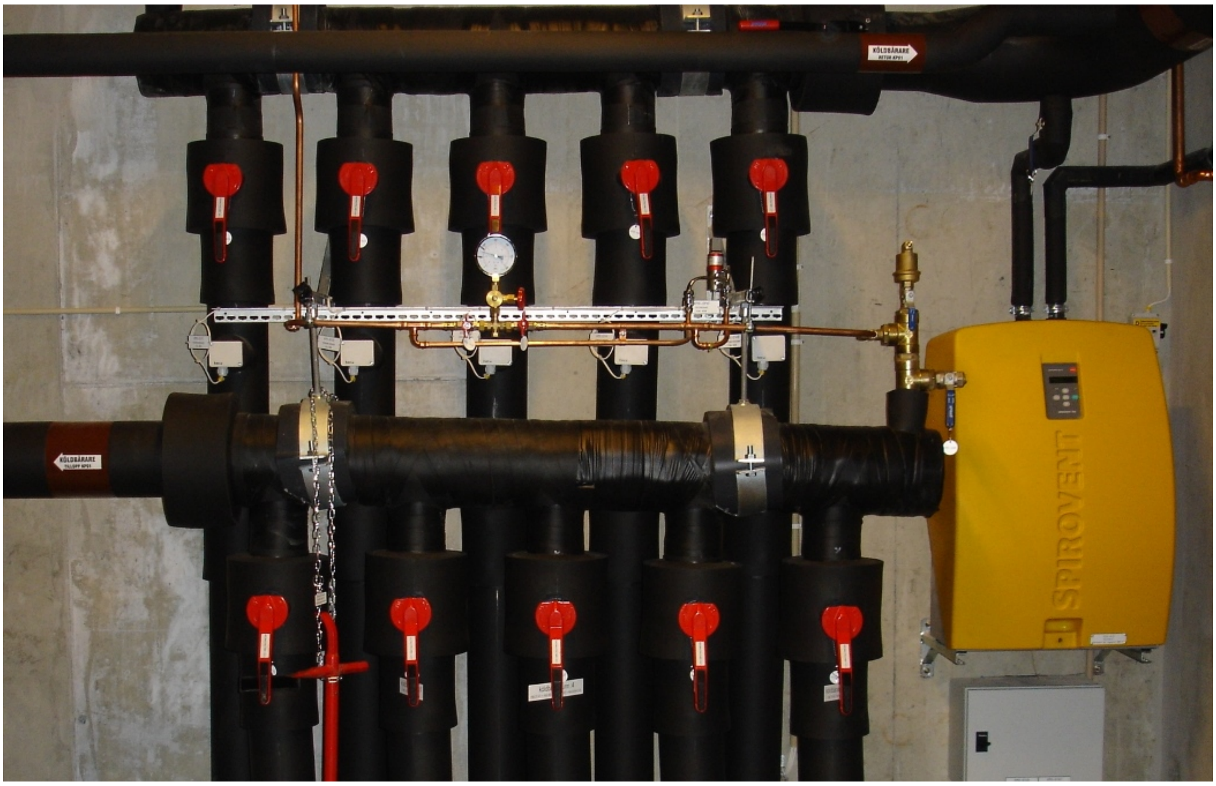


Figure 11. A vacuum degasser (yellow) installed on the suction side of the brine system. It takes a minor portion of the flow and after degassing returns it to the pipe. Photo: Olof Andersson

LITERATURE

AFS 2006:4. Användning av arbetsutrustning (use of working equipment). Arbetsmiljöverket.

Allmänna Bestämmelser, Svensk Byggtjänst, 2004/2006

AMA Anläggning 13

BBR 18, chapter 9

EN ISO 17628:2015 Geotechnical investigation and testing – Geothermal testing – Determination of thermal conductivity of soil and rock using a borehole heat exchanger.

Gehlin, S., 2017. Guide för Geoenergi. SKL, Offentliga Fastigheter 2017.

Gehlin, S., and O. Andersson. (2016). Geothermal Energy Use, Country Update for Sweden. Proceedings from European Geothermal Congress 2016, Strasbourg, France, 19-24 September 2016.

Hjulström, J., 2014: Disposal of groundwater mixed with drill cuttings through storm drainage pipes: Risk assessment, characterization of drilling waste water and purification methods. Dissertations in Geology at Lund University, No 414, 46 pp. 45 hp (45 ECTS credits)

Konsumenttjänstlagen, 1985:716

Köldmedieförordningen, SFS 2007:846/2009:382

Miljöbalken, MB, SFS 1998:808, Chapter 11.

Miljö- och hälsoskyddslagen, SFS:1998:899

NFS 2003:16

Nordell B, Ahlström, AK (2006). Freezing Problems in Borehole Heat Exchangers. Pp.193204. Thermal Energy Storage for Sustainable Energy Consumption - Fundamentals, Case Studies and Design. NATO Science Series, Series II: Mathematics, Physics and Chemistry - Vol. 234. Ed. H Paksoy. ISBN-10 1-4020-5288-X (HB).

Prevent Arbetsmiljö 2008. Borrningssäkerhet (Safety at drilling), www.fab.w.se

SFS 1975:424

SFS 1985:245

SGU (2016). Normbrunn-16. Vägledning för att borra brunn. Sveriges Geologiska Undersökning.

Svenskt Geoenergicentrum (2015). Riktlinjer för Termisk Responstest (TRT).