

DESIGN AND OPERATION OF GROUND-SOURCE HEAT PUMP SYSTEMS FOR HEATING AND COOLING OF NON-RESIDENTIAL BUILDINGS

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Abstract: Ground-source heat pump (GSHP) systems represent an energy efficient technology for heating and cooling of non-residential buildings due to the relatively high and stable heat source temperature and the fact that a considerable share of the cooling demand can be covered by means of so-called “free cooling”. Installation of high quality GSHP systems therefore complies with the main goals of the new EU Directive on The Energy Performance of Buildings (Directive 2002/91/EC), i.e. reduction of the total primary energy demand and the associated CO₂ emissions in buildings.

The paper discusses the main characteristics of GSHP systems for heating and cooling of non-residential buildings in Norway including operational experiences. Several high-quality GSHP systems are presented, including installations in office buildings and a hospital. The latter GSHP system is connected to one of the largest underground thermal energy storages in Europe comprising as many as 350 boreholes in crystalline rock.

Key Words: *heat pump, rock, groundwater, non-residential bldgs., design, operation*

1 INTRODUCTION

The vast majority of the GSHP installations in Norway are indirect closed-loop systems utilizing vertical boreholes in crystalline rock as a heat source, heat sink and/or underground thermal energy storage (UTES). There are also a number of installations utilizing groundwater as heat source and heat sink. In order to obtain sustainable, energy efficient and reliable GSHP installations, it is important to implement a *Total Quality Concept* focusing on system integration during all stages of the project – i.e. planning, design, installation, commissioning, operation and maintenance for the heat source system, the heat pump, the distribution systems for heating and cooling as well as the overall control and monitoring system.

There are about 15,000 GSHP installations in Norway, including 250 medium- and large capacity systems for non-residential buildings, where the largest installation has a heating capacity of about 8 MW. The annual heat supply and energy saving for Norwegian GSHP systems are estimated to be approx. 2.0 and 1.4 TWh/year, respectively (NGU, 2008). The Geological Survey of Norway (NGU) has made a tentative overview of large-capacity GSHP systems in Norway (<http://www.ngu.no/no/hm/Georessurser/Grunnvarme>).

2 DIRECT GSHP SYSTEMS – GROUNDWATER

2.1 Temperature, Availability and Quality

In groundwater heat pump systems, the water is used as a heat source and heat sink or, in rare cases, as an aquifer thermal energy storage (ATES). In Norway, the temperature in groundwater reservoirs 10 to 15 metres below ground level is typically 1 to 2 K higher than the average annual air temperature at the site, and the temperature is virtually constant during the year. Figure 1 shows a rough overview of the groundwater temperatures in Norway, Sweden and Finland (NGU, 2008).

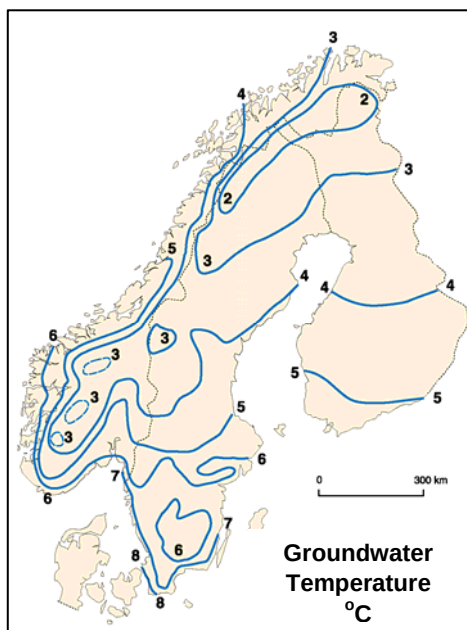


Figure 1: Groundwater temperature map for Norway, Sweden and Finland (NGU, 2008).

Figure 2 presents weekly temperature variations during one year for air, river water and groundwater at town of Elverum, which has an inland climate (NGU, 2008). During the winter the air temperature fluctuates between -25°C and +10°C, the temperature of river water is close to the freezing point, whereas the groundwater temperature remains more or less constant at +5 to 6°C. This clearly demonstrates the advantage of using groundwater as a heat source for heat pumps in Norway. Due to the relatively low temperature level, groundwater can also be used directly for cooling purposes in non-residential buildings. Groundwater heat pump systems for combined heating and cooling will therefore achieve a *high Seasonal Performance Factor* if they are correctly designed and properly operated. NGU has developed digital web-based groundwater maps (<http://www.ngu.no/kart/granada>). The borehole database contains detailed information from roughly 39,500 groundwater wells in crystalline rock, 3,200 wells in sand/gravel and 1,500 energy wells in crystalline rock (NGU, 2008). The borehole maps can be combined with detailed digital maps of crystalline rock and Quaternary geology (Chapter 3.4).

2.2 Design – Pitfalls and Operational Problems

In groundwater heat pump systems, groundwater is pumped to the heat pump evaporator (direct system design) or to a heat exchanger separating the heat pump circuit and the groundwater (indirect system design). In Norway the groundwater comes from wells drilled in sand or gravel deposits close to watercourses (rivers, lakes) or fractured crystalline rock. The largest groundwater inflow is found in sand and gravel deposits close to watercourses.

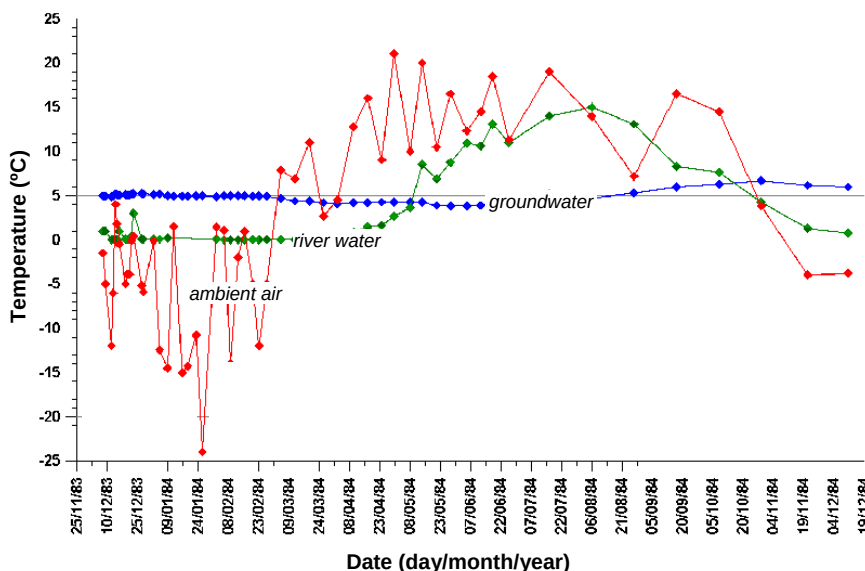


Figure 2: Weekly temperature variations during one year (1984/85) for air, river water and groundwater at Elverum, Norway – inland climate (NGU, 2008).

Typical specifications for Norwegian filter wells are (NGU, 2008):

- Well – diameter: ID 150 to 200 mm
- Well – depth: 10 to 40 m (groundwater level at -1 to -10 m)
- Water flow rate: 10 to 25 l/sec

In order to avoid lowering of the groundwater table the water is normally infiltrated to the ground after being cooled/heated by the heat pump system. Groundwater systems are designed as consumption or recirculation systems according to the available groundwater flow rate from the wells. In *consumption systems*, groundwater is pumped from the production wells, cooled by the heat pump evaporator and drained to separate injection wells (Figure 3). In *recirculation systems* the available groundwater flow is limited, and the groundwater is returned to the production wells after being cooled by the heat pump.

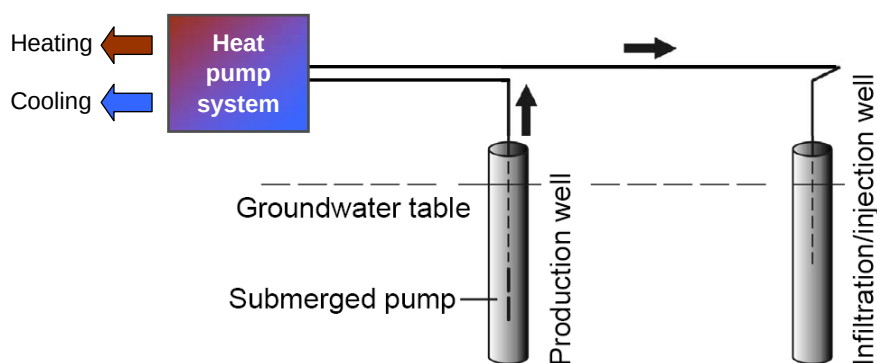


Figure 3: Principle of a groundwater heat pump system.

Prior to a groundwater heat pump installation it is of crucial importance with water analysis and test pumping that last long enough to reveal quality changes and ensure that the pumping wells and infiltration wells are sufficiently hydraulically connected. A high content of natural organic matter (NOM) as well as iron (Fe) and/or manganese (Mg) ions will lead to fouling and clogging of filter wells, heat exchangers and pumps. This will reduce the Coefficient of Performance (COP) of the heat pump unit and even cause serious operational problems. In crystalline rock wells covered with clay the salt can lead to corrosion problems.

The risk of ground consolidation and consequent damage to buildings adjacent to the groundwater wells should also be carefully analyzed by geological/geotechnical expertise when planning medium- and large-capacity groundwater heat pumps in non-residential buildings. E.g. in hard rock wells covered with clay there is a risk of land slides if the salt is pumped away or the pressure regime is disturbed. It is important that the infiltration pressure never comes close to the counter pressure from the overburden clay.

According to NGU (2008), about 30% of the Norwegian groundwater heat pump systems have had operational problems due to fouling in heat exchangers and clogging of pipelines and pumps in the groundwater system.

3 INDIRECT GSHP SYSTEMS – CRYSTALLINE ROCK/GROUNDWATER

3.1 Design

In indirect closed-loop GSHP systems utilizing rock as a heat source, heat sink and/or underground thermal energy storage (UTES), boreholes are drilled vertically in crystalline rock by means of pneumatically operated drilling rigs. In unconsolidated sediments, such as soil, sand, gravel and clay, a well casing (steel tubes) is required to stabilize the boreholes. Thermal energy is transferred between the boreholes and the heat pump system by means of a secondary fluid (anti-freeze, brine) that circulates in a closed-loop made from medium-density polyethylene (PE) tubes. The part of the plastic tubes that is located in the borehole is called the borehole heat exchanger (BHE).

Figure 4 shows a principle sketch of a GSHP system operating in heating and cooling mode. In *heating mode*, heat is extracted from the rock and transported to the heat pump evaporator. In *cooling mode*, the excess heat from the building is rejected to the rock. Due to the relatively low temperature level in the borehole, the entire or a large share of the cooling demand can be delivered as “*free cooling*” (direct heat exchange).

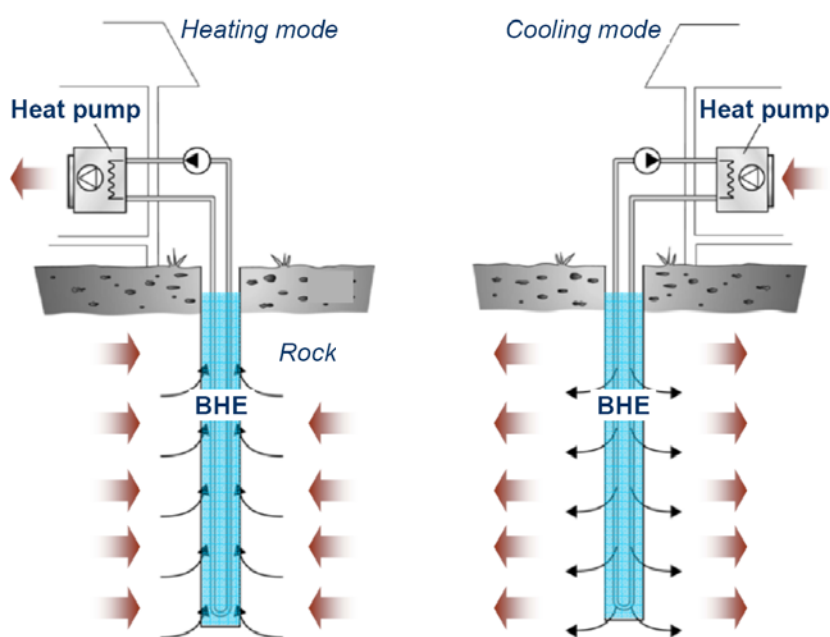


Figure 4: Principle of a GSHP system in crystalline rock for heating and cooling.

Typical specifications for closed-loop GSHP systems in Norway are as follows (NGU, 2008):

- Borehole – diameter: 130 to 165 mm
- Borehole – depth: 80 to 200 m (300 m)

3.3 Borehole Heat Exchangers (BHE)

In Norway single U-tubes (OD/ID 40/35 mm, PN6.3/8.0) are used as BHE in GSHP systems with normal heating and cooling loads. Double U-tubes (OD/ID 32/28 mm, PN6.3/8.0) have 30% lower wall thickness, 60% larger heat transfer surface and lower pressure drop than single U-tubes. Double U-tubes are mainly used in installations with cooling loads since the lower thermal resistance leads to a lower temperature difference in the borehole and a larger “free cooling” capacity. Coaxial BHE are not used in Norway. Figure 5 shows a sketch of single and double U-tubes BHE installed in vertical boreholes in crystalline rock (Lund et al., 2004). In order to ease the installation of the BHE and to avoid buoyancy caused by possible ice formation on the tubes, the BHE is equipped with a bottom weight (10 to 15 kg).

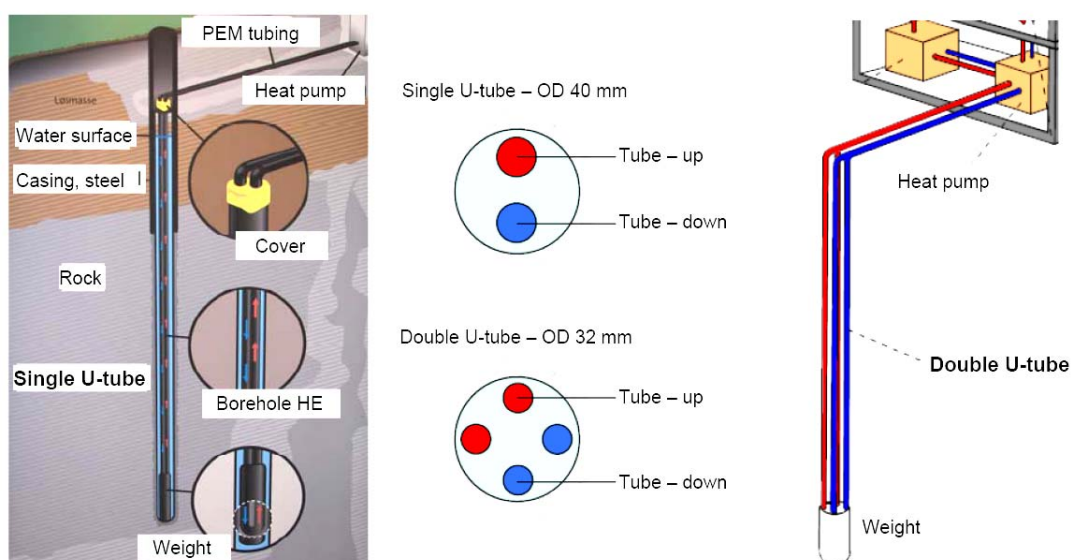


Figure 5: Single and double U-tubes as borehole heat exchangers (Lund et al., 2004).

In heating and cooling mode the maximum temperature difference between the tubes in the borehole is about 2-4 K and 5-10 K, respectively. Especially designed plastic spacers should be mounted on the tubes every 2-3 meters in order to reduce the internal heat transfer between the tubes and thereby increase the heating/cooling capacity of the BHE. Figure 6 shows example of spacers for single and double U-tube BHE (Hellström, 2006).

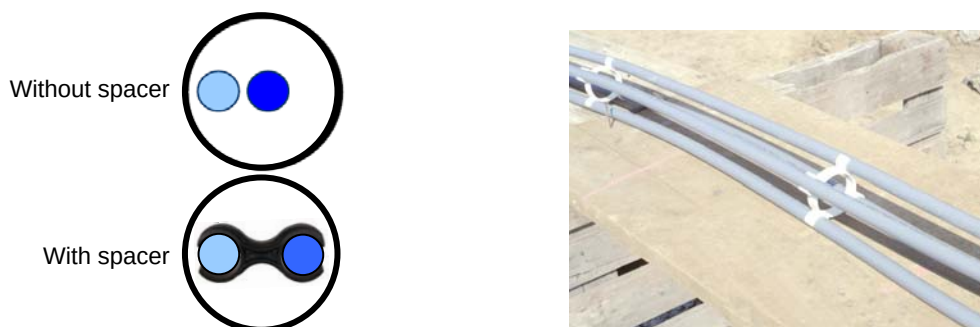


Figure 6: Plastic spacers for single and double U-tube BHE (Hellström, 2006).

3.4 Heat Extraction – Borehole Design – Thermal Response Testing

The heat extraction rate from vertical boreholes in crystalline rock in Norway typically ranges from 20 to 60 W/m, with an average level of 30-40 W/m. The lower value reflects a well without groundwater seepage drilled in an nearly impermeable rock, whereas the high value reflects permeable crystalline rock with high thermal conductivity and a significant groundwater flux. The annual heat transfer from the ground (kWh/year) should also be taken into account when designing the boreholes, and the short-/long-term temperature development in the ground should be analyzed by means of computer simulations.

The heat extraction rate, and with that the *required borehole depth and the total length of the BHE*, is mainly dependent on the properties of the crystalline rock (rock type, permeability etc.), the amount of flowing groundwater, the groundwater level, the temperature of the ground and the borehole configuration. The groundwater level in Norway is normally 1 to 10 metres below the surface, and because of fractures in the crystalline rock, most boreholes will be filled with water. In boreholes with low groundwater level or in dry boreholes, the holes are backfilled with fine grained quartz sand in order to improve the heat transfer between the rock and the BHE. Especially developed groutings (concrete) or a mixture of bentonite and quartz sand are used when it is necessary to prevent groundwater pollution.

Figure 7 shows measured ranges for thermal conductivity of different rock types in Norway (NGU, 2008). For GSHP systems less boreholes will be required in sandstone compared with e.g. limestone or syenite due to sandstone's considerably higher thermal conductivity.

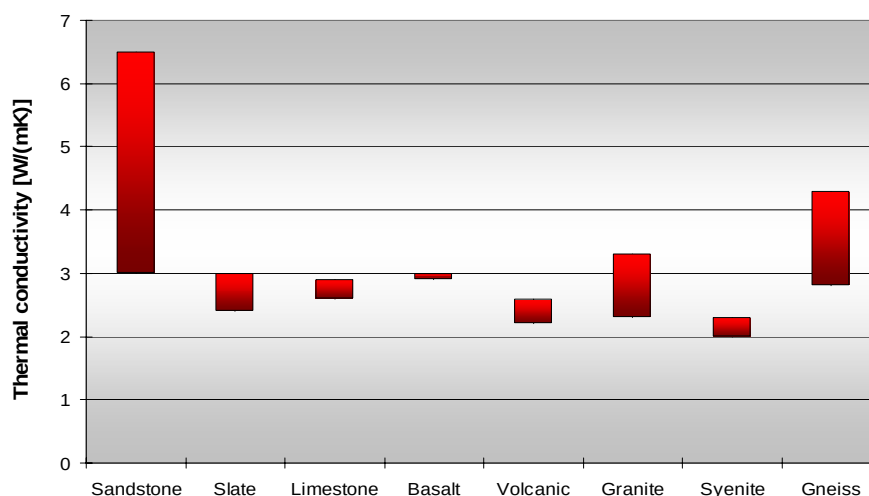


Figure 7: Measured thermal conductivity of different rock types in Norway (NGU, 2008).

The Geological Survey of Norway (NGU) has developed digital maps showing distribution of crystalline rock (<http://www.ngu.no/kart/bg250>) and maps for surficial deposits such as sand, gravel and clay (<http://www.ngu.no/kart/losmasse>). These maps can be combined with digital groundwater maps (Chapter 2.1). Geological maps are essential tools for planning and designing GSHP installations, and geological expertise may be required to optimize dimensioning and drilling of the borehole systems.

For larger installation with more than 15 to 20 boreholes, initial thermal response testing (TRT) will lead to a more precise dimensioning and design of the borehole system. The TRT is a method developed in Sweden for measuring the thermal properties of the rock and the thermal resistance of a borehole. With this information it is possible to predict the heat extraction rate from a given borehole (Gehlin, 2002). In Norway, NGU and Geoenergi AS have TRT rigs.

3.5 Thermal Charging of Boreholes – Thermal Energy Storage

In Norwegian non-residential GSHP projects, the number of boreholes typically range from 5 to 50. The annual temperature development in boreholes depends on, among other things, the heat extraction rate for each borehole (W/m), the properties of the crystalline rock, the groundwater flow, the borehole configuration (I-shape, L-shape, rectangular shape) and the distance between the wells. When the groundwater flow is insufficient to provide thermal recharge of the wells after the heating season, the temperature will drop, and this will in turn reduce both the heating capacity and the COP of the heat pump. However, excess heat from the cooling system in the building or heat from the discharge air after the heat recovery heat exchanger in the ventilation system can be used to increase the temperature level in the boreholes, and “recharge” the system with thermal energy. Simple solar collector systems can also be used if ventilation air is not available or has insufficient charging capacity.

For larger GSHP systems with more than 20 to 30 boreholes, the rock volume around the boreholes will act as a *thermal energy storage* since the thermal influence from flowing groundwater and the adjacent rock volume declines with the number of boreholes. The distance between the 150 to 200 metre deep boreholes typically ranges from 5 to 10 metres. (NGU, 2008). When designing thermal energy storage systems it is important to ensure a *long-term energy balance*, which means that the annual heat flow into and out of the system should be in the same order of magnitude. Figure 8 shows the principle of a thermal energy storage system, whereas Figure 9 shows an example of a monthly energy account.

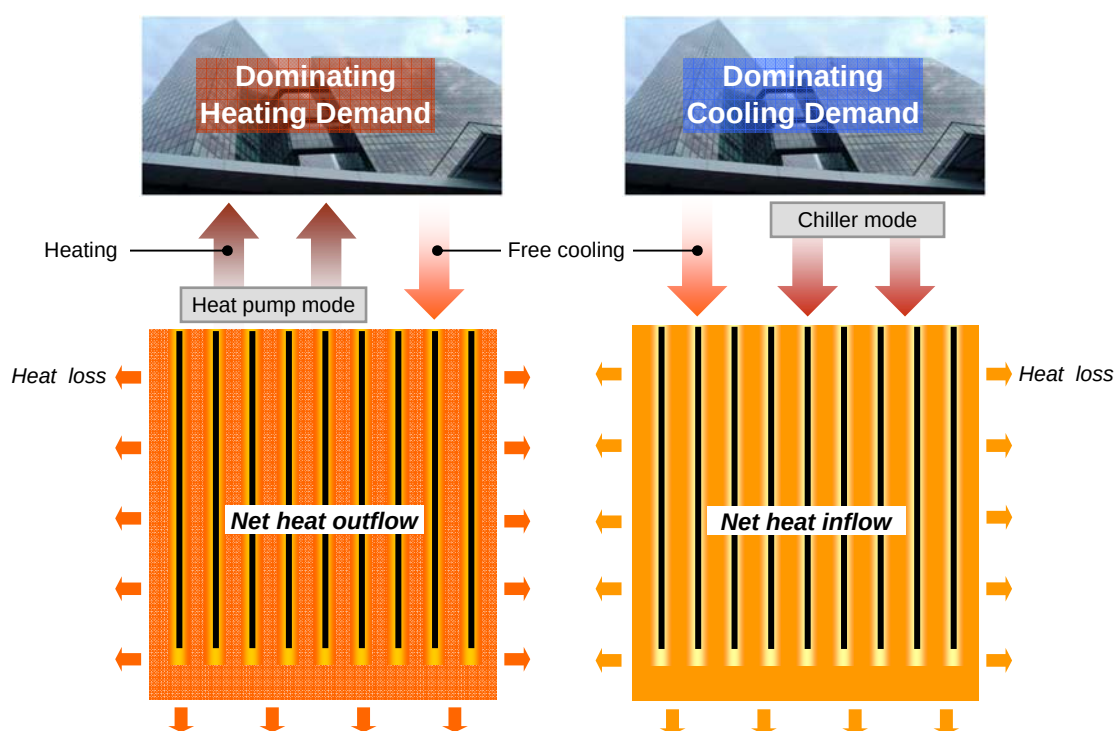


Figure 8: Principle of a thermal energy storage with boreholes in crystalline rock.

In Figure 9, the sum of the extracted heat, supplied heat and heat loss during a normal year is more or less zero (i.e. thermal energy balance). As a consequence, the average annual temperature of the system will remain relatively constant from year to year.

In periods with a *dominant heating demand*, the heat pump extracts heat from the boreholes, and the heat pump evaporator has sufficient capacity to cover the space cooling demand in the building (“free cooling”). In these periods there will be a net extraction of thermal energy from the storage, and the temperature will drop gradually.

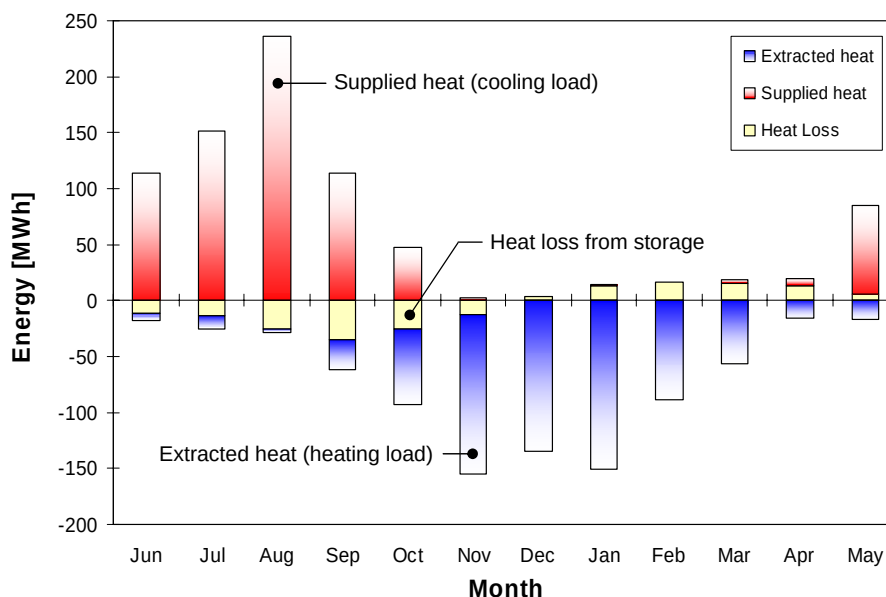


Figure 9: Example of a monthly energy account for a thermal energy storage (Hellström, 2006).

In periods with a *dominant cooling demand*, the cooling demand is covered by means of “free cooling” from the boreholes. If this is not sufficient, the heat pump is operated as a chiller, and the surplus heat is rejected to the boreholes. In these periods there will be a net input of thermal energy to the storage, and the temperature will rise gradually. During the year, the temperature in a thermal energy storage system may typically fluctuate between 5 and 20°C.

GSHP systems in Norway using vertical boreholes in crystalline rock as a heat source/sink and/or thermal energy storage system, achieve *high Seasonal Performance Factor (SPF)*. The reason is that 80 to 90% of the annual heating demand for the building is covered by the heat pump units (bivalent system) operating at a relatively high evaporation temperature, and a considerable share of the annual cooling demand is covered by means of “free cooling” from the heat pump evaporator and the boreholes.

3.6 Pitfalls – Operational Problems

Typical design failures in Norwegian indirect closed-loop GSHP systems include:

- Combinations of – undersized borehole heat exchanger (BHE), insufficient distance between boreholes, low groundwater flow in combination with insufficient thermal recharging of boreholes, low groundwater table and no/insufficient backfilling
 - Low borehole temperature or gradually decreasing annual average borehole temperature – low/decreasing heating/cooling capacity for the heat pump system and low/decreasing COP
- Lack of tube spacers for the borehole heat exchanger (BHE)
 - Relatively large internal heat transfer and reduced heating/cooling capacity
- Serial connection of two borehole heat exchangers in combination with high flow rates
 - Excessive pressure losses and high pumping power
- Low brine temperatures combined with insufficient insulation of header pipelines
 - Ground consolidation due to freezing and consequent tube breakage etc.
- Boreholes drilled in areas with thick-bedded unconsolidated sediments
 - High costs due to expensive well casing – low heating capacity and poor COP

4 INSTALLATION EXAMPLES

4.1 Groundwater Heat Pump System at an Environmental Research Centre (2007)

The Centre for Interdisciplinary Environmental and Social Research (CIENS) in Oslo, Norway, is a 13,500 m² office building including laboratories. The estimated heating and cooling loads for the building at design conditions are 650 kW and 870 kW, respectively, and the calculated specific energy demand is 120 kWh/(m²year). The heating and cooling system for the building comprises a groundwater heat pump unit connected to 9 groundwater wells, heat exchangers connected to a district heating system based on garbage incineration and a biofuel-fired boiler for peak load. The energy central will in the future also supply heating and cooling to several adjacent buildings. The 650 kW R134a heat pump unit, which uses two slide valve controlled compressors, is designed to cover about 65% of the annual heating demand and about 90% of the annual cooling demand for the buildings.

The aquifer is a brittle, vertical standing volcanic dyke a few meters wide, located in between a more elastic impermeable shale. During movement in the crust the dyke is fractured into small rock pieces with a very large heat exchanging area. The dyke itself acts like a thermal storage in conjunction with the surrounding shale. The wells are located in pairs, down to two levels – from 6 m below the rock surface down to 100 m, and from 100 m depth and down to 200 m. By this design it is possible to activate enough groundwater and sufficient rock volume to cover the seasonal cooling and heating demands of the building.

The rock is covered by 20 to 40 m of soft impermeable clay vulnerable to reduced pore pressure. Consequently, all water that is pumped up must be injected back with reasonable pressure to avoid geotechnical problems.

To ensure trouble-free operation it is of great importance to keep the pressure in the ground water circuit high enough to prevent degassing. With special valves it is possible to inject water into the same well, and later this is used as a pumping well. Using the same wells both for pumping and injection reduces the expenses. The valves are mounted just above the pumps at 25 m depth. The pressure in the pumping circuit is adjusted to the actual flow by a moving piston that limits the opening of several small blow-out ports. The pistons counter pressure is regulated by the force from a coil spring that are fine tuned with a hydraulic flow beneath the piston.

After one year of operation the ground water heat exchanger has been in operation without any signs of clogging or iron fouling. Each of the 9 groundwater pumps has a maximum flow rate of 17 l/s, and can be operated from 30 to 50 Hz (60-100%). During hot days with 30°C ambient air temperature, the entire cooling demand of 550 kW can normally be covered by “free cooling” only by operation of the 11 kW pump. It has not been necessary to operate the heat pump in cooling mode since the groundwater covers the entire cooling demand.

4.2 Large Scale Ground-Source Heat Pump System in a Hospital (2008)

The new University hospital in Akershus County, Norway, is currently under construction. The buildings have a total floor area of about 160,000 m², and the hospital will be fully operational in October 2008. The annual heating demand is expected to be about 20 GWh/year. One of the goals for the energy systems of the hospital has been that renewable energy sources should provide a minimum of 40% of the supplied energy for heating and cooling.

A combined ammonia-chiller and heat-pump system (CHPS) will supply heating and cooling to the buildings, and the system will be connected to one of the largest UTES in Europe, consisting of 220 (350 in 2nd phase), 200-m-deep boreholes in crystalline rock (Sweco, 2008). OD 40 mm single PEM U-tubes will be installed in each borehole, and the different

pipelines will be connected to manifolds that transport the secondary fluid (ethanol) to three central manholes. Two ID 450 mm plastic tubes will be used to transport the secondary fluid between the manholes and the energy central. The boreholes are located in a grain field, and when the installation is completed the fields will again be used for grain production.

The large thermal energy storage in crystalline rock will be used as a high-quality heat source for the CHPS, and excess heat from the cooling system and ventilation air will be used to charge the thermal storage during spring, summer and autumn, thus maintaining the annual average storage temperature. In heating mode, the storage system will reject heat since the temperature of the secondary fluid will be lower than the ground temperature. In cooling mode, the storage system will absorb heat since the temperature of the secondary fluid will be higher than the ground temperature. During periods with high cooling demands the heat pump unit will be used as a chiller, and the excess heat from the condenser will be returned to the thermal energy storage. Figure 10 shows an overview of the 20,000 m² area with the ground heat exchanger installations and header pipelines (Ahus, 2008).



Figure 10: Overview of the 20,000 m² area for the thermal energy storage (Ahus, 2008).

The CHPS from York Refrigeration comprises three single-stage screw-compressor units with slide valve control and variable volume ratio, and one single-stage unit with two large reciprocating compressors. Each unit has a maximum cooling capacity of roughly 2 MW.

The CHPS is designed according to a maximum cooling load of about 7.7 MW, and the heating capacity at design outdoor temperature (DOT) is about 8 MW. The units will be supplying condenser heat to a low-temperature circuit at a maximum supply temperature of 52°C (space heating, heating of swimming pools etc.), and desuperheat to a high-temperature circuit at a maximum supply temperature of 75°C (hot water heating).

The heating system is designed as a bivalent system. The heat pump will cover about 85% of the total annual heating demand of the hospital, whereas oil-fired and electric boilers will be used as peak load covering the remaining 15%.

4.3 Groundwater Heat Pump System in an Office Building (2007)

Papirbredden in the city of Drammen, Norway, is a 22,000 m² office building with a large library, auditoriums, practice-rooms, laboratories and offices. Due to the relatively large heating and cooling demands and the fact that the building owner wanted to avoid the application of wall- or roof-mounted dry-coolers or cooling towers, it was determined to install a groundwater heat pump (Geoenergi, 2008). Figure 11 shows the building by the riverside.



Figure 11: The office building “Papirbredden” in Drammen, Norway.

Two heat pump units with a total heating capacity of 650 kW are connected to six, 300 metre deep boreholes. In *heating mode*, groundwater is pumped from three of the “warm wells” and returned to the three “cold wells” after being cooled by the heat pump evaporator. Space cooling and computer cooling is covered by “free cooling” from the cold side of the system.

The estimated COP in heating mode is about 3.5 to 4.0. The heat pump units have an annual heat supply of about 750,000 kWh/year, and the heat is being used for heating of ventilation air and snow melting. Since the building is located in a concessionary area for district heating, the space heating demand (radiators) is covered by district heating.

In *cooling mode*, the flow direction of the groundwater is reversed, and groundwater is pumped from the “cold wells” and used for cooling of ventilation air, cold ceiling panels etc. The maximum cooling capacity from “free cooling” is about 500 kW. If the cooling capacity is insufficient, the heat pump units are operated as chillers with a maximum cooling capacity of 500 kW. The excess heat from the condensers is given off to the groundwater, and returned to the “warm wells”. Consequently, the rock volume around the groundwater boreholes are being utilized as an aquifer thermal energy storage (ATES).

The estimated COP in cooling mode range from about 4, when the heat pump units are used as chillers, to about 30 when the entire cooling demand is covered by the cool groundwater. The annual cooling demand for the building is about 820,000 kWh/year, which is even larger than the annual heat supply from the heat pump units.

The estimated annual energy saving for the heat pump system is 700,000 kWh/year, and the extra costs compared to a conventional heating and cooling systems was about €240,000. This gives a pay-off period of approximately 4.5 years.

5 THE TOTAL QUALITY CONCEPT FOR NON-RESIDENTIAL GSHP SYSTEMS

Ground-source heat pump systems for heating and cooling of non-residential buildings are complex installations. In order to achieve a high seasonal performance factor (SPF) and trouble-free operation during the entire lifetime of the installation, the following factors needs special attention (Geoenergi, 2008; Volla Karlsen, 2007):

The Total Quality Concept for ground-source heat pump installations – important factors:

- Contract practice – project organization
 - o Application of a well arranged contract practice – one main qualified responsible for design, installation, construction and commissioning
- Pre-project period
 - o Investigation of the geographical and geological suitability for a GSHP installation
 - o Calculation of heating and cooling demands for the building
 - o Design of the heat pump system (overall level)
 - o Estimation of profitability (present value, specific cost for heating/cooling etc.)
- Design period
 - o Clarification of critical interfaces
 - o Detailed calculation of heating and cooling demands for the building
 - o Design of the heat pump according to The Norwegian Refrigeration and Heat Pump Standard – working fluid (R134a, R717, R407C), heating and cooling capacity (bivalent system), part load characteristics, temperature and mass flow requirements for heat source, heating and cooling systems etc. – focus on safety, reliability and high energy efficiency (COP) at all operating conditions
 - o Design of the heat source system – simulation and design of boreholes and BHE – possibly thermal response testing (TRT) to increase accuracy
 - o Design of heating and cooling systems – possibly reduce temperature level in the heat distribution system to increase heat pump COP and increase temperature level in the cooling system to increase “free cooling” capacity
 - o Optimization of the control algorithms for the heat pump units, peak load units and heat source system at full/part load operation, heating mode and cooling mode – coordination with the central control and monitoring system for the building
 - o Implementation of adequate instrumentation with good accuracy in order to acquire sufficient data during commissioning and operation
- Commissioning period
 - o Detailed commissioning for the entire heat pump system
 - o Tuning of the heat pump system during the first year of operation
- Operating period
 - o Monitoring and operation with web interface – competent evaluation and follow-up
 - o Regular maintenance of the entire heat pump system

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