IEA HPT Annex 52 - Long-term performance monitoring of GSHP systems for commercial, institutional and multi-family buildings

Case study report for Frescati NPQ, Sweden

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Preface

This report is part of the work within IEA HPT Annex 52 - IEA HPT Annex 52 - Long-term performance monitoring of GSHP systems for commercial, institutional and multi-family buildings, with project period January 1st 2018 to December 31 2021. Annex 52 Operating Agent is Sweden.

Annex 52 aims to survey and create a library of quality long-term measurements of GSHP system performance for commercial, institutional and multi-family buildings. While previous work will be surveyed, the emphasis of the annex is on recent and current measurements. The annex also aims to refine and extend current methodology to better characterize GSHP system performance serving commercial, institutional and multi-family buildings with the full range of features shown on the market, and to provide a set of benchmarks for comparisons of such GSHP systems around the world.

The results from the annex will help building owners, designers and technicians evaluate, compare and optimize GSHP systems. It will also provide useful guidance to manufacturers of instrumentation and GSHP system components, and developers of tools for monitoring, controlling and fault detection/diagnosis. This will lead to energy and cost savings.

The work reported in this document was mainly performed by Alberto Lazzarotto at the Royal Institute of Technology (KTH) with support from his colleagues also involved in Annex 52: Willem Mazzotti, José Acuña and Mohammad Abuasbeh.

The building and geothermal system investigated is located at Stockholm University and is part of a local thermal network of buildings. The building is owned and maintained by Akademiska Hus that kindly supported the project. We would like to thank Anders Larsson from Akademiska Hus, and Farhad Basiri and Otto Sandström from iQuest for providing the access to data for this site.

The work that has led to this report has been funded by the Swedish Energy Agency (Energmyndigheten) through the project 45979-1.
Summary

The report presents the system performance for Frescati NPQ, a building located in the Stockholm University campus. In this system, heating and cooling demand of the building are supplied with a geothermal heat pump connected to a borehole field with 130 boreholes 230 meters deep. The system supplies around 550 MWh/year of cooling and 600 MWh/year of heating to NPQ. However, the thermal extraction and injection into the ground recorded are respectively up to 1650 MWh/year and up to 3470 MWh/year. This data shows how the borehole system is part of a thermal network and delivers heat to several buildings in the surrounding area during wintertime and absorbs a very large amount of heat from the network during summertime. This geothermal system works effectively as a storage system and helps minimizing heat losses from the network and maximizes the heat recovery.

The monitoring period comprises 3 years, between 2017-01-01 until 2019-12-31. The data are recorded at a sampling rate that is often down to 1 minute. The system was analyzed according to the Annex 52 framework and monthly and seasonal performance factors for boundary layers 0, 1, 2, 3, 4 was calculated looking both at heating and cooling performance. The analysis highlighted a significant decrease in performance between boundary layer 1 and boundary layer 2 due to the continuous operation of the borehole pumps. Moreover, it was found that the pumps are operated at lower flow rates when compared to design condition. This yields higher thermal resistance and therefore lower thermal performance for the borehole heat exchangers.

Several challenges related to data quality raised during the analysis phase. In the report we discuss the importance of time resolution for the discovery of faulty or inconsistent data and we show with examples that clear problems in the data cannot be appreciated for very coarse time resolutions like the ones used for seasonal performance indicators. We, therefore, encourage for analysis that look at both coarse resolution and finer resolutions to ensure that the result provided is reliable.

In conclusion, the analysis that is presented in this report shows the potential of local thermal networks which includes buildings with a variety of heating and cooling demands profiles, heat pumps and borehole heat storage systems. The report also highlights that taking full advantage of the great flexibility offered by this system requires the ability of easily access, inspect, verify, and analyze data.
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BACKGROUND

The building

Frescati NPQ, is a building located at the Stockholm University campus, in Stockholm Sweden. The climate in the area is dry and relatively cold with temperature ranging between -15 and 33 °C characterized by a long heating season and a short cooling season.

The building has been inaugurated in 2015 and offers a surface of 16500 m² dedicated to office spaces, classrooms, and labs. The building is part of a cluster of buildings that form a small district in terms of energy. Cooling and heating pipelines are set up between buildings to maximize the synergies of the demand and production patterns in the individual buildings. Figure 1 shows a render of the campus including all the buildings in the thermal network (Monzó, 2018; Monzó et al., 2016).

During the construction of the building a large borehole storage was built under the NPQ building plot with the goal of reducing the district heating requirement by the building cluster by 40%. Figure 1 shows a render of the campus including all the buildings in the thermal network. Each building is marked with a letter of the alphabet. This naming convention is used within this report to refer to these buildings. Additionally, the picture provides a schematic of the operation of the borehole field and how it is integrated in the network. We can see the concept of reinjecting excess heat from the thermal network during summertime and extracting heat during winter to supply the buildings heating demand.

The borehole field exchanges a significant amount of heat with the network and detailed information of thermal loading conditions of each individual building in the cluster is necessary to assess the performance of the geothermal system. Due to limited access to data, only information regarding buildings NPQ were collected. Table 1 and Table 2 provides information about the the main characteristics of buildings NPQ and of the energy supply system.

Figure 1. Photo of Frescati NPQ and of the surrounding buildings part of the energy district.
Figure 2. Map of Sweden and location of the Frescati NPQ

Table 1. Summary of the building features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Stockholm, Sweden</td>
</tr>
<tr>
<td>Year of building construction</td>
<td>2013-2015</td>
</tr>
<tr>
<td>Ground source system operation start date</td>
<td>2016</td>
</tr>
<tr>
<td>Building Type</td>
<td>Office/ university building</td>
</tr>
<tr>
<td>Building floor area (net, gross)</td>
<td>16500 m² net</td>
</tr>
<tr>
<td>Analysed monitoring start date</td>
<td>2017-01-01</td>
</tr>
<tr>
<td>Analysed monitoring period</td>
<td>2019-12-31</td>
</tr>
<tr>
<td>Unique features of the system</td>
<td>Free text to describe special features worth noting</td>
</tr>
</tbody>
</table>

Table 2. Summary of the system configuration

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat distribution</td>
<td>Radiators / Ventilation</td>
</tr>
<tr>
<td></td>
<td>(distribution temp 45°C/ 35°C )</td>
</tr>
<tr>
<td>Cooling distribution</td>
<td>VAV</td>
</tr>
<tr>
<td>Heating load</td>
<td>600 MWh/year (36 kWh/m²,y)</td>
</tr>
<tr>
<td>Cooling load</td>
<td>550 MWh/year (33 kWh/m²,y)</td>
</tr>
<tr>
<td>Heat pump type</td>
<td>E.g. water-to-water</td>
</tr>
<tr>
<td>Reversible</td>
<td>No</td>
</tr>
<tr>
<td>Compressor type</td>
<td>2 screw compressor heat pumps / 1 Not Available</td>
</tr>
<tr>
<td>Speeds</td>
<td>2 variable speed / 1 on-off</td>
</tr>
<tr>
<td>Heat pump system</td>
<td>Centralized</td>
</tr>
<tr>
<td>Number of heat pumps</td>
<td>3</td>
</tr>
<tr>
<td>Nominal total heat pump heating capacity</td>
<td>1750 kWn</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>2 Ammonia / 1 not available</td>
</tr>
</tbody>
</table>
The ground source system

The ground in the surrounding of building NPQ is granite. The borehole fields consist of 130 boreholes 230 meters deep for a total drilled length of around 30000 meters. The boreholes are ground water filled and the water table is at around 5-6 meters of depth. Figure 3. Illustrate the borehole field design. The boreholes are placed along lines that surround the building. The distance between borehole at the surface can be very small (down to 1-2 meter) but the borehole field is designed to spread under the surface in order to occupy as much rock as possible so the average distance between the boreholes is around 15 meters. Please notice, that the configuration reported below is the design configuration and no measurements of the actual inclination was performed during installation.

The 130 boreholes are divided into 14 groups. Each group is connected in parallel to a local manifold which is in turn connected to a main branch that goes to the heat pump room. The collectors utilized are U-pipes with 115 mm of diameter. The

Table 3 and Table 4 summarize information regarding the geometry of the pipes and of the borehole field. Data regarding thermal conductivity and borehole thermal resistance were determined in a test performed before the design phase of the system. The test yielded a thermal conductivity of 3.9 W/m K and an effective thermal resistance of 0.091 Km/W. It should be noted that this value of thermal resistance was obtained for a test with a flow 0.51 l/s. This flow is higher than the actual flow measured in the borehole field. As a result, the actual borehole resistance in practice is expected to be higher than the one estimated during design.

Figure 3. Top view of borehole of building NPQ and borehole field layout. The figure illustrates also the manifolds layout and measurement extra measurement equipment temperature sensors and flow meters installed in individual boreholes (Lazzarotto et al., 2016; Monzo et al., 2017).

Table 3. Summary of the ground source and sink

<table>
<thead>
<tr>
<th>Ground source</th>
<th>Vertical boreholes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Loop type
Closed loop or Open loop
Ground composition
Granite
Groundwater level [m]
5-6 m
Undisturbed ground temperature
9°C
Design ground thermal conductivity
3.9 W/m.K
Specific ground heat capacity
2600 J/kg.K
Minimum ground heat exchanger exiting fluid temperature (ExFT_{min})
3°C
Maximum ground heat exchanger exiting fluid temperature (ExFT_{max})
26°C

Table 4. Summary of the ground heat exchanger – Boreholes

<table>
<thead>
<tr>
<th>Number of boreholes</th>
<th>130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole length</td>
<td>230 m</td>
</tr>
<tr>
<td>Total borehole length</td>
<td>29900 m</td>
</tr>
<tr>
<td>Average distance between boreholes</td>
<td>15 m</td>
</tr>
<tr>
<td>Borehole geometric distribution</td>
<td>Around the building but spread in the subsurface</td>
</tr>
<tr>
<td>Borehole diameter</td>
<td>115 mm</td>
</tr>
<tr>
<td>Borehole filling material</td>
<td>Groundwater</td>
</tr>
<tr>
<td>Borehole heat exchanger type</td>
<td>Single U-tube</td>
</tr>
<tr>
<td>Design Effective thermal resistance per unit length</td>
<td>0.091 Km/W (test performed with a flow of 0.51 l/s)</td>
</tr>
<tr>
<td>Source side pipe characteristics</td>
<td>E.g. PEM DN40 PN8 (40 mm/35.2 mm)</td>
</tr>
<tr>
<td>Source side brine type</td>
<td>E.g. Water-Ethanol 28%</td>
</tr>
</tbody>
</table>

Figure 4 and 5 provide a schematic view of the system. The main piping branch coming from the borehole is connected to

- two large heat pumps of 800 kW\textsubscript{h} nominal capacity,
- a smaller heat pump of around 150 kW\textsubscript{h} nominal capacity,
- a heat exchanger in series with evaporators and a borehole loop that provides the cooling load to the building.
- a shunt heat exchanger which connects the borehole loop with the warm loop and is utilized to reinject heat into the borehole during summertime.

A water tank is placed in between the borehole loop and the heat pump as a short-term storage solution. A system of valves and modulating pumps is utilized to switch between operational mode: e.g. injection and extraction.

As showed in figure 4 and 5 the system has two main operation modes: **Heating and Cooling** and **Cooling mode**. In **Heating and Cooling** mode, the heat pumps use as heat sources both the borehole field and the cooling demand from the building. The heat pumps extract low temperature heat from these to sources and delivers heat at higher temperature that is suitable to satisfy the heating demand of the building.

In **Cooling** mode, the evaporator of the heat pumps is connected to the building to deliver the cooling demand. The condenser heat generated by the heat pump is injected into the borehole field. Additionally, surplus heat available in the local network during summer is injected into the ground.
Figure 4. Simplified schematic of the Frescati system in **heating** and **cooling** mode. In the sketch are highlighted the boundary levels used for the analysis of the system. *Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52.*

Figure 5. Simplified schematics of the Frescati system in **cooling mode**. *Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52.*
Monitoring

Frescati NPQ is equipped with a Building management system. The monitoring system comprehend sensors for the measurement of flow, temperature, pressure, valves opening and control signal. The sampling frequency varies depending on the sensors and is between 1 to 5 minutes. The data are mostly used to control the operation of the system but monitoring data are stored permanently without reduction in resolution. For the current project data are available from the beginning of 2017.

The monitoring system is an off the shelf system and to the author knowledge sensor calibration has been done only by the sensors manufacturer.

Circulation pump’s power is not measured, but values for power are recorded in the building management system according to the control signal and pump curve. Accuracy value of such indirect measurement is not available. The electricity necessary to operate the heat pumps is not recorded or at least not readily available to the author of this report.

In Table 5 are reported the specification of the flow meters installed. No data regarding accuracy of the thermistors installed are available to the author.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Instrumentation</th>
<th>Description</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature sensors</td>
<td>-</td>
<td>4 wires thermistors</td>
<td>NA</td>
</tr>
<tr>
<td>Source side flow rate</td>
<td>Armatec AT7185</td>
<td>Magnetic-induction</td>
<td>±0,5 %</td>
</tr>
<tr>
<td>Warm side flow rate</td>
<td>Kamstrup Ultraflow 54</td>
<td>Ultrasonic</td>
<td>±0,5 %</td>
</tr>
</tbody>
</table>
Performance metrics

The performance metrics considered to evaluate the system are based on the framework developed within the Annex 52 project. Indicators are defined for each of the system boundaries as defined in Figure 4. The objective of such metrics is visualizing how performance changes moving through the boundary layers. For a given boundary layer, a performance indicator is defined as the ratio between useful energy gained and energy spent. Another aspect that must be considered to define the performance indicators is the time frame considered. Within this report we will present results of seasonal performance factor which consider a time window of one year for the performance evaluation, and monthly performance indicators which consider a time window of a month.

In this section we present the formulation used to calculate the seasonal performance factor and monthly performance factor. We provide a definition for XPF where X can be replaced with any time frame of interest, e.g. week, month, year. As an example, let’s consider the definition of \( XPFF_0^h \) (X performance factor for boundary level 0 in heating mode).

\[
XPFF_0^h [j] = \frac{\sum_{i \in j} Q_{\text{extraction}}[i]}{\sum_{i \in j} P_{\text{pumps extraction}}[i]}
\]

In the equation above the summation add all the contributions at all time step \( i \) within the time frame of interest \( j \). If we look at monthly performance (MPF), the summation will contain all the time-steps within month \( j \). Similarly, if we are interested in calculating the seasonal performance factor (SPF), the summation would add up all the time-step within year \( j \).

In the definition of XPFs we will use the load ratio \( \beta[j] \) defined as follow.

\[
\beta[j] = \frac{\sum_{i \in j} Q_{\text{demand}}[i]}{\sum_{i \in j} Q_{\text{demand}}[i] + Q_{\text{condenser}}[i]}
\]

Since during the whole heating season, which goes approximately between September and May, the system will provide both heating and cooling, it is necessary to have a way to divide the compressor power for cooling and for heating.

In the specific case of this system, the coefficient \( \beta \) is calculated based on the data available. Since no data are available regarding the contribution of the system to the heating load of buildings DEFGH (other buildings in the district), the coefficient \( \beta \) is overestimated and cooling performance are underestimated.

As compressor power is not measured, its value is evaluated as the difference between the condenser heat exchange and the evaporator heat exchanged. This evaluation should provide a lower bound for the compressor power as it does not include the thermal losses between the compressor towards the environment.

\( XPFF^h \) (heating) and \( XPFF^c \) (cooling) from level 0 to 4 and \( XPFF_4^h \) (overall performance at level 4), are defined as follow:

\[
\begin{align*}
XPFF_0^h [j] &= \frac{\sum_{i \in j} Q_{\text{extraction}}[i]}{\sum_{i \in j} P_{\text{pumps extraction}}[i]} \\
XPFF_1^h [j] &= \frac{\sum_{i \in j} Q_{\text{extraction}}[i]}{\sum_{i \in j} P_{\text{injection pumps}}[i]} \\
XPFF_2^h [j] &= \frac{\sum_{i \in j} Q_{\text{condenser}}[i]}{\sum_{i \in j} P_{\text{compressor}}[i] (1 - \beta[i])} \\
XPFF_3^h [j] &= \frac{\sum_{i \in j} Q_{\text{condenser}}[i]}{\sum_{i \in j} P_{\text{compressor}}[i] \beta[i]} \\
XPFF_4^h [j] &= \frac{\sum_{i \in j} Q_{\text{condenser}}[i]}{\sum_{i \in j} P_{\text{compressor}}[i] (1 - \beta[i]) + \sum_{i \in j} P_{\text{pumps extraction}}[i]} \\
\end{align*}
\]
Table evaluation within this report.

Table extraction these pumps on the cooling condenser side are utilized both for heating and cooling. For the sake of simplicity, we considered the component included in the system boundaries for the system according to the Annex 52 boundary schema.

In the definition above the symbol * stands for “during borehole heat extraction”, while ** stands for “during borehole heat injection”. This distinction is introduced to consider the operation mode in definition of the performance. During heating and cooling mode, the pumps on the evaporator side and condenser side are utilized both for heating and cooling. For the sake of simplicity, we accounted for these pumps on the cooling $XP^{F_C}$ during borehole heat injection and on the heating $XP^{F_H}$ during extraction.

Table 6 summarizes the component included in the system boundaries considered for performance evaluation within this report.

<table>
<thead>
<tr>
<th>Boundary description</th>
<th>H0/C0</th>
<th>H1/C1</th>
<th>H2/C2</th>
<th>H3/C3</th>
<th>4/H4/C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Source (circulation pumps+ ground source)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Heat pump unit including internal energy use, excluding internal circulation pump</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Buffer tank (including circulation pumps between heat pump and buffer tank)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circulation pump on load-side (between buffer tank &amp; building Heating/Cooling distribution system)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 6. Calculated system boundaries for the system according to the Annex 52 boundary schema.
PERFORMANCE MONITORING RESULTS

Building heating and cooling loads

Frescati NPQ has a relatively balanced heating and cooling load over a year as can be appreciated from Table 7 and Figure 8. The heating demand is concentrated during the winter season whereas the cooling demand is more evenly distributed during the whole year with peaks during summertime. This fact can be appreciated in Figure 6 which presents the building signature during year 2018 and Figure 7 that presents the heating and cooling loads monthly. Figure 6 shows that the heating demand is zero when the temperature is greater than 17 °C whereas there is a cooling need even when the temperature is -15°C. The mean binned heating load has a rather linear relationship with respect to the outdoor temperature down to -9°C. Yet there can be a significant variation of hourly heating demand within a given binned temperature. For the mean binned cooling load, four operating regions can be highlighted. Between -15°C and 4°C the load is constant. Then up to 17°C the load increases slowly. From 17°C there is an abrupt change in the slope and the binned mean cooling load increases more rapidly with temperature up to 27°C where it reaches stagnation. It should be noticed that the region between 17°C and 27°C presents very large variations when looking at hourly loads within a temperature bin meaning that outdoor temperature is not sufficient to describe/predict the cooling load and other variables should be considered.

Table 7. Overall load characteristics: The table cover only the loads of building NPQ.

<table>
<thead>
<tr>
<th>Start of evaluation period</th>
<th>NPQ Building space heating load met by system [MWh]</th>
<th>DEFGH Building heating load met by the system [MWh]</th>
<th>NPQ Building cooling load met by system [MWh]</th>
<th>DEFGH Building cooling load met by system [MWh]</th>
<th>Total district cooling load met by the system [MWh]</th>
<th>Thermal energy extracted from the ground [MWh]</th>
<th>Thermal energy injected to the ground [MWh]</th>
<th>Thermal balance ratio (extracted/rejected)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan 1, 2017</td>
<td>Jan 1, 2018</td>
<td>Jan 1, 2019</td>
<td>Jan 1, 2019</td>
<td>Jan 1, 2019</td>
<td>Jan 1, 2018</td>
<td>Jan 1, 2018</td>
<td>Jan 1, 2019</td>
</tr>
<tr>
<td>Dec 31, 2017</td>
<td>731</td>
<td>650</td>
<td>598</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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</tr>
<tr>
<td></td>
<td>415</td>
<td>658</td>
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<td>1331</td>
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<td></td>
<td>1001</td>
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<td></td>
<td>2606</td>
<td>3471</td>
<td>2855</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.38</td>
<td>0.47</td>
<td>0.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6. Measured building energy signature for Frescati NPQ building from 2018-01-01 until 2019-12-31.

Figure 7. Monthly space heating and cooling energy and monthly β coefficient (ratio between monthly cooling demand and monthly total energy demand).
Figure 8. Annual heating and cooling provided, MWh/year

Figure 9. Ratio between heating and cooling load vs ODA Temperature in the period 2018-01-01, 2018-12-31.
Ground heat exchanger performance

While the yearly heating and cooling loads are balanced for building NPQ, the ratio between injection and extraction with the borehole field is very uneven and ranges between 0.37 and 0.47. Moreover, the amount of heat extracted/injected is much higher compared to the demand of NPQ presented above. As already mentioned in this report, the reason of this discrepancy is that the borehole system does not supply exclusively Frescati NPQ. Instead, it provides heating and cooling to other buildings in the same local district network (namely house K,M,A,C,D,E,F,G).

The monthly extraction and injection (Figure 11) show the distribution pattern of injection and extraction over a year. The distribution is what we would expect with sole injection during the summer, sole extraction during winter and some overlap of extraction and injection during the shoulder season.

The ground is operating between -1°C and 31°C but these temperatures were registered only on a few occasions. Figure 12 displays inlet and outlet temperatures with hourly resolution. It is possible to appreciate how the minimum temperature registered increases from 2018 to 2019 due to the imbalance in the ground load and to a reduced heat extraction during the 2018/2019 winter.

Figure 13 displays number of hours operation where a given temperature was registered. The curve seems to be bimodal with a very large number of hours at 20°C and around 9°C. These two modes correspond respectively to injection and extraction mode.
Figure 11. Monthly ground heat exchange over the monitoring period.

Figure 12. Entering and exiting temperatures and system hourly flows over the monitoring period.
Heat pump performance

The borehole is connected in parallel with three heat pumps. Two heat pumps with nominal capacity of 800 kWth and a smaller heat pump with nominal capacity of 150 kWth. In this report we will refer to the first two as heat pump 1 an 2 and to the smaller one as heat pump 3. The large heat pumps are delivering heat at 30°C whereas the small heat pump is providing heat at 40°C. Figure 15 shows the monthly MPFth for the three heat pumps.
and an average MPF for the whole system. As mentioned previously, since no compressor power was available, the MPF was calculated as the ratio between the condenser heat and the difference of condenser and evaporator heat.

Heat pumps 1 and 2 show an MPF between 3 and 6. Heat pump 3 show a lower MPF of around 3 and very low values during summertime although it must be noticed that in this period heat pump 3 is hardly used. The overall lower MPF for heat pump 3 compared to heat pumps 1 and 2 is consistent with the fact that its size is smaller and that it operates at higher condenser temperature. The mean MPF for the three heat pumps is around 4.

![Figure 15. MPF for the three heat pumps during the monitored period. In this case the MPF is calculated considering that the compressor power is used exclusively for high temperature heat delivered at the condenser.](image)

Another difference between heat pumps 1 and 2, and heat pump 3 is that the first ones are operated by continuous modulation the compressor frequency while the latter one is operated with on-off control. Figure 16 and Figure 17 showcase the operation of the three heat pumps between February 18, 2019 and February 21, 2019. The control signal modulating the compressor control the heating capacity of the heat pumps. The condenser heat follows rather accurately the signal. Heat pumps 1 and 2 are operating alternatively during periods of low load while they operate synchronously when the load is higher.

Heat pump 3 is operating in on-off mode but has two compressor and therefore can be controlled between half power and full power. The cycles are between one hour and 15 minutes.

As it can be appreciated from the figure, the system is always modulating, and it is unlikely to be in steady state condition. In such a situation the instantaneous COP is not an accurate figure of the performance since it does not consider the dynamics of the system. In order to obtain a meaningful static COP we considered moving averages of condenser and evaporator heat. For this plot a sliding window of 2 hours was used to compute the averages.
Figure 16. Operation heat pump 1 and 2 during wintertime.

Figure 17. Operation heat pump 3 during wintertime.
In the system considered there are nuances in the operation modes that are achieved using pumps and valves. To understand such modes is useful to display both operations as well as temperature and power during these periods. Figure 18 shows temperature, valve opening and power during a period that presents a transition between two operational modes: a high-power mode and a low-power mode. The transition between the two modes takes place on November 29, 2019. In high-power mode the valve highlighted in red is fully open, the borehole field and the evaporator are in series and the inlet temperature into the evaporator is equal to the outlet temperature from the borehole field. During low-power mode, valves highlighted in red and blue are partially open. As a result, part of the flow coming from the borehole is mixed with the flow coming from the storage tank in the loop, and is circulated to the inlet of the evaporator which is then recirculated to the tank. During this period, the inlet/outlet temperature to the heat pump and the outlet/inlet temperature from the borehole are decoupled and the evaporator operate at lower temperature compared to the temperature of the borehole loop.

![Graph showing temperature, valve opening, and power.](image)

Figure 18. Example of operation in the cold side of the heat pump loop.
Overall system performance

The performance of the system has been evaluated according to the methodology presented in the performance metrics section and in line with the Annex 52 methodology. Figure 19 illustrates that MPF0 oscillates over a large range of values but it is in general very high. The SPF0 was found to vary between the values 85 and 100. Inspecting how the system is operated (Figure 20 and Figure 21), we can see that the circulation never stopped during the monitoring period. At least one of the two variable speed circulation pump was operated. For most of the operational time, the pumps are operated at their minimum speed. The very high MPF0 resulting from the monitored data was quite surprising to the author given the continuous operation of the circulation pumps.

An additional observation that can be done by analyzing Figure 21 is that the flow supplied to the borehole field is bimodal with a peak around 40 l/s and a second one at 55 l/s. The field is operated in parallel, and these flows correspond respectively to a flow of roughly 0.3 l/s and 0.42 l/s per borehole. Both flows are lower compared to the 0.51 l/s used during the thermal response test performed before designing the system. Lower flows will result might result in laminar flow and a rather high borehole thermal resistance that can penalize the thermal performance of the geothermal system.
Figure 21 Histograms of flow in the borehole loop

MPF1 has been evaluated for each individual heat pump considering that the heat pump delivers both heating and cooling at the same time (Figure 22). The contribution of the compressor is divided between heating and cooling using the coefficient β as described in the performance metrics section. The results follow the same trend as the one presented in Figure 15 but the potential of using both condenser and evaporator heat increases the performance significantly.

The values displayed are upper bounds for the performance since the compressor power was not available and was calculated via energy balance without accounting for the losses in the process.

Figure 22: MPF1h and MPF1c for the three heat pumps in the system

Figure 23 presents the results for MPFh from level 1 to level 4. We can see a significant variation from level 1 to level 2 and 3 mostly due to the contribution of borehole pumps. The performance then further decreases significantly to level 4. This is due to circulation pumps on the distribution side but more importantly because a large portion of the condenser heat available at boundary levels 2 and 3 is injected into the local thermal network. It is unclear what portion of this heat is useful for the end user as there could be losses in the network and because part of the heat is occasionally rejected to the environment when the network does not find any other place for dumping this heat. For this reason, only the heat delivered to the building NPQ was accounted in the calculation. As there is a
large mismatch between the available heat and the heat delivered to NPQ, the calculated MPF is very low and it is not indicative of the actual performance of the system.

Figure 23: MP1h, MPF2h, MPF3h and MPF4h during the monitoring period.

Figure 24 presents the results for MPFc from level 1 to level 4. This case as well shows a decrease in performance from level 1 to level 2 due to circulation pumps on the borehole side. Stepping from level 2 to level 3 there seems to be nearly no difference. Finally, going to level 4 shows a severe performance decrease during wintertime and a performance increase during summertime. The first behavior is essentially due to the *heating and cooling* mode. In this operation mode, the evaporator heat is shared between the building cooling load and the heat extracted from the borehole field. As a result, only a portion of the evaporator heat is available at boundary 4 for cooling. On the other hand, the increase in performance during summertime does not make sense physically and is due to biases in the measurement of the power exchanged at the evaporator side of the heat pump. In this period the heat delivered by the evaporator according to the measurement is lower than the cooling load delivered. This is clearly not possible as in this period the system is operated only in cooling mode. We are aware that one flow meter and a few temperature sensors in this region showed problems with measurements.

From this reasoning we infer that the measurements underestimate the evaporator energy exchange. This is very problematic since we based on this value our computation of the compressor power. We can then conclude that it is highly probable an overall underestimation of the performance using the methodology proposed in this report.

Figure 24 shows the results for MPF at level 4 computed considering all the useful heat delivered and all the electricity used during the operation. As we underestimate the former one, and we overestimate the latter one, the result presented is highly pessimistic and there is a high probability
that the real performance yields significantly higher values.

Figure 24. MPF1c, MP2c, MPF3c and MPF4c during the monitoring period.

Figure 25. MPF4 during the whole monitoring period.

Figure 27, and Figure 28 show the results we just presented but looking at seasonal performance (SPF). The seasonal performance is indeed the most important figure as it provides an overall value that describe the performance of the system.

On the other hand, if we look at these three plots, we cannot make any observation on the quality of the results obtained. We see a decaying trend from level 1 to level 4 both for SPFh and SPFc which is what we expect. The monthly values had more detail and revealed limitation in the data analyzed and contradictions in the results that are not visible looking at the seasonal level.
Figure 26. SPF1h, SPF2h, SPF3H and SPF4h during the monitoring period.

Figure 27. SPF1c, SPF2c, SPF3c and SPF4c during the monitoring period.

Figure 28. SPF4 during the monitoring period.
A useful tool for assessing the quality of the measurement is displaying heat flows in various parts of the system and perform a sort of visual heat balance. This tool enables to uncover problems with the measurements, e.g. cooling demand greater than evaporator heat, or to show clear patterns such as the very small heating demand (in the available measurements) in comparison to the available condenser heat. These two effects are clearly visible in Figure 28 and show the limitation of the measurement data collected.

Figure 29. Monthly values of energy exchanged in main loops.

Table 8. Performance factors over the monitoring period.

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<th>year</th>
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<th>2019</th>
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<td>97.8</td>
<td>105.2</td>
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</tr>
<tr>
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<td>4.6</td>
<td>5.2</td>
</tr>
<tr>
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<tr>
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<td>4.4</td>
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<tr>
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LESSONS LEARNT

System design and operation

The choice of operating circulation pumps in a continuous fashion is often explained as a control requirement. If the flow is stopped, the fluid within the pipe will tend to get in equilibrium with the environment, and only information about the environment condition at the measurement device location will be available. While this is true, we believe that it is not a good reason to operate the pumps all the time, especially when it comes to large pumps that circulate in the borehole field. The data show that the values obtained for SPF0h and SPF0c are rather large, but analyzing the decaying in performance from SPF1h to SPF2h and from SPF1c to SPF2c it is rather clear that there is a lot of potential of improvement regarding borehole pumps operation.

Moreover, it was found that the borehole pumps are operated at lower flow rates compared to the ones utilized when determining the borehole thermal resistance during the design phase. This mismatch in flows yields an increase in the borehole thermal resistance and a reduction in the thermal performance of the borehole heat exchanger which in turn results respectively in lower secondary fluid temperature during extraction and higher secondary fluid temperature during injection.

The network design provides flexibility, e.g. a large amount of excess heat during summertime is available and can be damped into the borehole. On the other hand, the network presents also challenges in terms of optimal control of the system. We have insufficient data to analyze the performance of the network as we do not know how much of the heat delivered by the heat pumps and chillers is used, how much is lost in the network during transportation and how much is damped towards the environments when the network reaches excessive temperatures. It is clear, that the complexity of the system provides great potential in terms of flexibility but at the same time it is quite challenging to operate and to verify the quality of the operation in practice. This is possible but requires expertise, resources, and proper infrastructures in terms of measurement equipment.

Improvement measures

**Change operations of borehole pumps.** The continuous operation of the borehole pumps at low flow has an impact on both the electricity required for the operation, but also on the performance of the borehole heat exchanger. A different operational strategy that promotes operation at higher flows in the borehole for longer time and does not require circulation at minimum speed within the borehole field should be encouraged.

**Monitor electricity consumption.** One of the limitations of the analysis provided in this report is the lack of electricity measurements of the compressor power and of the overall electricity consumption of the circulation pumps. At least the compressor power should be monitored with an individual meter.

**Replacing faulty sensors.** The system is well equipped with measurement sensors and data are recorded with high frequency which is very positive and favorable to perform analysis and assess performance. However, it was found that a few key sensors were faulty. We suggest replacing these sensors. This kind of issues are very problematic when it comes to performance evaluation. Only a few missing or corrupted data points can highly affect the outcome of the data analysis or in the worst-case scenario, they can prevent the analyst from performing the evaluation at all. In some cases, it is possible to engineer workarounds to perform the analysis even when corrupted data are discovered. However, these procedures increase the uncertainty on the results and should be exceptions and not the norm.
Make data easily accessible. Finding problems in the data requires analysis. Some of the faults can be found automatically but some others are harder to evaluate, and expert knowledge is currently required to identify and understand the nature of the fault. In the future it might be possible to automatize more the process and decrease the necessity of manual work for this purpose. Both for the case of automatic or manual analysis, it is necessary to make access to data easier and more standard. Easier access would enable earlier discoveries of faults in the measurements and would encourage for verification and maintenance of the monitoring equipment.

REFERENCES


Project data access

Akademiska Hus owns the measurement data used in this project and has to be contacted to request access.

Project participants and their contribution

Alberto Lazzarotto: methodology, software/coding, database, validation, analysis, investigation, writing, visualization.
Willem Mazzotti Pallard: methodology, investigation.
Mohammad Abuasbeh: methodology, investigation.
José Acuña: methodology, investigation, project administration, funding.
Signhild Gehlin: project administration, funding.