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

Case study report for Rosenborg, Sweden

GSHP installation coupled with aquifer thermal energy storage ATES suppling heating and cooling for two commercial buildings

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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.

In this study case, the installation in Rosenborg consist of two office buildings with a combined net heated floor area of 18000 m² located in Stockholm, Sweden. The buildings are owned and operated by Vasakronan. The buildings have been constructed in 2015 and the ATES-GSHP system has been in operation since fall 2016. The building energy footprint ambition were high and received LEED Platinum certification. The design value for the yearly energy usage intensity (EUI) is 50 kWh/m². The work perform in this study was performed Mohammad Abuasbeh (abuasbeh@kth.se) in Energy Technology Department at KTH.

The work that has led to this report has been funded by the Swedish Energy Agency through Effsys Expand and TERMO research programs.
Summary

In this study case, the installation in Rosenborg consist of two office buildings with a combined net heated floor area of 18000 m² located in Stockholm, Sweden. The buildings are owned and operated by Vasakronan. The buildings have been constructed in 2015 and the ATES-GSHP system has been in operation since fall 2016. The building energy footprint ambition were high and received LEED Platinum certification. The design value for the yearly energy usage intensity (EUI) is 50 kWh/m². The system has two heat pumps with a total cooling and heating nominal capacity of 1.5 MW and 1.8MW. The GSHP system is connected to an aquifer thermal energy storage ATES with allowable groundwater extraction and injection of 50 l/sec. The system is also connected to district heating. In this study, the monitoring period reported is March 2019 - March 2020 (but ATES is evaluated since 2016). For the year 2019/2020, the total heating load (including domestic hot water) and cooling load was 456 and 381 MWh respectively. The report presents the seasonal performance factors SPF for boundary levels 0, 1 and 2 according to Annex 52 suggested boundaries for the period March 2019- March 2020. For SPF0 (ATES system), the period of analysis is Oct 2016- March 2020. Furthermore, the report discusses possible improvements to be implemented regarding the system boundary definition and GSHP-ATES coupled operation.
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BACKGROUND

The building

This project revolves around a GSHP system located in Solna, Sweden. The location sites are two office buildings named Rosenborg 3 and 4. The facility is divided into two main buildings and the system provides both heating and cooling. The buildings have a combined area of 29,500 $m^2$ (out of which 18,000 $m^2$ is heated and cooled area) and provide roughly 500-600 MWh/year. The system has two heat pumps with a total cooling and heating nominal capacity of 1.5 MW and 1.8 MW. The GSHP system is connected to an aquifer thermal energy storage ATES.

*Figure 1 Photo of the exterior of the two building in Rosenborg 3, 4*

*Figure 2 The system in this study is located in Stockholm Sweden*
### 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>2015</td>
</tr>
<tr>
<td>Ground source system operation start date</td>
<td>2016</td>
</tr>
<tr>
<td>Building Type</td>
<td>Office building</td>
</tr>
<tr>
<td>Building floor area (net, gross)</td>
<td>29500 m² gross, 18000 m² net (heated area)</td>
</tr>
<tr>
<td>Analysed monitoring start date</td>
<td>2019-03-01 (data from 2016-04-01 available only for ATES)</td>
</tr>
<tr>
<td>Analysed monitoring period</td>
<td>2020-04-01</td>
</tr>
<tr>
<td>Unique features of the system</td>
<td>For cooling demand, ATES provide free cooling and HPs coupled chillers are used as auxiliary cooling machines. The heating demand is supplied by the HPs coupled with the ground water from the ATES as heat source. District heating is used as auxiliary source of heating and DHW</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>Ventilation (60/30°C) + Radiators (60/40°C) + floor heating (40/33 °20°C) + ground heating “Markvärme” (36/21°C)</td>
</tr>
<tr>
<td>Cooling distribution</td>
<td>Ventilation (6/14°C)</td>
</tr>
<tr>
<td>Domestic hot water (DHW) production by system</td>
<td>Heat Pumps (same as space heating) + district heating</td>
</tr>
<tr>
<td>Supplementary heat for space heating</td>
<td>District heating</td>
</tr>
<tr>
<td>Supplementary heat for DHW</td>
<td>District heating</td>
</tr>
<tr>
<td>Supplementary cooling</td>
<td>Heat Pumps coupled with chillers</td>
</tr>
<tr>
<td>Nominal capacity of supplementary heating for space heating</td>
<td>District Heating</td>
</tr>
<tr>
<td>Nominal capacity of supplementary heating for DHW</td>
<td>District Heating</td>
</tr>
<tr>
<td>Nominal capacity of supplementary cooling</td>
<td>701 + 814 kW</td>
</tr>
<tr>
<td>Heating load + DHW</td>
<td>456 MWh/year (2019/2020) (25 kWh/m².y)</td>
</tr>
<tr>
<td>Cooling load</td>
<td>381 MWh/year (2019/2020) (21 kWh/m².y)</td>
</tr>
<tr>
<td>Heat pump type</td>
<td>water-to-water</td>
</tr>
<tr>
<td>Reversible</td>
<td>No</td>
</tr>
<tr>
<td>Compressor type</td>
<td>6 x Semi-Hermetic screw compressors (3 for each heat pump)</td>
</tr>
<tr>
<td>Speeds</td>
<td>Variable speed (variable stages)</td>
</tr>
<tr>
<td>Heat pump system</td>
<td>Centralized</td>
</tr>
<tr>
<td>Number of heat pumps</td>
<td>2</td>
</tr>
<tr>
<td>Nominal total heat pump heating capacity</td>
<td>849 + 986 kW</td>
</tr>
<tr>
<td>Nominal total heat pump heating capacity available for DHW</td>
<td>No separate heat pumps for DHW (DHW supplied by HPs + DH)</td>
</tr>
<tr>
<td>Nominal total heat pump cooling capacity [kWth]</td>
<td>701 + 814 kW</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>R134a</td>
</tr>
</tbody>
</table>
The ground source system

The main geological feature is the Stockholm esker stretching nearly in the north-northwest direction. The landscape is under the level of the highest marine shoreline giving a more complex soil stratigraphy with deposits of clay but also remains of relic saltwater (Boman & Hanson, 2004). The top of the ridge of the esker has partly been subject to excavation due to a former use as gravel pit. The core of the esker is passing through the southern side of the property. Depth from surface to bedrock within the property ranges from 12 to 20 m and aquifer thickness ranges from 8 to 15 m from north to south. The hydraulic conductivity of the esker was estimated from pumping tests to be in the range of 2.5-2.9*10^{-3} m/s. During a pumping test carried out over 35 days with a stable flow of 27 l/s, transmissivity estimates ranges were 4.0-5.8 * 10^{-3} m²/s. Drillings had shown that the main geological material in the esker comprises sand and gravel. However, at the northern part, it was presented that the aquifer have fillings of finer grained material as silt (WSP, 2014). The aquifer is mostly unconfined shallow aquifer with some parts in the north covered with clay. The estimated yearly energy consumption are approximately 500 and 600 MWh/year of heating and cooling, respectively. The ATES system is connected to two Carrier heat pumps of 700 and 800 kW cooling capacity. The ATES system has been in operation since autumn 2016 and consists of 4 hot (one of which is not currently used) and 2 cold wells in the north and south of the property respectively. The allowed pumping flowrate for both extraction and injection is up to 50 l/s groundwater (Abuasbeh & Acuna, 2018).

Figure 3 Top view of the two commercial buildings at Rosenborg and the locations of the ground water wells
Figure 4 Schematic of the heating and cooling system in Rosenborg with the boundary levels for SPF0-SPF5. [Pictograms in the drawing used with the permission from TU Braunschweig IGS (Institut für Gebäude- und Solartechnik, Technische Universität Braunschweig)]

Table 3 Summary of the ground source and sink

<table>
<thead>
<tr>
<th>Ground source</th>
<th>Groundwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop type</td>
<td>Open loop</td>
</tr>
<tr>
<td>Ground composition</td>
<td>Gravel, Sand &amp; silt</td>
</tr>
<tr>
<td>Groundwater level [m]</td>
<td>6-7 m below surface (+0.10- +0.17 m RH2000)</td>
</tr>
<tr>
<td>Annual mean air temperature (measured)</td>
<td>8.6°C</td>
</tr>
<tr>
<td>Undisturbed ground temperature</td>
<td>10°C</td>
</tr>
<tr>
<td>Design ground thermal conductivity</td>
<td>2.4 W/mK (saturated Gravel from literature)</td>
</tr>
<tr>
<td></td>
<td>2.4 W/mK (saturated Sand from literature)</td>
</tr>
<tr>
<td></td>
<td>1.8 W/mK (saturated Clay/Silt from literature)</td>
</tr>
<tr>
<td></td>
<td>2.4 W/mK (saturated Till/Loam from literature)</td>
</tr>
<tr>
<td>(Santa et al., 2017)</td>
<td></td>
</tr>
<tr>
<td>Minimum groundwater temperature exiting for Cooling (GWCFT_{min})</td>
<td>5 °C</td>
</tr>
<tr>
<td>Maximum groundwater temperature exiting for Cooling (GWCFT_{max})</td>
<td>14°C</td>
</tr>
<tr>
<td>Minimum groundwater temperature exiting for Heating (GWHFT_{min})</td>
<td>10 °C</td>
</tr>
<tr>
<td>Maximum groundwater temperature exiting for Heating (GWHFT_{max})</td>
<td>16°C</td>
</tr>
</tbody>
</table>
### Table 4 Summary of the ground heat exchanger - Groundwater

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of production wells</td>
<td>5</td>
</tr>
<tr>
<td>Number of injection wells</td>
<td>5</td>
</tr>
<tr>
<td>Well depth</td>
<td>13m (warm wells) - 20m (cold wells)</td>
</tr>
<tr>
<td>Distance between production and injection wells</td>
<td>≈70 m</td>
</tr>
<tr>
<td>Type of aquifer</td>
<td>Semi-confined</td>
</tr>
<tr>
<td>Aquifer thickness</td>
<td>6-15 m</td>
</tr>
<tr>
<td>Hydraulic gradient</td>
<td>0.0001-0.0003</td>
</tr>
<tr>
<td>Permeability</td>
<td>216-250 m/day (2.5-2.9 * 10^-3 m/s)</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>346 - 501 m²/day (4.0-5.8 * 10^-3 m²/s)</td>
</tr>
<tr>
<td>Porosity</td>
<td>20%-25%</td>
</tr>
<tr>
<td>Lithology of the unsaturated and saturated zones</td>
<td>Unsaturated (Fill-Clay-Sand-Silt)</td>
</tr>
<tr>
<td></td>
<td>Saturated (Gravel-Sand-Silt)</td>
</tr>
<tr>
<td>Type of source pump</td>
<td>GRUNDFOS SP 46-4-C &amp; GRUNDFOS SP 60-4</td>
</tr>
<tr>
<td>Groundwater pumping rate, heating</td>
<td>50 l/s</td>
</tr>
<tr>
<td>Groundwater pumping rate, cooling</td>
<td>50 l/s</td>
</tr>
<tr>
<td>Anti-fouling/scaling/corrosion measures</td>
<td>Periodic flushing of the ground water loop system</td>
</tr>
</tbody>
</table>
Monitoring

Each well in the ATES system is installed in an underground concrete structure (small room) accessible by a ladder. The concrete structures (rooms) are linked with each other and with the pumps control room by underground pipes. These pipes are used as connection paths for signal and electric cables linking different components installed in the wells with the control room in the building garage. Each well room consists of a pumping and an observation well. Each observation well is equipped with a submerged diver of type STS ATM/N/T DMM029 that measures both the temperature and water level. The diver has a measuring range and accuracy of -25 to 80 ± 1°C and up to 25 ± 0.25% bars. Each pumping well is equipped with a pump of type GRUNDFOS SP 46-4-C for warm wells and GRUNDFOS SP 60-4 for cold wells, as well as a pressure sensor (Siemens QBE2103-P4) and temperature sensor (Siemens QAE2121.010) measuring range and accuracy of up to 4 ± 0.1% bars and -30 to 130 ±0.5°C respectively. The latter sensors are installed on the main pipe just outside the well. All wells on each side (warm and cold) are grouped into one main supply pipe to extend towards the building. The building is equipped with a secondary heat exchanger that separates the ground water loop and the heat pump secondary fluid loop to avoid clogging in the evaporator of the heat pump. Energy meters (Siemens Sitrans F M MAG 5000 & Siemens QAE21) are installed on both sides of the secondary heat exchanger to monitor energy exchange between the ATES and buildings.
Performance metrics

The system boundaries proposed by Annex 52 consists of six boundaries level for heating and cooling modes operation of operation, as in Table 6 below

<table>
<thead>
<tr>
<th>SPF Boundary Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
</tr>
<tr>
<td>Ground Source Side (circulation pumps+ ground water Pumps)</td>
</tr>
<tr>
<td>Heat pump unit</td>
</tr>
<tr>
<td>Buffer tank (including circulation pumps between heat pump and buffer tank)</td>
</tr>
<tr>
<td>Circulation pump on load-side before distribution system</td>
</tr>
<tr>
<td>Building distribution system</td>
</tr>
<tr>
<td>Auxiliary heating or cooling</td>
</tr>
<tr>
<td>Equivalent in the SEPEMO boundary schema</td>
</tr>
</tbody>
</table>

Each group of components of the system is described by a certain of boundary level, when any auxiliary heating or cooling is used in certain level, the superscript (*) is used as an indication. In this study case, the focus will be on evaluating the performance for the boundary levels SPF0, SPF1 and SPF2. Based on Annex 52 boundary levels, SPF0, SPF1 and SPF2 can calculated as the following:

\[
\text{SPF}_{\text{co}} = \frac{Q_{\text{ATES}},_{\text{c}}}{W_{\text{GWP},_{\text{fcm}}} + W_{\text{MCP},_{\text{fcm}}} + W_{\text{CP},_{\text{hp}}}}
\]

During ATES free cooling mode, the circulation pumps near the heat pumps will not be operated, then \((W_{\text{CP},_{\text{hp}}})\) in equation 0-1 will be zero.

\[
\text{SPF}_{0,0} = \frac{Q_{\text{ATES},_{\text{a}}}}{W_{\text{GWP},_{\text{hm}}} + W_{\text{MCP},_{\text{hm}}} + W_{\text{CP},_{\text{hp}}}}
\]

When ATES is providing heat, the circulation pumps near the heat pumps will be in operation, then \((W_{\text{CP},_{\text{hp}}})\) in equation 0-1 will not be zero. But it is worth mentioning that \((W_{\text{CP},_{\text{hp}}})\) would be partially used to circulate water coming from the building side to be
used as a source for the evaporator while simultaneously cooling the building. But this would not be taking into account without exceeding $SPF_0$ boundary level.

$$SPF_{C1} = \frac{Q_{Evap}}{W_{Comp}}$$

Similarly in equation 0-3 and 0-4, $SPF_i$ in this formulation, mainly provides information about the heat pump unit performance. This does not necessarily take into account if the heat pump was used for simultaneous heating and cooling.

According to Annex52 system boundary levels, electrical consumption of circulation pumps $W_{CP}$ between the heat pump and the building would be counted in $SPF_4$ which is just before the building distribution system. But in reality, they are also used to circulate water as a heat source (though it is not ground source) for the evaporator. Therefore, if we strictly follow Annex 52 $SPF_2$ boundary level, $SPF_{C2}$ and $SPF_{h2}$ can be expressed as in equations 0-5 and 0-6.

$$SPF_{C2} = \frac{Q_{Build,c}}{W_{GWP, fcm} + W_{MCP, fcm} + W_{CP, hp, cm} + W_{Comp,c}}$$

$$SPF_{h2} = \frac{Q_{Cond}}{W_{GWP, hm} + W_{MCP, hm} + W_{CP, hp, hm} + W_{Comp,hm}}$$

The previously mention Annex 52 definitions of $SPF_0$, $SPF_1$ and $SPF_{C2}$ would be suitable for a wide range of installation and provide valuable information about the performance of specific component of the system such as the ATES groundwater loop and the heat pump unit. But it would benefit from additional suggestions to take into account the performance of operational modes and strategy of the heating and cooling system operation especially in more complex systems where dual operation is considered.

The heating and cooling system has three main operation modes:

**Free Cooling**: during which the ATES provides direct cooling (without the use of the heat pumps) towards the building cooling distribution network and domestic hot water demand is supplied using district heating.

**Machine Cooling**: during which the heat pumps are used to supply cooling towards the building cooling distribution network and domestic hot water demand usually supplied by the heat pumps condenser while using district heating as a backup. The excess heat from the condenser is rejected to air chillers on the roof. This means that during machine cooling, there will be some form of heating as well.
**Heating:** during which the heat pumps are used to supply heating towards the building heating distribution network and domestic hot water while using district heating as a backup. On the heat pump evaporator side, the heat source is being divided between the ATES and the building cooling distribution network. This means that while heating, the heat pump is simultaneously cooling the building as well.

![Schematic of the heating and cooling system in Rosenborg with the boundary levels for SPF0-SPF2 showing the energy flow in each the main operation conditions, heating (red arrow), free cooling (dark blue arrow) and machine cooling (light blue arrow).](image)

**Data Acquisition and Management**

Thermal energy utilized and the electrical energy consumption measurements are measured by electromagnetic flowmeter (0.5% uncertainty) and two matched pairs of temperature sensors on the forward and return lines with maximum uncertainty of ±0.05K. The electrical energy is measured with power meters that has an uncertainty of ±1%.

Electrical power consumption with measurement resolution of 5 min of the circulation pumps near the heat pumps’ evaporators and near the buffer tanks has sometime been missing from the data, but instead, the electrical energy in kWh was provided for
longer period of time (per day). This would make it difficult to separate the electrical energy consumed during each operation conditions. To solve this issue, the electrical power was estimated based on the thermal power passing through that line. This was done using the ratio of the total electrical energy consumed to the thermal energy utilized during a specific period of time. Then using this ratio to calculate the electrical energy by multiplying it with the thermal power measurement at that time step (with the high resolution, 5 min).
PERFORMANCE MONITORING RESULTS

Building heating and cooling loads

Table 6 Overall load characteristics

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Building space heating + DHW load met by system [MWh]</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>456</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building cooling load met by system [MWh]</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>381</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal energy extracted from the ground [MWh]</td>
<td>182</td>
<td>168</td>
<td>122</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal energy injected to the ground [MWh]</td>
<td>9</td>
<td>239</td>
<td>275</td>
<td>236</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal balance ratio (extracted/rejected)</td>
<td>21</td>
<td>0.71</td>
<td>0.45</td>
<td>0.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating load (incl. DHW) met by ground source (%)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling load met by ground source (%)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 Monthly Building Cooling, Space Heating and Domestic Hot Water Load in MWh
From April 2019 to March 2020, the total space heating and domestic hot water was 381 MWh and the cooling demand was 456 MWh as in Figure 7. The total monthly heating and cooling demands are shown in Figure 6. It is important to note that during January 2020, there was lack of data for approximately 2 weeks, therefore the actual demand is expected to be higher than what is shown in Figure 6 & Figure 7. The energy usage intensities (EUI) are 25 (kWh/m²) and 21 (kWh/m²) for heating and cooling consecutively for a total heated and cooled area of around 18000 m² for both buildings. The designed EUI including electricity consumption during heating and cooling are 40(kWh/m²), and 50 (kWh/m²), the measured total EUI was 46 (kWh/m²). The system seems to have reasonable values of EUI, though a performance gap still exist which might lead to the building being just shy of the Platinum LEED certification requirement (51 kWh/m²) which is designed to fulfill.

![Figure 7 Yearly Building Cooling, Space Heating and Domestic Hot Water Load in MWh](image)

The energy signature of the building is shown in Figure 8 presents the energy consumed in MWh for each outdoor temperature bin. The heating load shows an expected negative correlation with the outdoor temperature. The cooling load though show a slight positive correlation but there seems to be cooling needs even during winter.
The building signature for thermal power in kW is shown for each outdoor temperature bin in Figure 9. The heating load shows a negative correlation with the outdoor temperature. The maximum heating load reached was around 475 kW in the winter with an average of 120 kW while decreasing to below 10 kW at the higher outdoor temperatures. The maximum cooling load during summer was 600 kW while decreasing to 10 kW-20kW in wintertime. This is due to the need for continuous cooling throughout the year in the ventilation system Figure 9.

The heating load is mainly to be supplied by the heat pump and the district heating when the heat pump is not able to cover the demand. In the other hand, cooling is mainly supplied by direct cooling from the ATES and the heat pump in case the ATES temperature is not sufficient enough.
Figure 10 shows that the use district heat accounted for a significant portion of the heating supply. Despite the heat pump not reaching half of its heating capacity as shown in Figure 11, the district heating is still covering nearly 40% of the total heating demand which is a signal for inefficient utilization of the available resources both the heat pump as well as the available warm temperatures in the ATES.

Figure 11 Hourly and Mean heating and cooling supply in Temperature bins for Rosenborg March 2019-April 2020
ATES Performance

The ground source loop (ATES) operation is evaluated in the first system boundary (SPF0). The operation of the ATES started since October 2016. Therefore, the ATES has completed three annual (heating and cooling) and a half storage cycle until end of March 2020 shown in Figure 12. Annually on average, ATES energy injection (summertime) and extraction (wintertime) are 246 MWh and 190 MWh respectively.

![Figure 12 Monthly Heating and Cooling Energy from ATES in MWh](image)

The evaluation of only SPF0 was possible since 2016 but given the data availability for the groundwater pumps ($W_{GWP}$) and the main circulation pump ($W_{MCP}$) but no other circulation pumps needed for the SPF levels. Heating and cooling monthly performance factors ($MPF0$) values for the ATES are presented in Figure 13. $MPF0$ values for cooling ranges between 73 and 11.
Figure 13 Monthly Seasonal Performance Factor for ATES (MPF0) excluding the circulation pump near the heat pumps

*MPF0C* values have decreased over the years. Compared to the first years of operation, an average monthly decrease in *MPF0C* values by 34% and 43% is measured in the last summer season. This indicates suboptimal utilization of the ATES or unsuitable choices for the flowrates and temperature difference on both sides of the main heat exchanger connecting the ATES and the building heat and cooling system network.

In contrast, *MPF0* for heating values have been more consistent over the years averaging 33. This indicates a more suitable operation in terms of flowrates and temperatures differences (compared to summertime) during winter over the years.

Given the high potential *MPF0* values, more optimized ATES operation in connection to the system would have a significant impact on the overall performance. Therefore, optimizing the ATES operation should be prioritized to utilize its full potential when operating the heating and cooling system as a whole.

The relative decrease in *MPF0C* values can attributed mainly to the imbalanced yearly operation of the ATES and suboptimal choice of groundwater flow (often too high) and temperatures differences (often too low). This is discussed in the next section.

**ATES Seasonal and Hydraulic balance**

During summertime, total energy used from ATES has increased (235 to 272 MWh) during the first three summer seasons. In contrast, the use of heating energy during wintertime has decreased from 189 to 83 MWh near the end of the fourth heating season. A similar trend can be seen for the ground water volume used during heating operation which decreased from 37,000 to 13,000 m³. In contrast, the ground water
volume utilized during cooling has increased from 49,000 to 112,000 m³ during the first 3 cooling seasons of operation. Most of the energy used during the fourth year was for heating since the data analyzed in this work is until March 2020 (Figure 14).

Figure 14 Total yearly energy [MWh] and water volume [10³ m³] used from the ATES (left axis) to heat and cool the building and the volume extracted per unit of energy [m³/kWh] (right axis) during the period Oct 2016-March 2020. (Abuasbeh et al., 2021)

The ATES has experienced an imbalanced operation the years that resulted in a gradual temperature increase in the ATES. In Figure 15, extraction temperatures from the warm wells and injection temperatures in the cold wells are represented in the red and blue dots respectively and the temperature difference between the inlet and the outlet of the heat exchanger on the ATES side during building heating mode ($\Delta T_{heating}$) is represented in yellow markings. In Figure 16, extraction temperatures from the cold wells and injection temperatures in the warm wells are represented in the blue and red dots respectively and the temperature difference between the inlet and the outlet of the heat exchanger on the ATES side during building cooling mode ($\Delta T_{cooling}$) is represented in yellow markings.
The average extraction temperatures from the warm side have increased from 10.5°C to almost 13°C as shown in Figure 15 when comparing the first and last storage cycles. On the cold side of the aquifer, the average extraction temperatures have increased from 9.7°C to 11°C continuously exceeding the undisturbed ground water temperature (see Figure 16). This gives an indication of the thermal break through between the cold and warm wells.
Heat pump performance

The heat pump data analyzed in this study is for the period April 2019- March 2020. To evaluate the heat pump operation is done in system boundary (SPF1). During the duration of Oct 2016-March 2020, the average energy exchange with the ATES annually are 256 MWh and 160 MWh during machine cooling and heating modes respectively (Figure 17).

![Figure 17 Monthly Heating and Cooling Energy from the Heat Pumps in MWh](image)

According to Annex 52 SPF1 boundaries, SPF1C & SPF1H are meant to evaluate the heat pump units’ cooling and heating performance. It necessary to not only look at the heat pump components, but rather take into account the operation condition in the building and what is the actual useful energy being utilized in a given period of time. This becomes more relevant given that the heat pumps provide simultaneous heating and cooling. The monthly average values of MPF1C & MPF1H are approximately 4.4 and 4 for the machine cooling and heating mode respectively (see Figure 18). These values do not take into account the fact that the heat pump provide both heating and cooling at the same time.

When considering the dual heat pump operation providing heating and cooling at the same time, the compressor energy is divided accordingly. This results in higher SPF values. In Figure 18, the MPF taking into account the dual heat pump operation is represented by MPF1H* in which the compressor energy is divided according to all of the useful energy utilized during a certain period of time for heating and cooling. A similar can be done to MPF1C but for purpose of this study, some of the necessary measurements are not yet available to do so. MPF1H* show consistently higher values compared to MPF1H* averaging around 6 over the year (see Figure 18). Compared to MPF1H, MPF1H* is averaging 20% increase (see green dots in Figure 18).
Using SPF1 for the heat pump unit would give insight on how well the heat pump component is operating. But when the aim is to evaluate the actual energy performance of the system in place, SPF1H* can have a more realistic and fair evaluation of the actual system operation performance.

SPF2 Boundary

SPF2 system boundary includes the groundwater pumps, the main circulation pump, heat pumps compressor, circulation pumps that are near the heat pump evaporator (before the cold buffer tank) that are used to deliver energy to the heat pump source side (see Figure 4).
In Figure 19, $MPF2_{Free\,Cooling}$, $MPF2_{Machine\,Cooling}$ refer to the performance factor when the system operating in free cooling only and machine cooling only respectively where $MPF2C$ refers to the performance factor of both free cooling and machine cooling. Similarly, $MPF2H$ refers to the performance factor when the system is operating in heating mode. The monthly average values of $MPF1C$ & $MPF1H$ are approximately 19 and 3 while the average value of the combination of both ($MPF2C$) is around 9.5. These values are based on the assumption that all heat rejected from the condenser side of the heat pump is being rejected to the chiller on the roof and not used for heating the building. For heating mode, $MPF2H$ value is around 3. These values do not take into account the fact that the heat pump provide both heating and cooling at the same time given that to obtain such information, one would need to exceed the boundary of levels specified in Figure 5. Which suggests that those MPFs are likely to underestimate the actual MPF value when the system is operating heating and cooling simultaneously. For instance, when simultaneous heating and cooling is taking into account, $MPF2H$ monthly values would have an average increase of 20%.

Giving that the heat pump is the main supplier of heat during the heating mode operation, the compressors had the majority share the total electric energy consumed accounting for around 80%. In the other hand, the total electric energy consumption during the cooling operation was equally dominated by the ground water pumps and circulation pumps taking around 35-50% and 50-65% respectively during free cooling mode. When machine cooling is used the compressor share of electrical energy consumption ranged 50-80% while the rest (20-50%) was equally shared between the ground water pumps and circulation pumps.
Table 7 Seasonal Performance factors over the monitoring period

<table>
<thead>
<tr>
<th>Start of evaluation period</th>
<th>October 1st 2016</th>
<th>April 1st 2017</th>
<th>April 1st 2018</th>
<th>April 1st 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of evaluation period</td>
<td>March 31st 2017</td>
<td>March 31st 2018</td>
<td>March 31st 2019</td>
<td>March 31st 2020</td>
</tr>
<tr>
<td>SPFH0</td>
<td>33.2</td>
<td>30.6</td>
<td>33.6</td>
<td>32.9</td>
</tr>
<tr>
<td>SPFH1*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.0</td>
</tr>
<tr>
<td>SPFH2*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.6</td>
</tr>
<tr>
<td>SPFHC0</td>
<td>22.1</td>
<td>53.1</td>
<td>38.5</td>
<td>23.9</td>
</tr>
<tr>
<td>SPFC1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.4</td>
</tr>
<tr>
<td>SPFC2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.4</td>
</tr>
<tr>
<td>SPFHC0</td>
<td>33.1</td>
<td>40.4</td>
<td>36.8</td>
<td>25.8</td>
</tr>
<tr>
<td>SPFC1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.9</td>
</tr>
<tr>
<td>SPFC2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.5</td>
</tr>
</tbody>
</table>

In Table 7, SPFH1* & SPFH2* were calculated considering that the heat pump has been used for heating and cooling at the same time, therefore the compressor energy was divided accordingly.

At the time of writing this report, the data available for the secondary fluid on the sink (condenser) side of the heat pump was not complete enough. Therefore, it was not possible to calculate how much of the rejected heat from the condenser was useful (for space heating and domestic hot water). Hence SPFC1 & SPFC2 values in Table 7 were calculated as if the heat pump has been used for only cooling. In reality, the heat pump has been used simultaneously for cooling and heating. This means the values of SPFC1, SPFC2, SPFHC1, SPFHC2 presented in Table 7 underestimate the actual cooling performance.
Data Collection and management

Data collection and preprocessing has been by far the most time-consuming task of this project. Some of the challenges that was encountered were:

- The data was obtained in raw format and building a data management system was essential.
- Different naming systems for the sensor provided even from the same source (Siemens).
- Syncing data provided by several sources (Siemens, ClimaCheck, DTS) in terms of sampling time steps.
- Account for the time delay in measurement, this delay is due to:
  - Data being provided by several sources.
  - The system dynamics. For instance, when heat pump start running it need time to reach steady state.
  - The delay caused by the fact that Siemens’ measurement system log the data from the sensors in series, which lead to few minutes (5-10 min) of delay between some measurements in the system.

- Syncing the time step. The time steps for the sensors in the majority ranged between 1-15 min and in few cases up to 1 hour. Therefore, it was of importance to unify the time step between all sensors used in the analysis.

System Boundary

Usually, we try evaluating the performance of subsystems by placing boundaries (SPF0, SPF1 etc) to better explain the overall system performance. But in more complex system (both in terms of component configuration and operation protocol) we are not able to accurately evaluate performance of these subsystems solely based on the information within that boundary without the need for information from outside these boundaries.

By strictly following such component-based boundaries, especially on the lower levels such as SPF0 and SPF1, the performance values would give us a valuable insight into how well a particular component in the system is operating compared to the nominal or design value. In the other hand, this approach would lack the information about how this component is performing within the system which leads to inaccurate evaluation of the impact the system operation protocol has on the system levels performance. This often underestimates the actual system performance by Up to 32%.

The main issue lays on the way to divide the electrical consumption of the various groundwater pumps, circulation pumps and compressors relative to the useful energy used. In particular, when the system is providing useful heating and cooling energy simultaneously. In such case, it is more reasonable to divide the total useful energy supplied (heating, cooling or both) by the corresponding electrical energy
consumption. But when attempting to calculate the partial electrical consumption used of heating or cooling for a certain system boundary, it is sometime necessary to go beyond that boundary level in order to account for that.

Auxiliary heating or cooling component is usually thought of as a component with relatively low share (for heating or cooling) of the total supplied energy that is used to cover the demand during peak load periods when the main source is not able to cover the demand. This usually means that the auxiliary component is used to cover a relatively small portion of the energy demand compared the main supplier of heating or cooling. In GSHP systems, usually the heat pump is used as the main source for heating or cooling while typically an electric heater is used as an auxiliary heating source. On the other hand, in more complex systems such as our study case, the operation modes may vary between heating, direct cooling, machine cooling or combined heating and cooling. Additionally, the proportions of demand covered by several available sources may vary significantly. For instance, during heating, the heat pump is usually thought of as main source to cover the demand while auxiliary heating would be district heating. But in reality, the district heating seemed to have covered substantial portion of the heating energy demand (up to 40%) which is unconventional for an auxiliary heating component. Similarly, during cooling, the heat pump doesn’t cover the major part of the demand, instead the ATES does through free cooling. Therefore, a suggestion would be to define the auxiliary component based on the order of the operational priority of that component during heating or cooling which is usually set based on the most efficient option to supply the demand. For instance, during heating, the heat pump has the highest priority (given it is the most efficient option) followed by the district heating (DH) in which case the DH can be considered the auxiliary heating option. Similarly, during cooling, the ATES has the highest priority (given it is the most efficient option) followed by the heat pump (HP) in which case the HP can be considered the auxiliary cooling option.

**ATES-GSHP Operation**

The ATES, if operated in an optimal way, is by far the most efficient option to consider while heating and cooling (reaching MPF of more than 70).

Though in this study case, from the ATES prospective, the heating and cooling system in the building has been operating in suboptimal way throughout the years of operation. This is highlighted by several indication such as:

- Continuous imbalanced annual energy exchange with the ATES (much more cooling than heating).
- Low temperature differences from the ATES side (4.7 K during heating and 2 K during cooling).
- High (and increasing) extraction of groundwater volume.

This seems due to the heating and cooling system in the building controls the operation of the ATES in a way to achieve the maximum or minimum temperatures usable to be a heat source for the heat pump or cold source for free cooling. This led to extracting groundwater with temperature exceeding the undisturbed temperatures of the ATES. Although these temperatures are still suitable to be used for free cooling for the HVAC system, it will risk the ability to use the ATES for cooling in the future.
Furthermore, due to that the heat pump capacity was too high, the district heating was used more than it was intended to, further reducing the chance to utilize the already available heat stored in the warm side of the ATES. This led to thermal breakthrough in the ATES from the warm to cold side. More detailed investigation about the ATES performance was performed by (Abuasbeh et al., 2021) and additional KPIs were suggested to optimize the operation for both the ATES and the heating and cooling system in the building.

Therefore, further study conducted on ATES-GSHP system coupling is of high significance in order to optimize the system operation as a whole and achieve long-term sustainable operation for the ATES.
REFERENCES


Peer reviewed publications from the project

Project participants and their contribution

Mohammad Abuasbeh: Data collection, data preprocessing & management, investigation, software programming, data analysis, visualization, writing the final report done.

Willem Mazzotti Pallard: methodology, investigation.

Alberto Lazzarotto: methodology, investigation.

Jose Acuna: methodology, investigation, project administration, funding.

Signhild Gehlin: project administration, funding.