Performance of a mixed-use ground source heat pump system in Stockholm

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Abstract. The 6300 m^2 two-story Studenthuset building at Stockholm University in Stockholm, completed in 2013, was thoroughly instrumented. Space heating and hot water are provided by a ground source heat pump (GSHP) system consisting of five 40 kW off-the-shelf water-to-water heat pumps connected to 20 boreholes of 200 m depth in hard rock. Space cooling is provided by direct cooling from the boreholes. This system has now been monitored for five years. This paper presents the results in the form of a range of performance indicators that describe the short-term and long-term system performance. Performance factors are computed for several boundaries defined by the IEA HPT Annex 52 boundary schema. Seasonal, monthly, daily, and binned performance factors for both heating and cooling operation are presented and discussed. Contrary to expectations based on thermodynamic theory, the performance is better correlated to the quantity of heating or cooling provided than it is to the exiting fluid temperatures from the ground heat exchanger. Despite being in Stockholm, the building rejects about 30% more than it extracts, leading to a minimal temperature increase over the five measured years. The analysis indicates that if operated as is, the GHE will not exceed its temperature constraints for many decades. The five-year seasonal performance factor (SPF) for combined heating and cooling is 5.2±0.2 considering only the heat pump and source-side circulating pump. However, the load-side distribution system and Legionella protection systems result in a significant decrease in the 5-year combined heating and cooling SPF at the outer boundary to 1.8±0.3.

Keywords. GSHP, system performance, monitoring, SPF, Annex 52
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1. Introduction

The energy consumption of building heating and cooling systems often exceeds design expectations. This difference is often referred to as the "building energy performance gap." [1-4] Reasons for the gap include errors in design and installation, as well as non-optimal operating and control settings. Problems that don't lead to occupant discomfort may neither be detected nor mitigated for months or years unless performance measurements are made. Despite the need for such measurements, published results from long-term performance monitoring of building energy systems are scarce.

Gleeson and Lowe [5] reviewed field measurements of heat pump systems for residential buildings, mainly single-family buildings, comprising 600 heat pump systems in six European countries. For larger non-residential ground-source heat pump (GSHP) systems. Spitler and Gehlin [6] give an overview of published long-term (> 1 year) measured SPF and COP values reported in the literature for 55 systems worldwide. Such systems are necessarily more complex than GSHP systems for small residential buildings, and often include both heating and cooling as well as supplementary heating and cooling sources and heat recovery.

In 2018 a four-year international collaboration project IEA HPT Annex 52, *Long-term performance measurement of GSHP systems for commercial, institutional and multi-family buildings* [7] was initiated with the aim to monitor and analyze the long-term performance of a large number of GSHP systems in several countries. The emphasis in the project was on heat pump and system performance, e.g. determining coefficients of performance, seasonal performance factors and other system efficiency indicators. The project closed at the end of 2021, with performance measurement results from 30 large GSHP systems in seven countries. At the time of writing, the Annex has yielded a number of case study reports as well as guidelines for instrumentation [8] and uncertainty analysis [9].

One of the monitoring projects within IEA HPT Annex 52 is the GSHP system at the student union building Studenthuset at Stockholm University in Sweden. “Studenthuset” literally translates as “The Student Building”, and so will be referred to simply as “Studenthuset” in this paper. Analysed performance data for one year of operation (April 2016-March 2017) were presented by Gehlin et al. [10] and Spitler and Gehlin [6], including seasonal performance factors and monthly, daily, and binned average values of coefficients of performance. Spitler and Gehlin [6] also include a detailed uncertainty analysis. Spitler and Gehlin [11] present an extended analysis of performance data from Studenthuset, including three years of analysed data and a discussion about the correlation between performance factors and heating and cooling load. The authors conclude that the system performance is strongly related to the load. With increasing load, the system performance also increases, and the system has relatively poor performance at times when the heating and cooling loads are low.

In this paper an extended analysis of 60 months of monitoring (January 2016 - December 2020) from the Studenthuset GSHP system is presented. Performance factors for multiple system boundaries and time frames as well as additional performance indicators and their correlation to load are analysed and discussed.

2. Studenthuset GSHP system

The student union building Studenthuset, located within the Stockholm University campus in central Stockholm, Sweden, is a 6300 m² four-story building completed in the fall of 2013. It contains office area, meeting rooms, study-booths for students and a café. The building services are thoroughly instrumented and maintained by highly skilled staff. The building services and GSHP system are described in references [6] and [11].

2.1 Building heating and cooling

The building’s heating, cooling and domestic hot water (DHW) loads are met by the GSHP system. No auxiliary heating or cooling is installed, except for an electric resistance heater that boosts the hot water temperature to protect against Legionella. Heat distribution is provided by radiators with extra-large surface areas at a distribution temperature of 40°C instead of 55°C, which is the more common distribution temperature in Sweden. The cooling distribution system is a combination of VAV (variable air volume) and CAV (constant air volume) with chilled beams for ventilation and cooling.

2.2 GSHP system

Space heating and DHW are provided by the GSHP system which consists of five 40 kW off-the-shelf water-to-water heat pumps connected to a borehole field with 20 groundwater-filled boreholes in hard rock. The boreholes are 200 m deep and are fitted with single u-tubes filled with an ethanol/water mixture. The bore field is located below a landscaped courtyard and the boreholes are drilled at an angle so that they reach under the surrounding building (Figure 1). Space cooling is provided by direct cooling from the boreholes, with the fluid temperature leaving the boreholes at maximum 16°C.

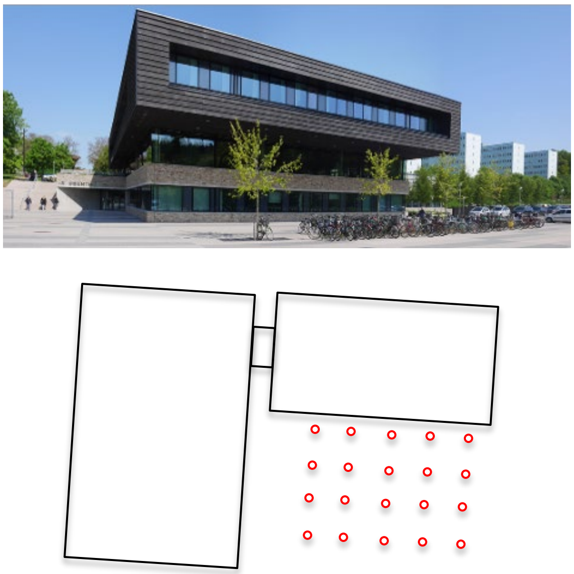

Fig. 1 - Studenthuset in Stockholm, front view (upper) and top view with borehole field (lower). Photo: JD Spitler.

2.3 System schematic and boundaries

Figure 2 shows a simplified schematic layout of the Studenthuset GSHP system. Six levels of system boundaries (0-5) are defined in the figure, for the evaluation of performance indicators.

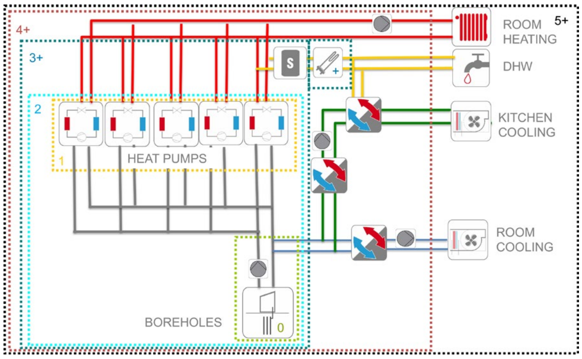

Fig. 2 - Schematic and Annex 52 system boundaries for Studenthuset. Pictograms in drawing used with permission from TU Braunschweig IGS

The six system boundary levels were developed within the IEA HPT Annex 52 project and represent an extension of the widely used system boundary schema developed within the EU project SEPEMO [12] in 2012. While the SEPEMO boundary schema was aimed at small monovalent or bivalent heat pump systems, the Annex 52 schema allows for a higher degree of system complexity such as in larger

GSHP systems like Studenthuset. The Annex 52 system boundary schema with six boundary levels and an indicator for use of supplemental heating or cooling is one of the outcomes from the IEA HPT Annex 52 project and is described in more detail in [13]. It is used in this paper and [11] for the analysis of the Studenthuset operation and performance, while the SEPEMO schema was used in [6] and [10].

The measured data for Studenthuset allows for calculation of heating performance at boundary levels H2, H3+ and H5+* and cooling performance at boundary levels C2 and C3(which are the same for this system). Performance factors may also be estimated for boundary levels H1* and C5*, with some approximations; the asterisk is used to indicate that the measured performance factor does not exactly correspond to the Annex 52 definition.

Specifically, the electrical measurements of the heat pumps include internal circulating pumps and control boards in the heat pumps. We therefore denote the boundary level as H1*, including the internal heat pump electricity use, with an asterisk. Level C5 includes the cooling provided by the ventilation air, but there are no measurements available for the airflow rate, and therefore we designate the boundary level as C5*.

2.4 Instrumentation and uncertainty analysis

A full description of the instrumentation is given in [6]. While most data points are collected with individual meters, the electricity use for the five heat pumps and the electricity consumed by the Legionella protection system are measured by one electricity meter. To estimate the electrical energy consumed by the heat pumps for boundary H2, the energy consumed by the Legionella protection system (LPS) is subtracted. The LPS electrical energy is estimated based on measured DHW flow rates and temperature rise, along with a nearly constant 3kW usage for recirculation pumps and heat losses from the piping to the space.

Measurements of the electrical energy consumed by the source-side circulation pump, fans used for ventilation and cooling, circulation pumps on the load side (distribution), and circulation pumps on the source side (boreholes), as well as electricity used for running the rotary exhaust air heat exchangers in the kitchen and building were measured with a single meter. A separate set of measurements over a two-week period was made to allow estimation of the electricity used by the source-side circulation pump as a function of flow rate. The electricity used for pumps respectively during the many hours of operation when both heating and cooling are being provided by the system, was allocated based on the amount of heating and cooling provided at each hour.

A detailed uncertainty analysis of the Studenthuset measurement is described in [6]. The same analysis is used here to determine uncertainty, as represented by error bars in the figures.

3. Energy loads

A common way to characterize the building space heating and cooling loads is the energy signature, shown in Fig. 3 for Studenthuset. To be clear, domestic hot water heating and kitchen refrigeration are not included. Surprisingly, the building uses a modest amount of cooling even down to low outdoor air temperatures. Presumably, this is due to chilled water being circulated and casually gaining heat from the space.

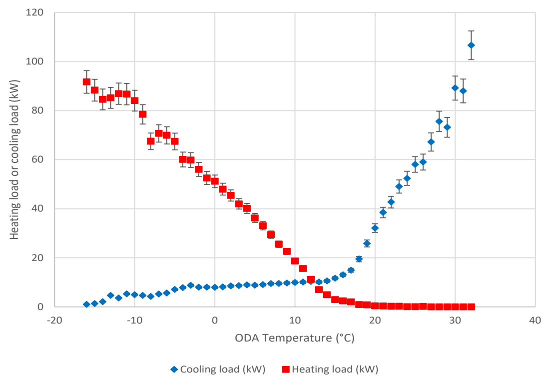

Fig. 3 – Energy signature showing building heating and cooling loads.

3.1 Annual balance

For ground-source heat pump systems, the balance between annual heat rejection and heat extraction is an important parameter. The instrumentation did not include an energy meter on the ground heat exchanger. Furthermore, the ground heat exchanger (GHE) flow rate was controlled to a minimum flow of 8 L/s, leading to low temperature differences, making it impossible to accurately measure the heat transferred to/from the ground. Therefore, annual loads on the ground were estimated as shown in Figure 4, with positive values representing heat extraction and negative values representing heat rejection or reductions in heat extraction. E.g. the heating provided to the building (red), of which the portion provided by the compressors (yellow) reduces the amount of heat extraction. If the annual heat transfer were perfectly balanced, the positive and negative portions in Figure 4 would have the same magnitude. It is notable that the load-side circulating pumps and fans (LSCPF) consume more energy than the heat pump compressors, while the source side circulation pumps (SSCP) use a very small amount of energy. As a result of the LSCPF energy consumption, even though the building heating loads are higher than the building cooling loads, the system rejects more heat than it extracts. In addition, some kitchen refrigeration also rejects heat to the ground, and further adds to the net imbalance, leading to the system rejecting about 30% more heat than it extracts. Uncertainty of these approximations have not been estimated, but the building heating and cooling loads have uncertainties on the order of 5-6%.

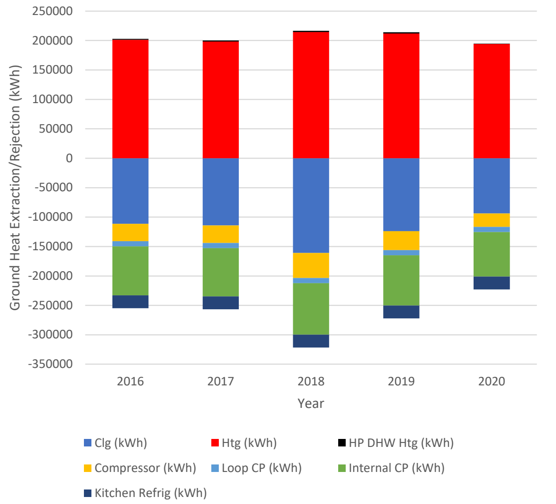

Fig. 4 – Estimated energy rejection and extraction components (to/from ground)

3.2 Ground heat exchanger performance

Ground-source heat pump systems usually have more favorable source temperatures than air-source heat pump systems. Figure 5 illustrates this, showing both the hourly outdoor air temperature and hourly exiting fluid temperature from the GHE. Not shown in the plot, if a trendline is fitted to the ground heat exchanger exiting fluid temperature (GHE ExFT), it shows a very slight (0.2°C) rise over the five-year period of operation. This is consistent with the annual heat rejection being higher than the annual heat extraction.

The cooling system was designed to operate with a maximum temperature of 16°C coming back from the boreholes. To date, the highest return temperature was 14.1°C during the unusually hot summer of 2018. This suggests that if the system continues operating as it does now, and if summers don't get hotter, the system will operate for many years before peak temperatures hit 16°C. That is, there is plenty of time to adjust system operation to mitigate this slight temperature rise.

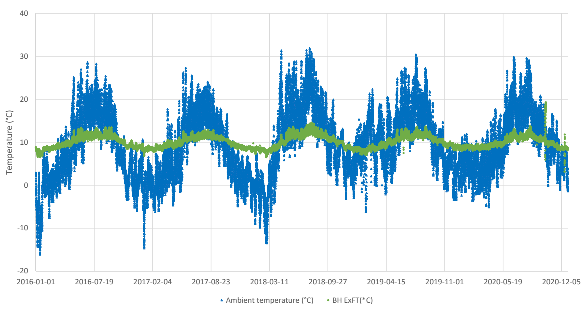

Fig. 5 – Ground heat exchanger entering fluid temperature and ambient temperature over the five years of measurement (2016-2020).

Figure 6 shows the relationship between the GHE ExFT and the outdoor air temperature, for 0.5°C bins. On average, the relationship is close to being linear – with hotter outside conditions corresponding to maximum cooling loads and accordingly warmer return temperatures from the ground.

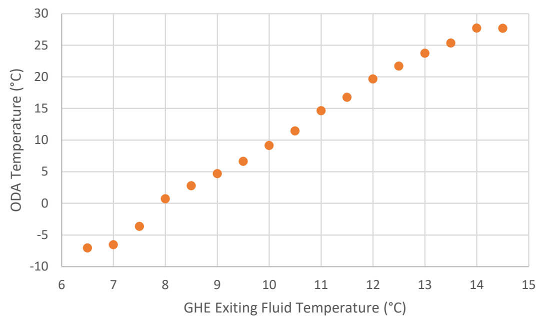

Fig. 6 – Binned ODA (Outdoor air) temperature vs. ground heat exchanger exiting fluid temperature .

4. Results

4.1 Energy consumption

The electrical energy consumption for each of the measured five years is summarized for heating (Fig. 7) and cooling (Fig. 8). The electrical energy for the load-side circulating pumps and fans (LSCPF) and the source-side circulating pump (SSCP) are allocated proportionally to the amount of heating and cooling provided. It's notable that the energy used for distributing heating (LSCPF) is similar to that used by the heat pumps for heating. This has a deleterious impact on the system performance. For cooling, the electrical energy used to distribute the cooling inside the building is about seven times the energy used to pump the heat carrier fluid through the ground heat exchanger. More careful analysis of the load-side distribution energy is needed to determine if the operation could be adjusted to reduce the energy consumption, but this has not been part of our study.

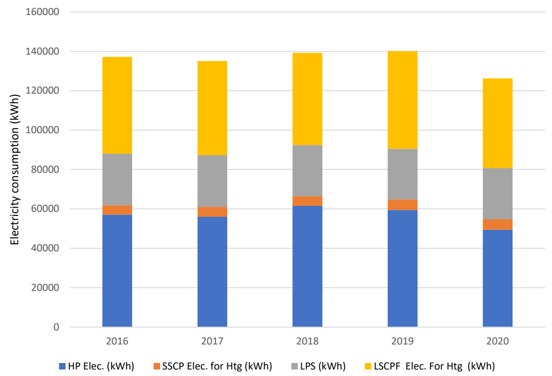

Fig. 7 – Electricity use breakdown for heating (2016-2020).

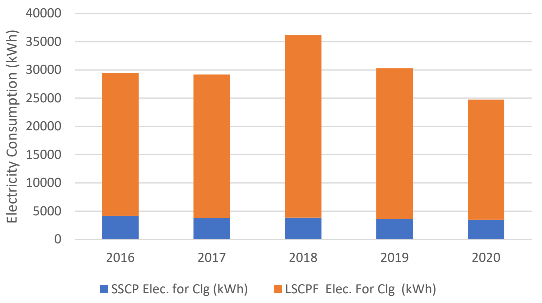

Fig. 8 – Electricity use breakdown - cooling (2016-2020).

4.2 Heating Performance

Seasonal performance factors for heating are computed for each year, grouped by the Annex 52 boundaries defined in Fig. 2, with deviations indicated with asterisks as discussed in Section 2. For each boundary, minor year-to-year fluctuations can be observed. From boundary 1* to 2, the SPF decreases due to the source-side circulating pump (SSCP). A further drop from boundary 2 to boundary 3+ is caused by the Legionella protection system (LPS), which consists of electric resistance heating to raise the hot water temperature to 60°C from the 55°C water provided by the heat pumps, and recirculation pumps that maintain high water temperatures throughout the piping network. Finally, from boundary 3+ to 5+*, the load-side circulation pumps and fans consume more electrical energy than the heat pump compressors and consequently reduce the seasonal performance factor (SPF) by more than 40% to approximately 1.5. The design and operation of the load-side pumping and piping was not part of our study, but it seems likely that there is significant room for improvement.

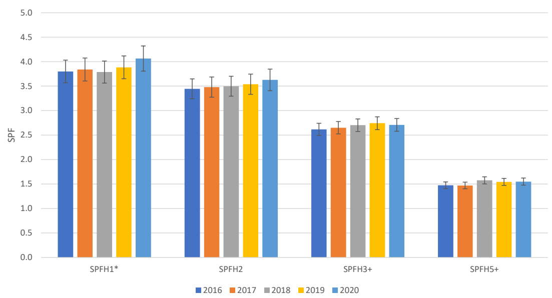

Fig. 9 – Heating SPF (2016-2020).

4.3 Cooling Performance

SPFs for the cooling system are given in Figure 10 for boundaries 2 and 5*. (Note the difference in scale.) Boundary 2 shows very high SPF values, as the only electrical energy accounted for is the source-side circulating pump. However, when accounting for the load-side circulating pumps and fans, with boundary 5*, the system performance is not so great. Meaningful comparisons can be difficult to make, but Southard, et al. [14] reported cooling SPFC5 (including fan energy) of a distributed GSHP system with much higher ground temperatures of 4.2±0.6. The distributed GSHP system did not have "free cooling" yet was able to provide cooling to the space significantly more efficiently than the Studenthuset system.

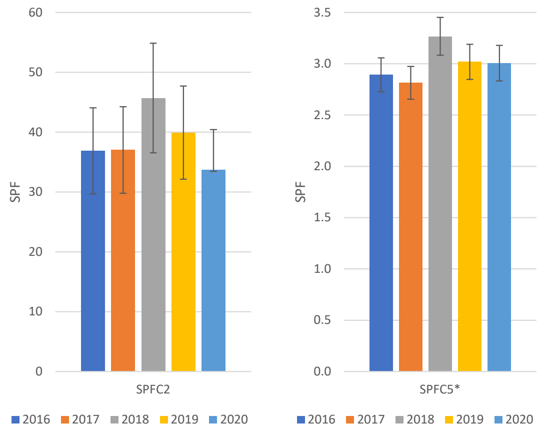

Fig. 10 – Cooling SPF (2016-2020).

4.4 Overall Performance

The performance factors shown above rely on allocation of the energy consumed by circulating pumps and fans between cooling and heating. An alternative approach is to calculate an overall performance factor for heating and cooling, as shown in Tab. 1. The impact of the internal heating and cooling distribution energy is still substantial, decreasing the 5-year SPF from 5.2 at boundary HC2 to 1.8 at boundary HC5+*.

Tab. 1 – Overall Seasonal performance factors

Year	SPF_{HC2}	SPF_{HC5+*}
2016	5.0±0.2	1.8±0.3
2017	5.1±0.2	1.7±0.3
2018	5.6±0.2	2.0±0.3
2019	5.2±0.2	1.8±0.3
2020	5.1±0.2	1.8±0.4
2016-2020	5.2±0.2	1.8±0.3

4.5 Monthly Heating and Cooling Performance

Monthly performance factors (MPF) for heating and cooling are shown in Fig. 11 and 12, respectively. Perhaps contrary to thermodynamic expectations, even MPFH1* is higher in the winter and lower in the summer, when the ground heat exchanger return temperatures are more favorable. As previously observed for this system and other systems – parasitic losses (e.g. control boards and energized solenoid valves) and cycling losses decrease the performance of GSHP under low-load conditions.

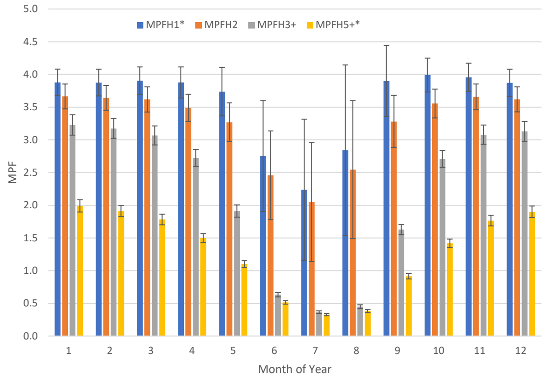

Fig. 11 –Heating monthly performance factors (2016-2020)

For cooling, MPF are higher during the winter months, when return fluid temperatures from the ground are lower. This is as expected, but the trend is also due to the allocation of pumping energy between heating and cooling, as will be shown in the next section.

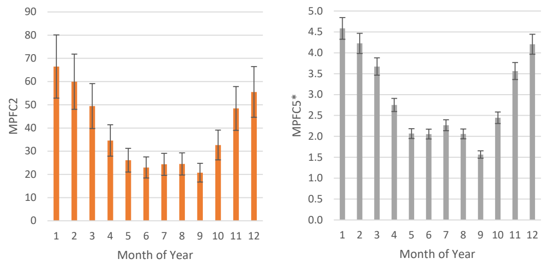

Fig. 12 – Binned monthly performance factors for cooling for each month in 2016-2020, with error bars.

4.6 Effect of source temperature

From a thermodynamic perspective, heat pump performance is expected to increase as source temperatures become more favorable. Binned performance factors have been calculated for heating and cooling, as shown in Figs. 13 and 14. Each symbol or bar in these figures represents performance for all hours in a certain bin. E.g., the symbol at a GHE exiting fluid temperature of 8°C represents all hours with temperatures between 7.75 and 8.25°C. The gray bars represent the number of hours in each bin.

Opposite to thermodynamic expectations for heating with heat pumps, the performance for every boundary trends downward with increasing entering fluid temperature to the heat pump. The decrease in performance is more dramatic for the boundaries H3+ and H5+*. The highest GHE ExFT occur in the summer period, which is a period with low use of Studenthuset and when the need for heating is mainly for DHW and Legionella protection. Energy use for circulation pumps and LPS will then be high compared to delivered energy, hence the low performance factors.

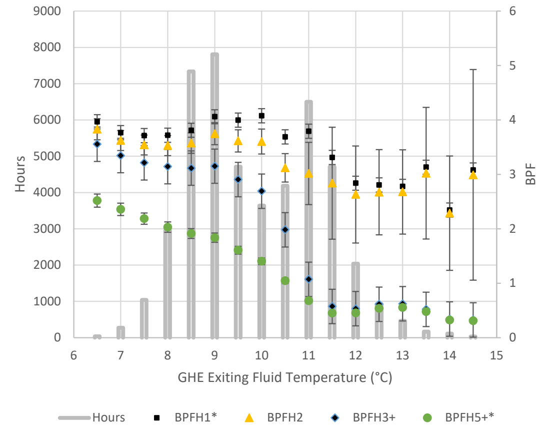

Fig. 13 – Binned performance factors for heating vs ground heat exchanger exiting fluid temperature.

For cooling, the performance factors show a V-shaped trend – highest at low or high temperatures, lowest at the middle point. For space reasons only boundary 5* is shown here, but the trend is the same for boundary 2. At low temperatures, where cooling is being provided simultaneously with heating, the amount of pump energy allocated to cooling is small, leading to high BPF. This is shown by calculating the BPF assuming that all of the pump and fan energy is allocated to cooling –shown as the orange triangles in Fig. 14. In this case the performance increases with increasing fluid temperature. This is also contrary to expectations – for any given amount of pump and fan energy, one would expect to see a decrease in performance factor for cooling, as the GHE ExFT increases. However, the temperatures are highest during periods of high loads, which is also when the amount of energy used for circulation pumps and fans are lowest compared to delivered cooling.

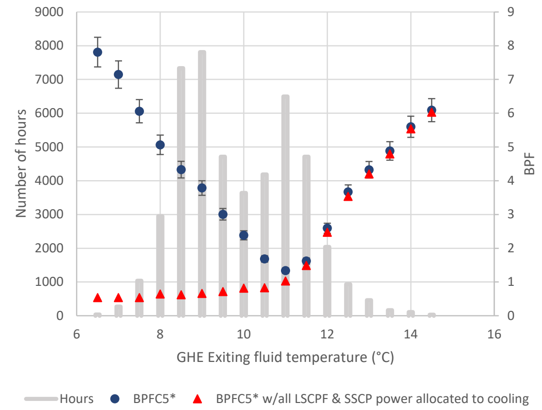

Fig. 14 – Binned performance factors for cooling vs ground heat exchanger exiting fluid temperature.

4.7 Effect of total heating and cooling

As may be inferred from the above results, the amount of heating and cooling being provided has a significant impact on the overall system performance, reducing the proportion of electrical energy used for pumping, blowing, and "parasitic" uses like control boards and solenoid valves.

Figure 15 shows binned daily system performance factors (boundary HC5+*) for heating and cooling combined, vs. the total amount of heating and cooling being provided. The performance factors are divided into days that are "mainly cooling", "mixed", and "mainly heating", based on the ratio of heating provided to total heating and cooling providing being less than 0.25, between 0.25 and 0.67, and greater than 0.67, respectively. The general trend for all categories is increasing performance with increasing total load. The mainly cooling days give relatively high performance as the better performance of the free cooling system becomes dominant with higher loads. The character of the "mixed" days follows the trend of the "mainly heating" days, although in the lower load and performance factor region. The "mixed" days (in the spring and fall shoulder seasons) show two bands of performance. The higher band occurs when there is low DHW consumption, correlated to low occupancy. Almost all of these days in the higher performance band are either weekend days or occurred in 2020 after the pandemic began and the university closed.

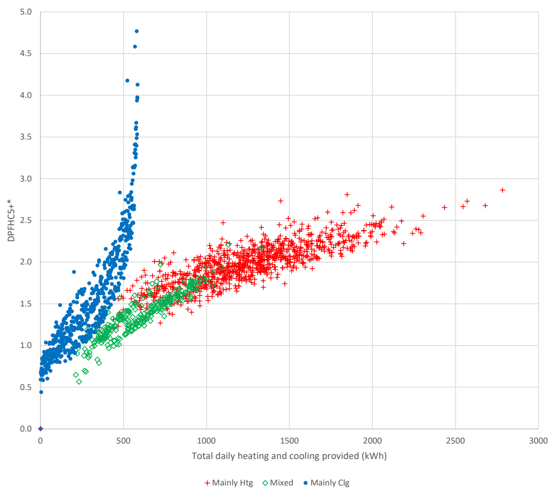

Fig. 15 – Binned daily total performance factors vs total heating and cooling provided at boundary 5+*.

5. Conclusions

In this paper, five years of data from the Studenthuset ground-source heat pump system have been analyzed from a system performance perspective. The GSHP system has previously been analyzed with data from one year [6, 10] and three years [11] and the general trends observed in those papers remain valid for the five-year period. Studenthuset was built in 2013 and the measured data for the period 2016-2020 show that the ground heat rejection exceeds the ground heat extraction by about 30%, leading to a minimal temperature increase over the five measured years. The analysis indicates that if operated as is, the GHE will not exceed its temperature constraints for many decades.

The five-year data analysis shows that the performance factors increase with increasing heating and cooling load. This confirms the results from the previously analyzed shorter data series.

The dominant factor for the overall system performance is the amount of heating and cooling provided by the GSHP system. The reason is that the proportion of electrical energy used for circulation pumps, fans and "parasitic" uses such as control boards and solenoid valves decrease when energy provided increases. The Studenthuset GSHP system performance factors are highest when the building is used heavily, and the lowest performance factors appear during those periods when students are off campus and the building is little used. During those periods standby circulation, DHW and Legionella protection are dominant.

The Studenthuset study pinpoints the deleterious effect of the load side distribution (piping, pumping, fans) and Legionella protection on the system performance factors. The distribution system and Legionella protection systems result in the 5-year combined heating and cooling SPF decreasing from 5.2 at boundary HC2 to 1.8 at boundary HC5+*. While it is important to maintain proper Legionella protection, the LPS operation ought to be optimized so that it does not use more energy than necessary. There is room for further system improvement and component development to minimize the energy use for load side distribution.

From a European perspective, where centralized heat pump systems are most common, it is tempting to argue that the load side distribution losses should not be taken into account, since they would be the same regardless of the heating and cooling source used, e.g. gas or district heating apart from heat pumps. Hence only system boundary 2, which includes the source side circulation pumps and the heat pumps, should be considered. However, in many countries, e.g. the USA, distributed heat pump systems are common. In such systems multiple smaller heat pump units are distributed in the buildings that they serve, and the main distribution losses appear on the source side of the heat pump. There are to our knowledge no systematic comparisons of the efficiency of centralized versus distributed heat pump systems, and to do that it is necessary to consider the load side system boundaries as well. Comparisons to a distributed GSHP system [14] in the USA suggest that the load-side system distribution energy in Studenthuset is excessive. It is our belief that additional comparative studies between centralized and distributed GSHP systems would be useful in shedding further light on the usage of energy for distribution of heating and cooling in heat pump systems.

6. Acknowledgements

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7. Data Access Statement

The datasets generated and analyzed during the current study are available in the ShareOK repository at: https://doi.org/10.22488/okstate.22.000005

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