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Three Years' Performance Monitoring of a Mixed-Use Ground Source Heat Pump System in Stockholm

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Abstract

The student center, Studenthuset, at Stockholm University in Stockholm, completed in the fall of 2013, is a thoroughly instrumented mixed-use 6300 m^2 four-story building. 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 in hard rock, drilled to a depth of 200 m. Space cooling is provided by direct cooling from the boreholes. The Studenthuset building monitoring project is part of the IEA HPT Annex 52 – *Long-term performance measurement of GSHP systems serving commercial, institutional and multi-family buildings*. This paper presents results from three years of measured performance data to calculate the long-term performance of the Studenthuset GSHP system. A number of performance indices are calculated and presented to describe the short-term and long-term system performance for selected system boundaries. Seasonal, monthly and binned performance coefficients for both heating and cooling operation are presented and discussed. The Legionella protection system, hot water continuous circulation system, and internal heating/cooling distribution system reduce the system energy performance.

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Keywords: Ground source heat pumps; performance monitoring; COP; SPF; system effects

1. Introduction

It is well known that many building heating and cooling systems consume excess energy due to errors in design and installation, as well as non-optimal operating and control settings. Such problems may not be detected and mitigated for months or years, unless performance measurements are made. Despite the obvious need for better knowledge and means to secure optimal energy performance in buildings, published results from long-term performance monitoring of building energy systems are scarce.

Gleeson and Lowe [1] reviewed field measurements of heat pump systems for residential buildings, mainly single-family buildings, comprising 600 heat pump systems in six European countries. Of these 216 were ground source heat pump (GSHP) systems. There are few published long-term performance measurements of larger, non-residential GSHP systems. Spitler and Gehlin [2] give an overview of published long-term ($\geq$ 1 year) measured SPF and COP values reported in the literature for 55 GSHP 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. With this in mind, a four-year international collaboration project IEA HPT Annex 52, *Long-term performance measurement of GSHP systems for commercial, institutional and multi-family buildings* [3] was initiated in 2018 with the aim to monitor and analyze the long-term performance of a large number of ground source heat pump systems in several countries. The emphasis is on heat pump and system performance, e.g. determining coefficients of performance, seasonal performance factors and other system efficiency indices.

One of these long-term performance monitoring projects within IEA HPT Annex 52 is the GSHP system at the student union building Studenthuset at Stockholm University in Sweden. Gehlin et al [4] and Spitler and Gehlin [2] analyze performance data for one year of operation (April 2016-March 2017) at Studenthuset including a detailed uncertainty analysis. The analyses include seasonal performance factors and monthly, daily, and binned average values of coefficients of performance. This paper aims to extend the analysis to include 45 months of monitoring (January 2016 through September 2019) and further investigate the correlation between performance factors and load provided.

1.1. Studenthuset building and GSHP system

The student union building Studenthuset is located within the large campus area of Stockholm University in central Stockholm, Sweden. The 6300 m^2 four-story building was completed in the fall of 2013 and contains office area, meeting rooms, study-booths for students and a café. The building services are thoroughly instrumented and maintained by highly skilled staff.

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 a borehole field. Space cooling is provided by direct cooling from the boreholes; with the maximum fluid temperature leaving the boreholes not to exceed 16°C. Heat distribution inside the building is provided by radiators with a larger-than-usual surface area so that the distribution temperature is 40°C instead of 55°C, which is more common in Sweden. Cooling distribution is done by a combination of VAV-system (variable air volume) and CAV-system (constant air volume) with chilled beams for ventilation and cooling. The system also includes heat recovery from the kitchen cooling circuit. No auxiliary heating or cooling is installed, except for an electric resistance heater that boosts the hot water temperature to protect against Legionella.

The borefield consists of 20 groundwater-filled boreholes in hard rock, drilled to a depth of 200 m, and fitted with single u-tubes filled with an ethanol/water mixture. The borefield is located below a landscaped courtyard. The boreholes are drilled at an angle so that they reach under the surrounding building (Figure 1).

Fig. 1. Studenthuset in Stockholm, front view (left) and top view with borehole field (right). Photo: Jeffrey D. Spitler.

1.2. System performance indicators

Performance of a GSHP system and its individual parts may be indicated in various ways depending on the purpose of the performance analysis, e.g. energy performance, technical performance and economic performance. The overall system performance is affected by the performance of the source side ground circuit, as well as the heat pump (HP) unit performance and the load side circuit performance, including supplementary heating and cooling. Energy use intensity (EUI), often expressed in kWh/m^2, is an example of a commonly used performance indicator for building heating and cooling systems. However, it does not differentiate between the effects of the building envelope, its usage, and the performance of the heating and cooling system. Therefore it gives little information about GSHP system performance. For GSHP systems, system coefficients of performance (COP and SCOP), energy efficiency ratio (EER and SEER) and seasonal performance factors (SPF) with various boundaries are used, however not in a consistent way [2]. Gehlin and Spitler [5] discuss target groups for GSHP system performance and indicators at various system levels identified by the IEA HPT Annex 52 workgroup. Such indicators, some of which we will use in this paper, are performance factors (PF) with a clear indicator of the time period (seasonal, monthly, weekly, daily, or binned – SPF, MPF, WPF, DPF, BPF) and with subscripts that correspond to the boundary conditions, e.g. H1, C4. Another type of performance indicator is the building energy signature, which shows the building heating and cooling loads at various outdoor air temperatures. The ground heat exchanger pressure drop and exiting fluid temperature (GHE ExFT) variation over time (seasons and multiple years) give indications such as of possible ground source circulation failure and ground heat balance.

1.3. System boundaries

One reason of the confusion in GSHP performance literature, pointed out by Spitler and Gehlin [2], is the inconsistent or non-existent declaration of chosen system boundaries for performance evaluation. Within HPT Annex 52 the system boundary schema developed within the EU project SEPEMO [6] was used for calculation of COP and SPF as a starting point. The SEPEMO boundary schema was therefore used in the performance calculations of the Studenthuset operation in 2016 by Gehlin et al. [4] and Spitler and Gehlin [2]. The SEPEMO boundary schema was aimed at small monovalent or bivalent heat pump systems and has limitations when accounting for the complexity of larger GHSP systems such as Studenthuset. HPT Annex 52 has therefore proposed a new system boundary schema [5], consisting of six defined boundaries and an indicator for use of supplemental heating or cooling. This system boundary schema is used in this paper for the evaluation of the Studenthuset operation over the period January 2016-September 2019 (Figure 2). The Annex 52 boundary schema and its relation to the SEPEMO boundaries is shown in Table 1.

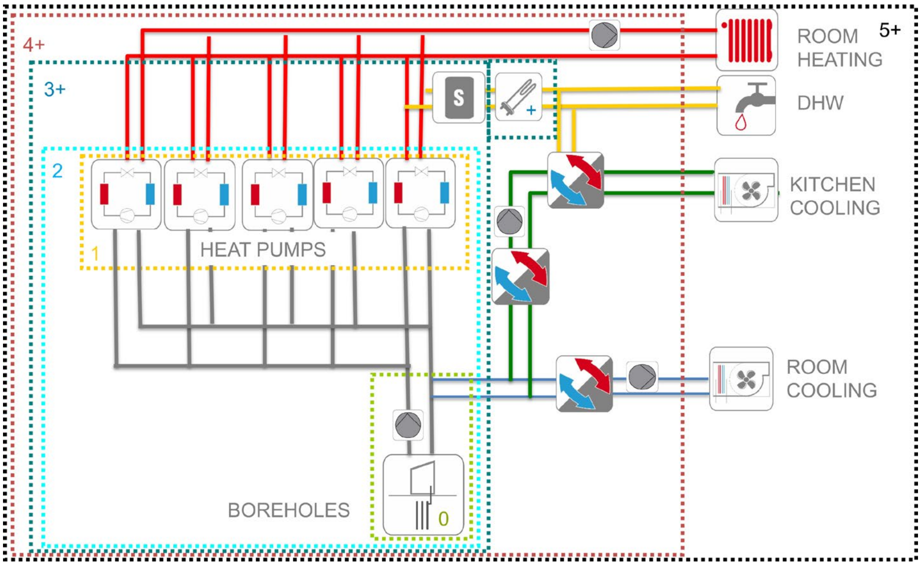


Fig. 2. Schematic and Annex 52 system boundaries for Studenthuset.
Pictograms in drawing used with permission from TU Braunschweig IGS.

Table 1: System boundaries according to the HPT Annex 52 schema and comparison with the SEPEMO boundaries. From [5].

Boundary description	HPT Annex 52 Boundary levels											
	0	0+	1	1+	2	2+	3	3+	4	4+	5	5+
Ground Source (circulation pumps+ ground source)	X	X			X	X	X	X	X	X	X	X
Heat pump unit including internal energy use, excluding internal circulation pump			X	X	X	X	X	X	X	X	X	X
Buffer tank (including circulation pumps between heat pump and buffer tank)							X	X	X	X	X	X
Circulation pump on load-side (between buffer tank & building H/C distribution system)									X	X	X	X
Building H/C distribution system											X	X
Auxiliary heating or cooling		X		X		X		X		X		X
Equivalent in the SEPEMO boundary schema			H1/C1		H2/C2	H3					C3	H4/C4

For Studenthuset the following performance factor levels exist and can theoretically be determined for the heating system; H0, H1, H2, H3+, H4+ and H5+. However, the available measurement data only allows for H1 (approximately), H2, H3+ and H4+ to be calculated. For the cooling system C0, C2, C3, C4 and C5 exist, but only C2, C3 (C2 and C3 are the same for this system) and C4 are possible to calculate from the available measurement data with a sufficient degree of accuracy. There is no cooling machine in the cooling system and no supplementary cooling.

2. Measurements and Analysis

2.1. Instrumentation

Compared to many buildings, the Studenthuset GSHP system is extensively instrumented. There are, unfortunately, no measurements made of airflow rates, so it is not possible to estimate either the heating or cooling provided to the ventilation air or the building by the heat recovery systems, which means that level 5 performance factors cannot be determined. The level 1 boundary for heating cannot be calculated without also including internal electricity use in the heat pump unit, i.e. internal circulation pump and control board. We therefore denote the performance factors for level 1, included its internal electricity use, with an asterisk. With the existing measurements, it is possible to estimate performance factors for the Annex 52 boundary levels 1*, 2, 3+ and 4+ for heating, and levels 2 (= 3) and 4 for the cooling.

A full description of the instrumentation is given in [2]. Briefly, heat transfer rates from the heat pumps to the building heat distribution system are measured with an energy meter that determines the heat transfer rate calorimetrically. The heat provided by the heat pumps to the DHW is determined using the volume flow rate measured with a flow meter, the controlled temperature provided by the heat pumps (55°C) and the estimated incoming temperature from the Stockholm water supply based on measurements made at seven different buildings in Stockholm [7,8]. Heating provided by the Legionella protection system is estimated based on a steady consumption of 3 kW of electricity due to the recirculation pump and dissipated energy from the hot water that was continuously circulated around the building, and energy provided by the electric resistance heater to heat the DHW from 55°C to 60°C. The cooling provided by the system is measured with the same type of instrumentation as used for measuring the building heating provided.

The system electrical energy consumption is monitored continuously and recorded on an hourly basis. Electricity use for the five heat pumps including the heat pump that is dedicated to DHW heating and the electricity consumed by the Legionella protection system are measured by one electricity meter. Electrical energy consumed by the heat pumps for boundary H2 is estimated by subtracting the energy consumed by the Legionella protection system.

Electrical energy consumed by the source-side circulation pump was metered along with the electrical energy for fans used for air conditioning, 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. 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 heating and cooling respectively during those 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.

2.2. Analysis and uncertainty analysis

Estimation of the uncertainty of the performance factors is highly desirable to understand the significance of the results as well as to shed light on design and specification of instrumentation for future monitoring projects. The uncertainty analysis in this study is described in detail in [2]. It involves calculation of the propagation of uncertainties from the physical measurements to the final quantities of interest, and follows the general procedures described by Taylor [9]. The uncertainty in the performance factor calculations are represented with error bars in Figures 4-6 and 8-11.

3. Results

This paper uses measured performance data to characterize the actual thermal performance of the GSHP system over 45 months of operation. Measured data from the period January 1 2016 through October 15 2019, are used.

3.1. Heating and cooling loads

The annual energy loads for space heating (excluding heat recovery), space cooling and domestic hot water (DHW) including the Legionella protection system (LPS) over the measured period are shown in Table 2. The heating load for each of these years is around 200 MWh, which is in accordance with the design heating load.

The cooling load for 2018 is nearly 50% higher than the other years due to an exceptionally warm summer in 2018.

Table 2. Annual energy loads 2016-2019

Year	2016	2017	2018	2019 Through Oct. 15th
Cooling (MWh)	111	114	161	107
Heating (MWh)	201	198	214	144
DHW including LPS	16	17	19	17

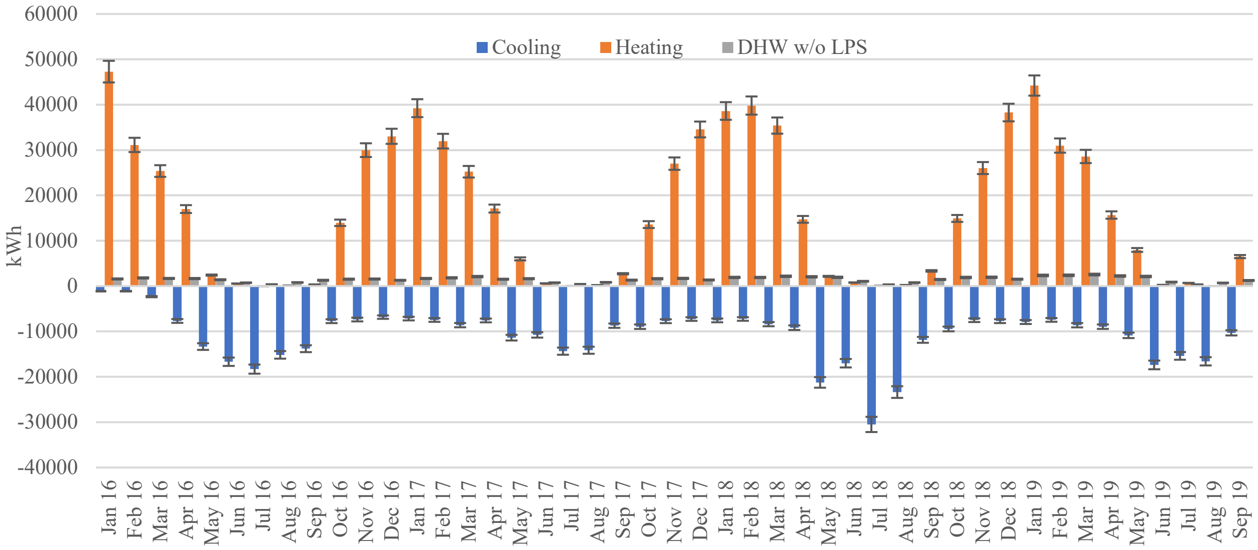


Fig. 3. Measured monthly heating and cooling loads for Studenthuset January 2016-September 2019. (DHW w/o LPS refers to domestic hot water heating, not including Legionella protection system energy use)

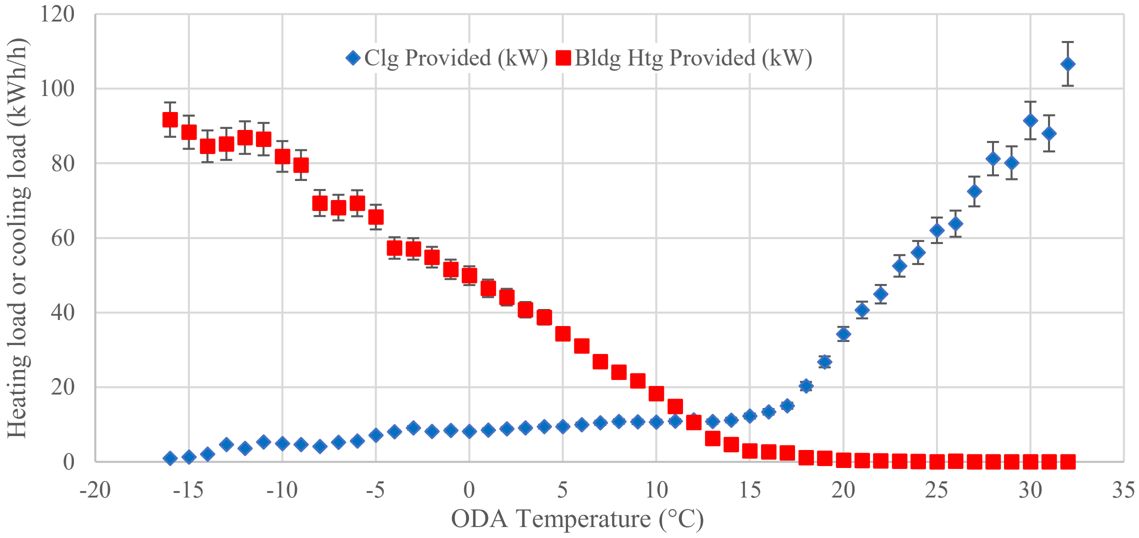


Fig. 4. Measured building energy signature for Studenthuset 2016-2019 with error bars.

Monthly energy loads for the measurement period are shown in Figure 3. Figure 4 shows the building energy signature for Studenthuset, i.e. the heating and cooling load respectively versus outdoor air temperature

(ODA). As can be inferred from Figure 3 and 4, heating and cooling is provided simultaneously over a substantial part of the year. The cafeteria in the building requires kitchen cooling throughout the year.

3.2. Monthly Performance

Monthly heating performance factors are presented in Figure 5. In order to keep the figure readable, only sample error bars are shown for January-February and July-August each year. Accuracy is generally good when heating loads are high or when boundaries H3+ and H4+ are used. One notable feature of Figure 5 is that the monthly performance factors are highest in the winter months and lowest in the summer months. This is counter to the expectation that the heating performance factors will be higher when the heat pump entering fluid temperatures are higher.

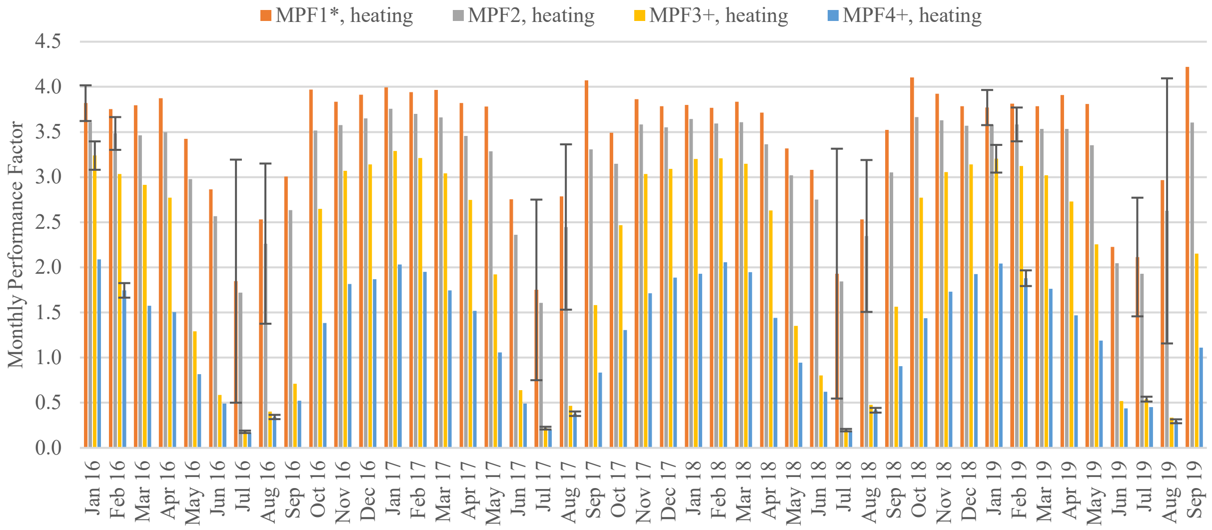


Fig. 5. Monthly heating performance factors with sample error bars, January 2016-September 2019. (The asterisk in MPF1* means that the heat pump internal electricity use is included).

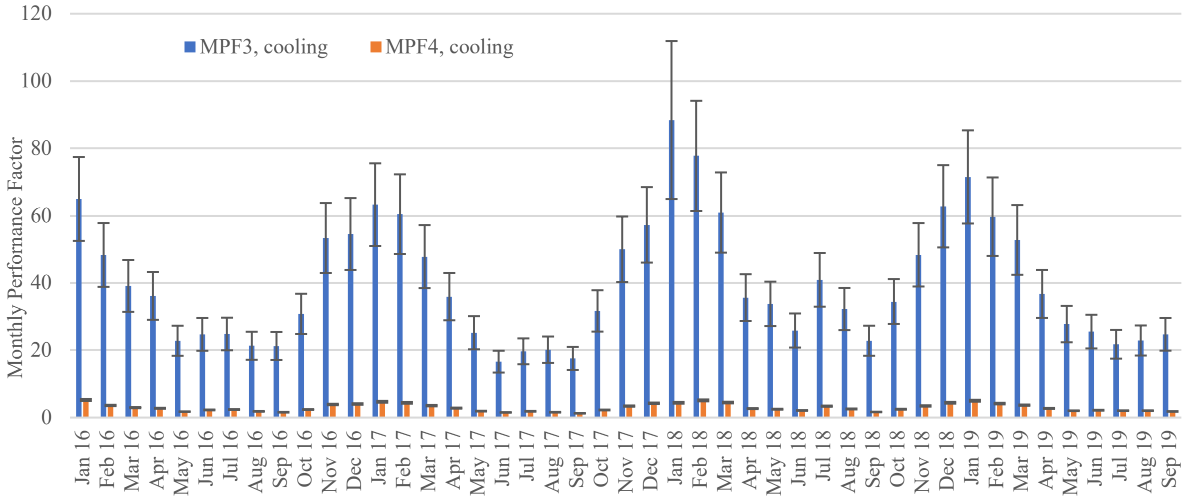


Fig. 6. Monthly cooling performance factors, January 2016-September 2019

Figure 6 shows very high MPFC3, which, in this system, is the same as MPFC2. Because the cooling is provided directly without a heat pump, the only power used at levels C2 and C3 is the source-side circulating pump. Furthermore, because the source-side circulating pump provides both cooling and the source fluid for heating with heat pumps, its energy consumption is allocated between cooling and heating, thus further lowering the required input energy, and increasing the cooling MPFC3. However, the energy required to distribute the chilled water to the air handling units, accounted for in boundary C4, substantially reduces the cooling performance factors. It may also be noted that the cooling MPFs are higher in the winter months when the ground loop fluid temperatures are lower.

3.3. Seasonal performance

Table 3 summarizes the seasonal performance factors for each boundary. In addition to those presented above, combined SPF for heating and cooling taken together are presented in the last two rows. This avoids the problem of having to allocate pumping power between heating and cooling and, for more complex systems, may make more sense than attempting to determine heating and cooling SPF separately. The SPF calculated for each year are fairly similar, though the unusually hot summer of 2018 significantly increased the cooling load and also increased the cooling and combined SPF values.

One notable feature is the significant reduction in SPF going from boundary level 3 to 4. The only difference is the inclusion of pumping power to distribute chilled water and hot water to air handlers and panel radiators. An interesting, but inconclusive comparison can be made between this system and the ASHRAE Headquarters building GSHP system in Atlanta. [10, 11] This system is a distributed system with reversible water-to-air heat pumps. The reported system heating and cooling COPs for a 2 year-period [10] are roughly equivalent to SPFH4 and SPFC4 and are 3.6±0.3 and 4.2±0.6, respectively. (The ASHRAE system includes the fan energy to deliver the heating and cooling to the space. But, like the Studenthuset system, the ventilation fan energy is not included.) The Studenthuset GSHP system serves about four times the area of the ASHRAE GSHP system; the building energy signatures are significantly different, and the ground temperatures in Atlanta are warmer than in Stockholm. Yet, the ASHRAE system SPFH4 and SPFC4 are both considerably higher than the Studenthuset system. At the very least, this suggests that the pumping power used to distribute heating and cooling in the Studenthuset building is quite high. Whether it could be reduced by modifying the controls settings, or whether the high pumping power is “baked in” by the hydronic design is an open question at this point.

Table 3. Seasonal performance factors 2016-2019. The asterisk denotes that the heat pump internal electricity use is included.

Year	2016	2017	2018	2019 until Oct 15th
SPFH1*	3.8±0.2	3.8±0.2	3.8±0.2	3.8±0.2
SPFH2	3.4±0.2	3.5±0.2	3.5±0.2	3.5±0.2
SPFH3+	2.6±0.1	2.7±0.1	2.7±0.1	2.6±0.1
SPFH4+	1.5±0.1	1.5±0.1	1.6±0.1	1.5±0.1
SPFC2(3)	37±7	37±7	46±9	38±7
SPFC4	2.9±0.2	2.8±0.2	3.3±0.2	2.9±0.2
SPFCH2	5.0±0.2	5.1±0.2	5.6±0.2	5.5±0.2
SPFCH4+	1.8±0.3	1.7±0.3	2.0±0.3	1.8±0.3

3.4. Factors influencing performance

As discussed in Spitler and Gehlin [2] the system performance for both heating and cooling was more dependent on the heating and cooling provided than the ground heat exchanger exiting fluid temperature. This was demonstrated somewhat indirectly by plotting the overall daily performance factor vs. the total daily heating and cooling loads. Here, we have refined the analysis to calculate performance factors that are binned by the amount of heating and cooling provided.

First, Figure 7 shows the monthly average temperature exiting the ground heat exchanger and entering the heat pump, along with the monthly average air temperature. As expected, the fluid temperatures are relatively moderate compared to the air temperatures. The GHE exiting fluid temperatures are slightly higher in the summer of 2018 than other summers due to the increased cooling loads; but, otherwise, the temperature cycle is fairly stable.

Figure 8 shows the binned heating performance factors relative to the ground heat exchanger (GHE) exiting fluid temperature (ExFT). The general trend is that the heating performance factors decrease as the GHE ExFT increases, contrary to expectations based on thermodynamic considerations for the heat pump. BPFH3+ shows a marked decrease between 10°C and 11.5°C. In this range, the building heating and cooling loads are low; the building heating loads go to zero at 12°C, and so the system heating performance becomes dominated by the domestic hot water heating. As can be seen, at 11°C and above, BPFH3+ and BPFH4+ are below one. This is due to the Legionella protection system, which consumes electricity to heat the water from 55°C to 62°C, and continuously circulates the water, dissipating about 3 kW heat to the building year-round. During the summer months, when there is little or no building heating needed, this energy is wasted, leading to performance factors less than one.

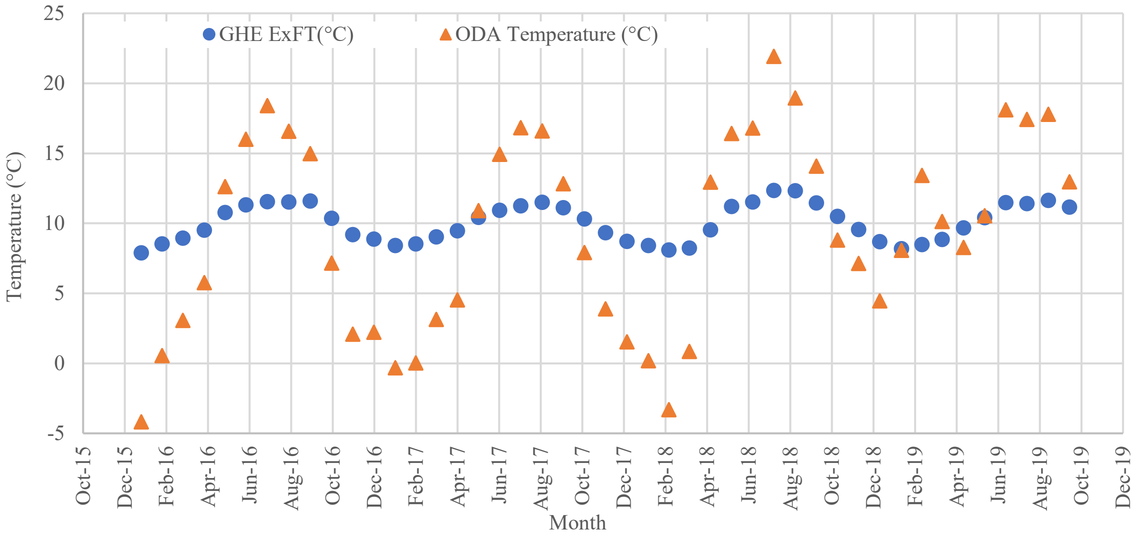


Fig. 7. Monthly average outdoor air temperatures (ODA) and borehole exiting temperatures January 2016 - September 2019

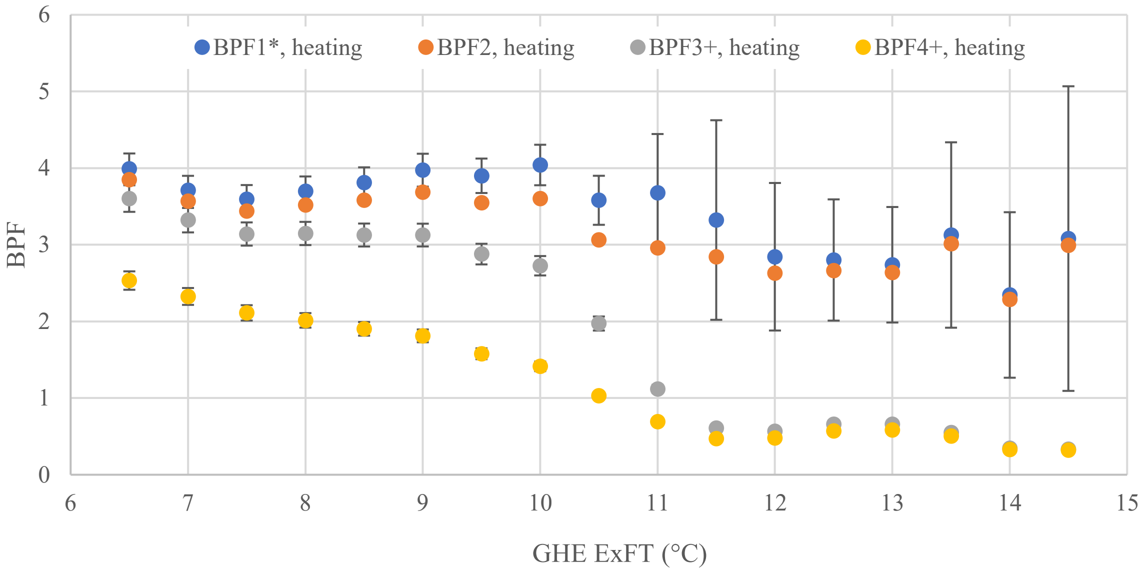


Fig. 8. Heating performance vs GHE Exiting fluid temperature (Error bars have been omitted on BPF2; they are similar, but between 5% and 35% lower than those shown for BPF1* (the asterisk denotes that the heat pump internal electricity use is included). 2016-2019.

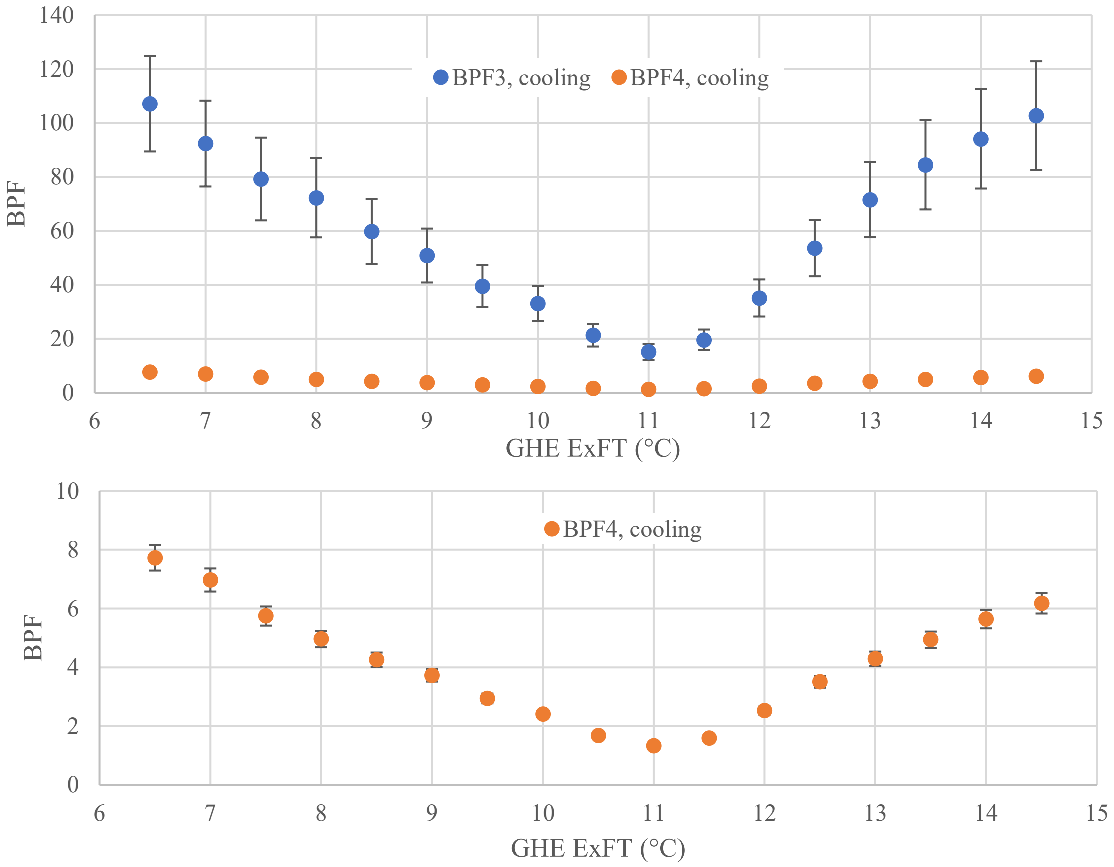


Fig. 9. Cooling performance vs GHE Exiting fluid temperature (°C). 2016-2019.

Figure 9 shows BPFC3 and BPFC4; the V-shaped trend is rather interesting. It is caused by a combination of effects. The cooling load is quite small below 11°C, and most of the pumping power is allocated to heating. Above 11°C, the cooling loads increase significantly. The pumping power also follows a V-shaped trend with a maximum of about 17 kW at both low and high GHE ExFT, and a minimum at 11°C of 11.5 kW. However, when plotted against the GHE ExFT, the pumping does not decrease near as much as the load and the result is the V-shaped profiles shown in Figure 9.

In Figure 10, the heating performance factors have been binned against the heating load. Likewise, in Figure 11, the cooling performance factors have been binned against the cooling load. With the exception of a slight wiggle at 30 kW of cooling provided, the performance factors increase monotonically with the load, demonstrating that the system performance is highly driven by the load. The decrease in the performance with decreasing load has been attributed [2] to cycling losses in the heat pump, parasitic losses within the heat pump (e.g. control hardware), pumping energy, and the use of electric resistance heating. For this system, there is a particularly strong influence of the Legionella protection and DHW recirculation systems, which use 3 kW continuously year-round to circulate hot water around the building.

Another factor is the source-side circulating pump. It is variable-speed, but the lower limit of flow is kept at 8 L/s and the pump uses about 1 kW. This relatively high lower limit often results in a very low temperature difference across the ground loop and continuous power consumption of 1 kW, even when the load is very low.

This sensitivity of the load is not unique to the Studenthuset building. Other systems with measured performance data, including a distributed GSHP system in the US [10, 11] and a central GSHP system in the UK [12] show similar trends.

Possible improvements to the system include lowering the minimum flow on the variable speed control and scheduling the operation of the Legionella protection system and DHW recirculation system. These actions should significantly decrease the energy consumption at low heating and cooling loads.

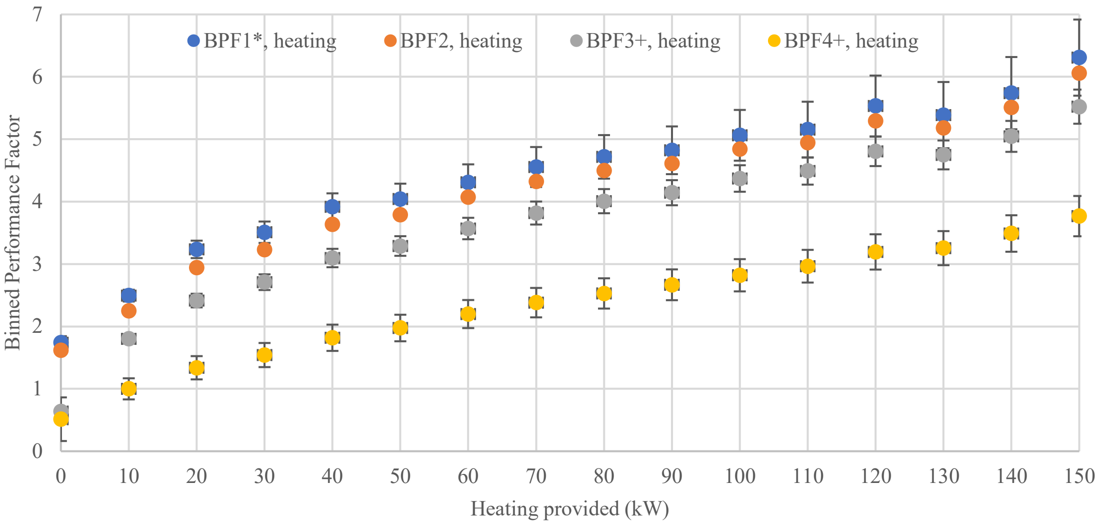
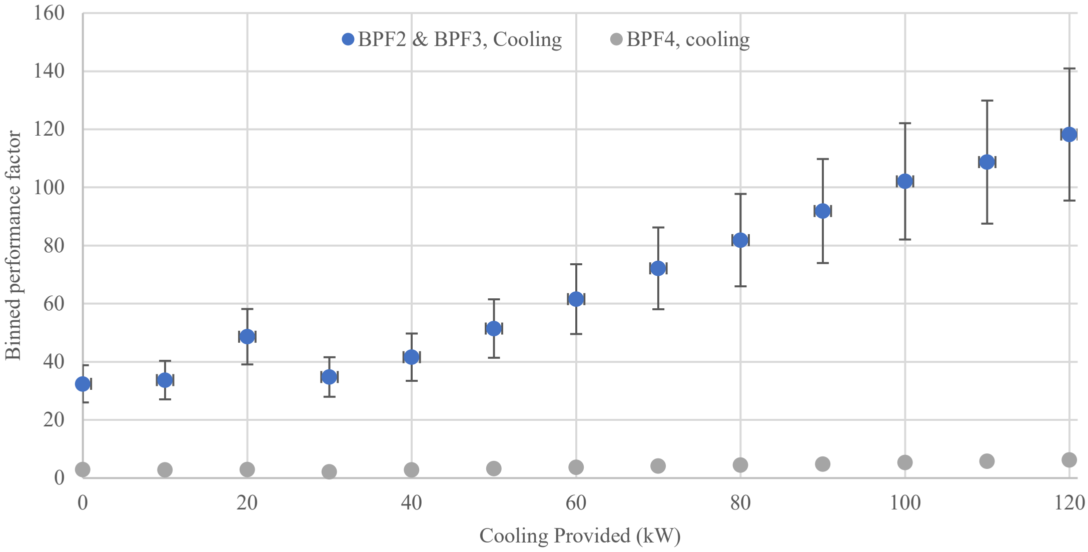


Fig. 10. Binned Performance Factors vs heating load, 2016-2019.
(The asterisk in BPF1* means that the heat pump internal electricity use is included).



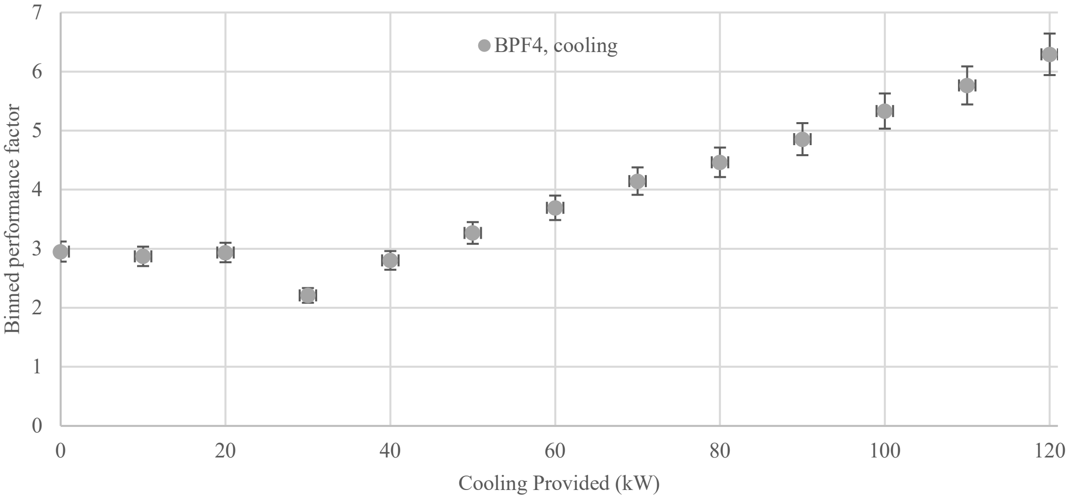


Fig. 11. Binned Performance Factor vs cooling load, 2016-2019

4. Conclusions

This paper has extended the previous one-year analysis [2] of the Studenthuset ground-source heat pump system to nearly four years. For the most part, the trends observed in the first year are still present. The system performance is now more clearly shown to be strongly related to the load – as the load increases, the system performance increases. This also means that the system has relatively poor performance at times when there is little heating or cooling load. A particularly warm summer in 2018 significantly increased the seasonal cooling load, but also increased the cooling performance.

It appears that reducing the minimum flow rate on the source-side (ground loop) circulation pump could improve the system performance at low loads. However, the distribution system that circulates hot water and chilled water from the heat pumps or ground loop to the air handlers and panel radiators consumes much more energy. Improvement of the distribution system could significantly improve the overall system performance. Design engineers, building owners and maintenance staff should take care to minimize energy usage by the distribution system.

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