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

Case study report for Studenthuset, Stockholm, Sweden

Long-term performance analysis of the GSHP system for a student union building

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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 31st, 2021. The 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.

This case study of the ground source heat pump system providing heating and cooling for the Stockholm university student union building, Sweden, has been carried out by Dr. Signhild Gehlin at the Swedish Geoenergy Center, and Professor Jeffrey D. Spitler at Oklahoma State University. Anders Larsson and Åke Annsberg at Akademiska Hus have provided the measurement data from the building automation system and information about the monitored building and its equipment and installations.

The work that has led to this report has been partially funded by the Swedish Energy Agency (TERMO research program Grant 45979-1). The second author's work has been made possible by the OG&E Energy Technology Chair.

Summary

This report covers a multi-year case study on performance measurements of the ground source heat pump (GSHP) system at the student union center, Studenthuset, at Stockholm University in Stockholm, Sweden. The construction of the building was completed in the fall of 2013. Studenthuset is a thoroughly instrumented, mixed-use, 6300 m^2 four-story building. Space heating and domestic 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.

More than five years (January 2016- May 2021, totally 65 months) of performance measurement data have been analyzed in this case study and published in one journal paper (Spitler and Gehlin 2019) and several conference papers (Gehlin et al. 2018, Spitler and Gehlin 2021, Spitler and Gehlin 2022a, Spitler and Gehlin 2022b). Two sets of open-access measurement data are available (Spitler and Gehlin 2019, Spitler and Gehlin 2022). This report gives an overview of the case study results, based on the previously published papers. For more details we refer directly to the original publications.

The system delivers heating according to design and more cooling than accounted for in the original design. Over the five-year analysis period, the building rejected 30% more heat than it extracted from the ground and the ground temperature increase over the five reported years was minimal, indicating that if operated as is, the borehole field will not exceed its temperature constraints for many decades.

The system seasonal performance factor for five measured years and considering only the heat pump and source-side circulation pumps (SPF_{HC2}) is 5.2±0.2. The Legionella protection system, hot water continuous circulation, and internal heating/cooling distribution system reduce the system energy performance, resulting in a five-year seasonal performance factor for combined heating and cooling at the outer system boundary (SPF_{HC5}) of 1.8±0.3.

Sammanfattning

Denna rapport redovisar en flerårig prestandamätstudie för det geoenergisystem som förser det nybyggda Studenthuset vid Stockholms universitet med värme, kyla och varmvatten. Byggnaden färdigställdes och togs i drift under hösten 2013. Byggnaden är en fyravåningsbyggnad med en uppvärmd yta på 6300 kvadratmeter, och innehåller kontor, studieplatser och restaurang. Byggnaden förses med rumsvärmning och tappvarmvatten genom ett heltäckande borrhålslager bestående av 20 borrhål till 200 m djup, kopplat till fem stycken 40 kW värmepumpar. Rumskylningen sker genom direktkyla från borrhålen.

Drygt fem års mätdata (januari 2016 - maj 2021, totalt 65 månader) har använts som underlag för prestandaanalysen i fallstudien och har publicerats i en vetenskaplig tidskriftsartikel (Spitler and Gehlin 2019) och flera konferensartiklar (Gehlin et al. 2018, Spitler & Gehlin 2021, Spitler & Gehlin 2022a, Spitler & Gehlin 2022b). Två serier med mätdata från anläggningen finns fritt tillgängliga för nerladdning (Spitler & Gehlin 2019, Spitler & Gehlin 2022). Den här rapporten ger en sammanfattande bild av fallstudiens resultat, baserat på tidigare publicerade artiklar. För mer detaljer hänvisas direkt till originalpublikationerna.

Geoenergianläggningen levererar värme enligt design och flerfalt mer frikyla än i den ursprungliga designen. Systemets sammantagna årsprestandafaktor för de fem uppmätta åren med endast värmepump och markkretsens cirkulationspump inräknad (SPF_{HC2}) var 5.2±0.2. Legionellaskyddet, den kontinuerliga varmvattencirkulationen (vvc) samt den interna värme- och kyldistributionen drar ner systemets energiprestanda. Detta resulterar i en sammantagen årsprestandafaktor för femårsperioden för kombinerad värme och kyla for vid den yttre systemgränsen (SPF_{HC5}) på 1.8±0.3.

Contents

BACKGROUND

The building

The student union building Studenthuset is located within the large campus area of Stockholm University in central Stockholm, Sweden (Figure 1). 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.

The climate in Stockholm is characterized by a humid continental climate, with average temperatures of around -3°C in the winter and +20°C in the summer. The building is heating dominated. 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.

Figure 1. Studenthuset in Stockholm, front view (left) and location in Sweden (right). Photo: Jeffrey D. Spitler

Table 1. Summary of the building features

Location	Stockholm, Sweden
Year of building construction	2013
Ground source system operation start date	2013
Building Type	Mixed-use university building
Building floor area (net, gross)	6300 m² gross, 6035 m² net
Analyzed monitoring start date	2016-01-01
Analyzed monitoring end date	2021-05-12
Unique features of the system	Off-the-shelf heat pumps

Table 2. Summary of the system configuration

Heat distribution	Radiators (distribution temp 40°C)
Cooling distribution	Chilled beams, VAV, CAV
Domestic hot water (DHW) production by system	One dedicated heat pump that alternates between DHW and space heating
Supplementary heat for space heating	None
Supplementary heat for DHW	Electric resistance heating
Supplementary cooling	None
Nominal capacity of supplementary heating for space heating [kW]	None
Nominal capacity of supplementary heating for DHW [kW]	9 kW
Nominal capacity of supplementary cooling [kW]	None
Heating load (annual average 2016-2020)	204 MWh/year (32 kWh/m^2/y)
Cooling load (annual average 2016-2020)	121 MWh/year (19 kWh/m^2/y)
DHW (annual average 2016-2020)	16 MWh/year (2.5 kWh/m^2/y)
Heat pump type	Water-to-water
Reversible	No
Compressor type	2 x scroll
Speeds	Variable speed
Heat pump system	Centralized
Number of heat pumps	5
Nominal total heat pump heating capacity [kW_{th}]	200 kW_{th}
Nominal total heat pump heating capacity available for DHW [kW_{th}]	40 kW_{th}
Nominal total heat pump cooling capacity [kW_{th}]	None
Refrigerant	R407c

The ground source system

The Studenthuset GSHP system is described in Gehlin et al. (2018), Spitler and Gehlin (2019), Spitler and Gehlin (2021) and Spitler and Gehlin (2022a and b). The borefield consists of 20 groundwater-filled boreholes in hard crystalline rock (granite), drilled to a depth of 200 m, and fitted with single u-tubes filled with an ethanol/water mixture. The bore field is located below a landscaped courtyard (Figure 2). The boreholes are drilled at an angle so that they reach under the surrounding building.

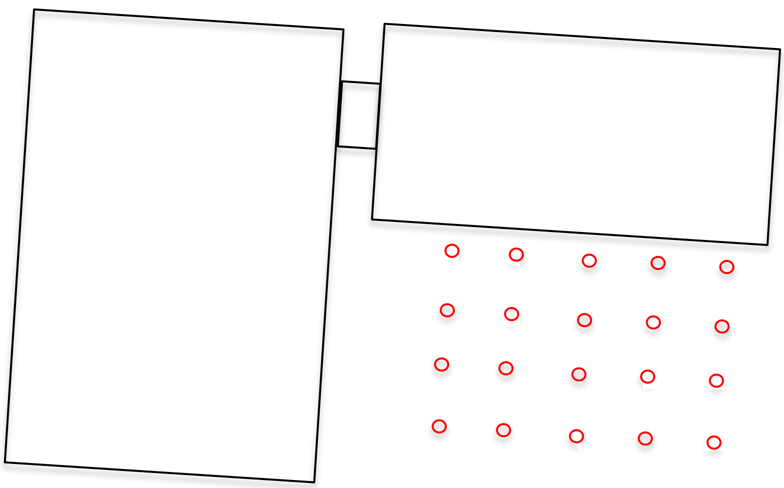

Figure 2. Illustration of the Studenthuset top-view with borehole field.

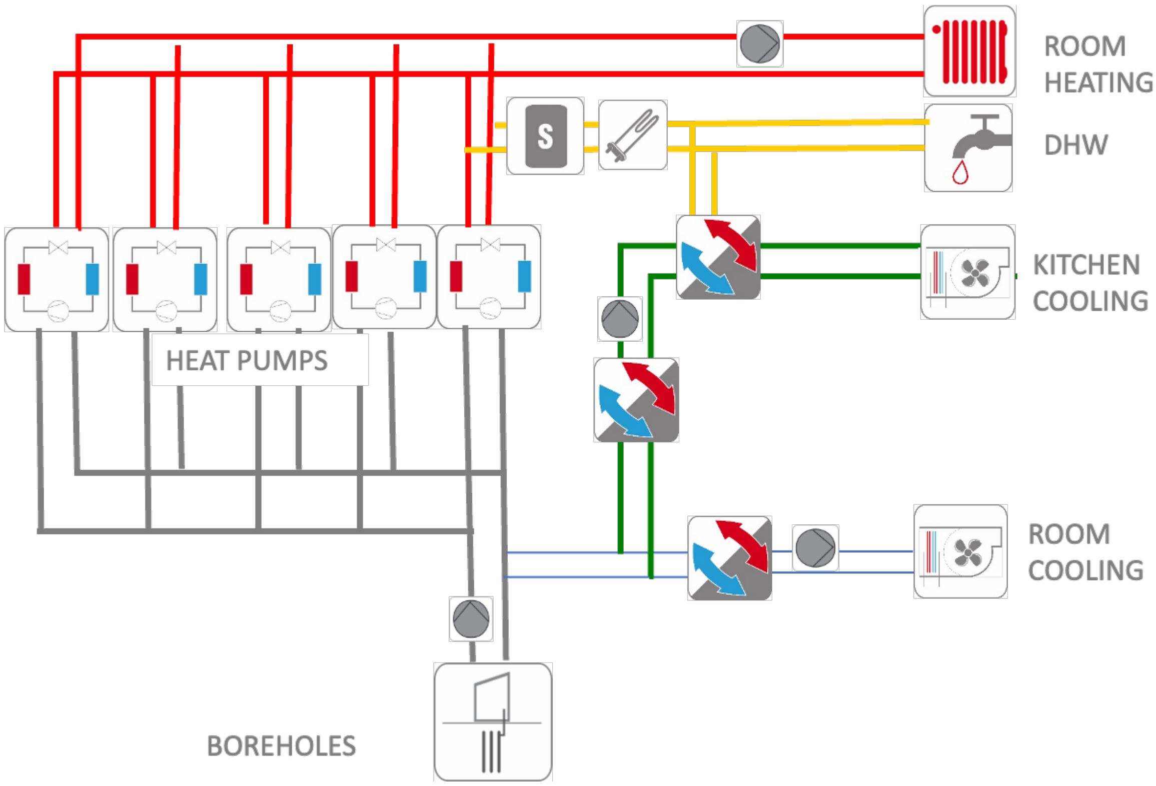

Figure 3. Simplified schematic for Studenthuset. *Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52.*

The GSHP system is schematically described in figure 3. It consists of a centralised heat pump system with five 40 kW off-the-shelf water-to-water heat pumps connected to the bore field. One of the heat pumps is dedicated to DHW heating when needed. DHW is stored in a buffer tank and an electric resistance heater in the tank boosts the DHW temperature to protect against Legionella.

Space cooling and cooling of the restaurant kitchen is provided directly from the boreholes. The system was designed on the basis of the maximum fluid temperature leaving the boreholes not exceeding 16°C, but to date it has not exceeded 14.5°C. The system also uses the return from the heat pumps to provide space cooling when the heat pumps are running.

The ground source and borehole heat exchanger features are summarized in Tables 3 and 4.

Table 3. Summary of the ground source and sink

Ground source	Vertical boreholes
Loop type	Closed loop
Ground composition	Granite
Groundwater level [m]	8 m
Annual mean air temperature (measured)	8.3°C
Undisturbed ground temperature	9.2°C
Design ground thermal conductivity	3.9 W/m·K (from TRT)
Specific ground heat capacity	Not measured
Minimum ground heat exchanger exiting fluid temperature ($ExFT_{min}$)	6.5°C
Maximum ground heat exchanger exiting fluid temperature ($ExFT_{max}$)	14.5°C

Table 4. Summary of the ground heat exchanger - Boreholes

Number of boreholes	20
Borehole length	200 m
Total borehole length	4000 m
Average distance between boreholes	8 m
Borehole geometric distribution	Rectangular net
Borehole diameter	115 mm
Borehole filling material	Groundwater
Borehole heat exchanger type	Single U-tube
Design Effective thermal resistance per unit length	0.07 Km/W
Source side pipe characteristics	PEM DN40 PN8 (40 mm/35.2 mm)
Source side brine type	Water-Ethanol 28%
Average source side brine flow in operation	8 l/s

Monitoring

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.

Heat meters and flow rates

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 supply temperature provided by the heat pumps (55°C) and the estimated incoming temperature from the Stockholm water supply. The time-varying estimate of the incoming temperature is based on measurements made at seven different buildings in Stockholm (Bergqvist 2015, Bergqvist 2016). 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.

Electricity use

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.

Additional details of the instrumentation and an uncertainty analysis are found in Spitler and Gehlin (2019).

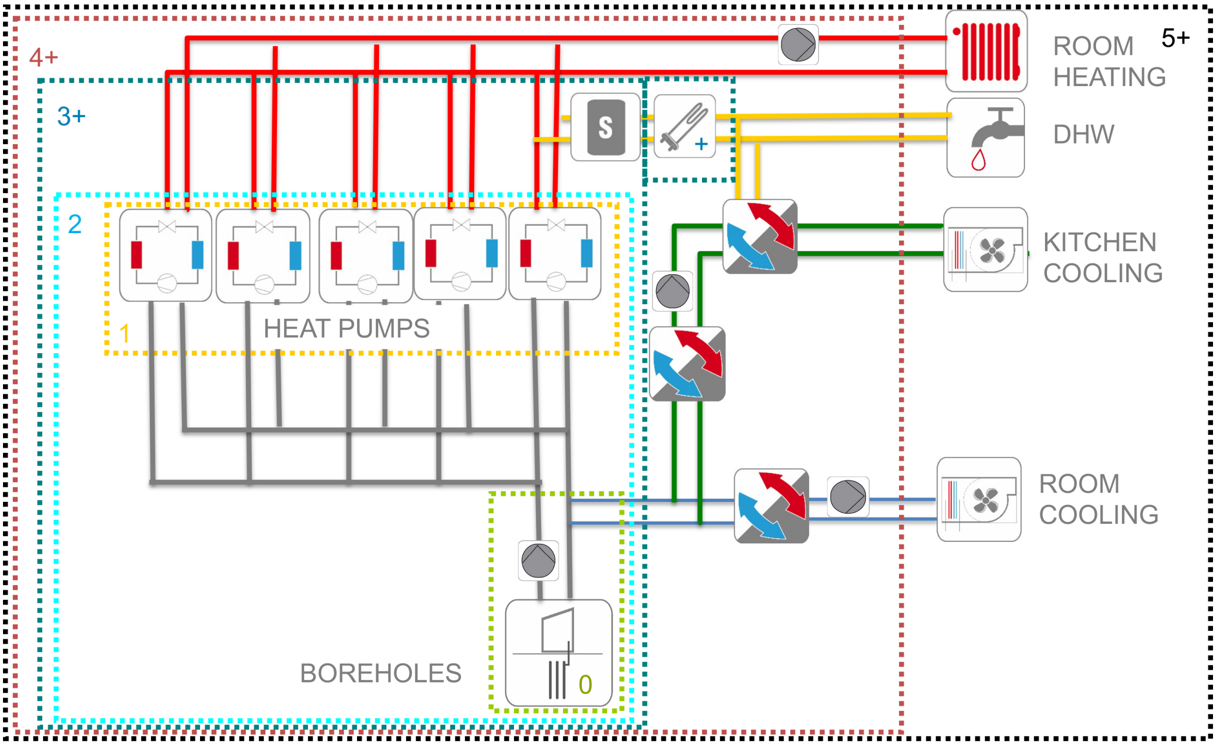

Figure 4. Schematic and Annex 52 system boundaries for Studenthuset. *Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52.*

The available measurement data for Studenthuset allows for the Annex 52 system boundaries (Gehlin and Spitler 2021) H1 (approximately), H2, H3+ and H4+ to be calculated. For the cooling system, C2, C3 (C2 and C3 are the same for this system) and C4 can be calculated from the available measurement data with a sufficient degree of accuracy. Figure 4 shows the Annex 52 system boundaries for Studenthuset and Table 5 summarizes the calculated boundaries and relates them to the SEPEMO system boundary schema as described by Nordman (2012).

Table 5. Calculated system boundaries for Studenthuset according to the Annex 52 boundary schema.

Boundary description	HPT Annex 52 Boundary levels						
	H1*	H2	C2=C3	H3+	H4+	C4	H5+*
Ground Source (circulation pumps+ ground source)		X	X	X	X	X	X
Heat pump unit including internal energy use, excluding internal circulation pump	X	X	X	X	X	X	X
Buffer tank (including circulation pumps between heat pump and buffer tank)				X	X	X	X
Circulation pump on load-side (between buffer tank & building H/C distribution system)					X	X	X
Building H/C distribution system							X
Auxiliary heating or cooling				X	X		X
Equivalent in the SEPEMO boundary schema	H1	H2	C2	~H3			H4

PERFORMANCE MONITORING RESULTS

The Studenthuset GSHP system long-term performance monitoring and uncertainty analysis are thoroughly described in Gehlin et al (2018), Spitler and Gehlin (2019), Spitler and Gehlin (2021) and Spitler and Gehlin (2022a and b).

The uncertainty analysis in this study involves calculation of the propagation of uncertainties from the physical measurements to the final quantities of interest. The uncertainty in the performance factor calculations is represented with error bars in the following figures.

Measured performance data to characterize the actual thermal performance of the Studenthuset GSHP system over 5 years of operation from the period January 1st, 2016 through December 31st, 2020, are presented in this report. The overall load characteristics, with annual energy loads for space heating (excluding heat recovery), cooling and domestic hot water heating (DHW) including the Legionella protection system (LPS) are shown in Table 6. The heating load is around 200 MWh for each of the measured years, which is in accordance with the design heating load. The building cooling load varies more and is three to five times higher than the design cooling load of 34 MWh (Spitler and Gehlin 2019). The summer of 2018 was an exceptionally warm summer causing a near 50% higher cooling load than the other years. In 2020 the Corona virus pandemic caused a lockdown of the university over a major part of the spring and summer. This resulted in a significantly lower cooling and DHW demand for that year.

Table 6. Overall load characteristics

Start of evaluation period End of evaluation period	January 1st 2016 December 31st 2016	January 1st 2017 December 31st 2017	January 1st 2018 December 31st 2018	January 1st 2019 December 31st 2019	January 1st 2020 December 31st 2020
Building space heating load met by system [MWh_{th}]	201	198	214	212	194
Building cooling load met by system [MWh_{th}]	111	114	161	124	94
DHW load met by system* [MWh_{th}]	16	17	19	19	7

* Including Legionella protection system (LPS)

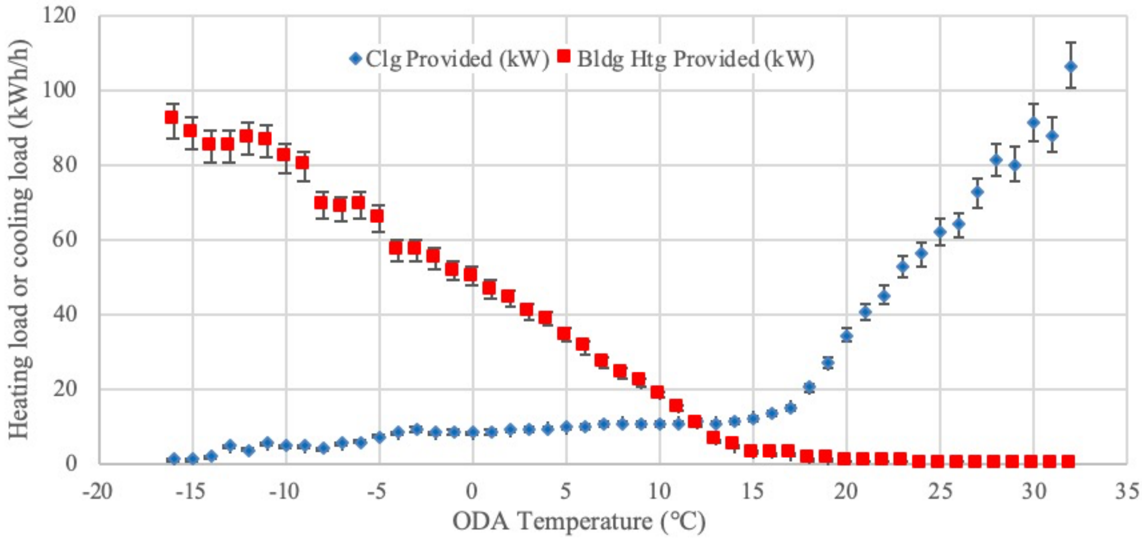

Figure 5. Measured building energy signature for Studenthuset 2016-2019 with error bars.

Figure 5 shows the measured building energy signature for Studenthuset. The figure includes only energy use for space heating and cooling and does not include energy use for domestic hot water and kitchen refrigeration. As can be seen, the building uses some cooling even at rather low outdoor air temperatures, presumably due to heat gains to the circulating chilled water from the building.

The Studenthuset instrumentation did not include an energy meter on the ground heat exchanger, and the ground heat exchanger (GHE) flow rate was controlled to a minimum flow of 8 L/s, leading to low temperature differences. This, combined with low accuracy temperature sensors measuring the temperature to/from the GHE, has made it impossible to accurately measure the heat transferred to/from the ground. Figure 6 shows estimated annual loads on the ground with positive values representing heat extraction and negative values representing heat rejection or reductions in heat extraction. The system rejects 30% more heat than it extracts. There are several reasons for this. The load-side circulating pumps and fans (LSCPF) consume more energy than the heat pump compressors, and this energy ends up rejected to the ground. The source side circulation pumps (SSCP) use a very small amount of energy, contributing less to the ground heat rejection. In addition, some kitchen refrigeration also rejects heat to the ground. Uncertainty of these approximations have not been estimated, but the building heating and cooling loads have uncertainties on the order of 5-6%. Figure 6 has been corrected after publication in Spitler and Gehlin (2022a), where the load from the heat pump DHW production was shown incorrectly.

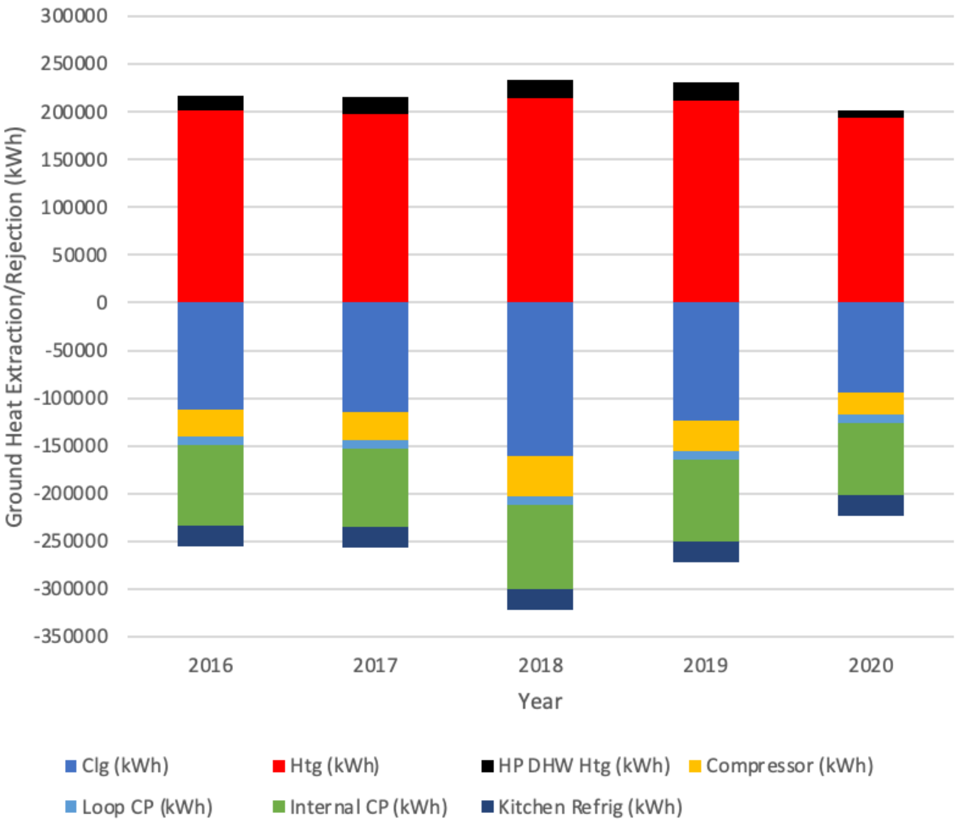

Figure 6. Estimated energy rejection and extraction components (to/from ground) for the monitoring period 2016-2020.

In Figure 7, the electrical energy consumption for each of the measured five years is broken down and summarized for heating (left) and cooling (right). The electrical energy use 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 at a given time. The energy used for distributing heating (LSCPF) is of the same order as that used by the heat pumps for heating. The high energy consumption of the LSCPF 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.

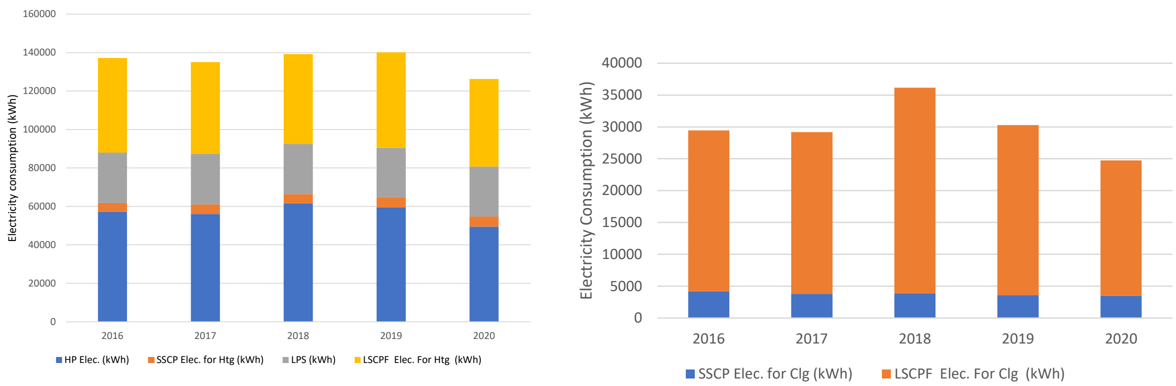

Figure 7. Electricity use breakdown for heating (L) and cooling (R) for the monitoring period 2016-2020.

Ground heat exchanger performance

Monthly energy loads for Studenthuset over the measurement period are shown in Figure 8. Heating and cooling are provided simultaneously over a substantial part of the year. The cafeteria in the building requires kitchen cooling throughout the year.

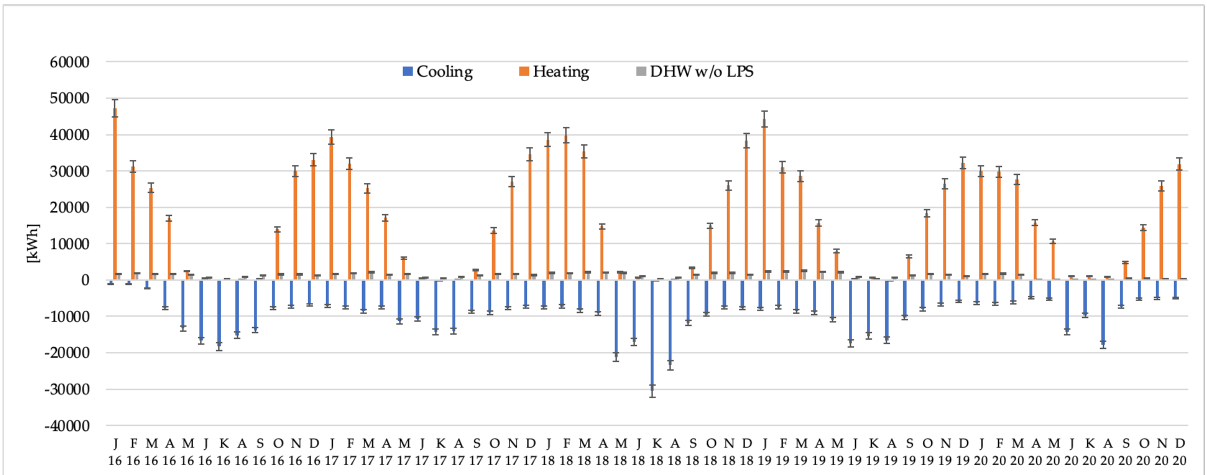

Figure 8. Measured monthly heating and cooling loads for Studenthuset 2016-2020. (DHW w/o LPS refers to domestic hot water heating, not including Legionella protection system energy use).

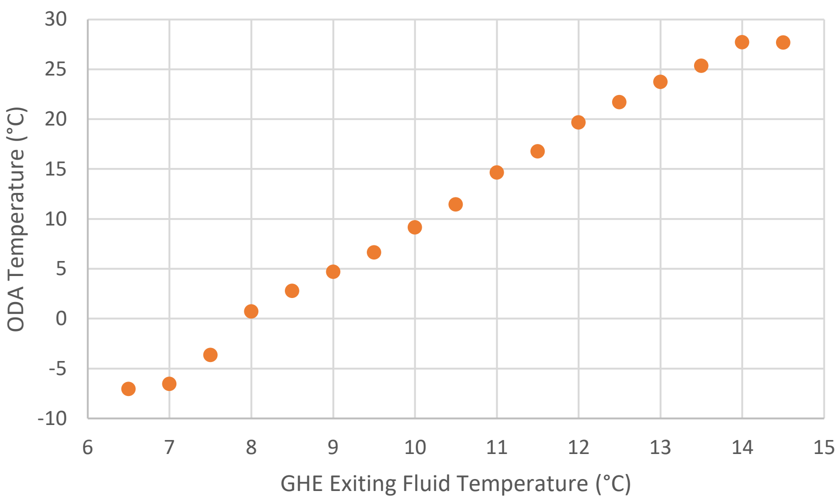

Figure 9. Binned ODA (Outdoor air) temperature vs. ground heat exchanger exiting fluid temperature.

In Figure 9 the relationship between the GHE ExFT and the outdoor air temperature is shown, 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

Figure 10 shows the hourly outdoor air temperature and hourly exiting fluid temperature from the GHE. The exiting fluid temperature from the GHE rises slightly (~0.2°C) over the measured five-year period of operation, which is consistent with the thermal imbalance of the system shown in Figure 6.

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.

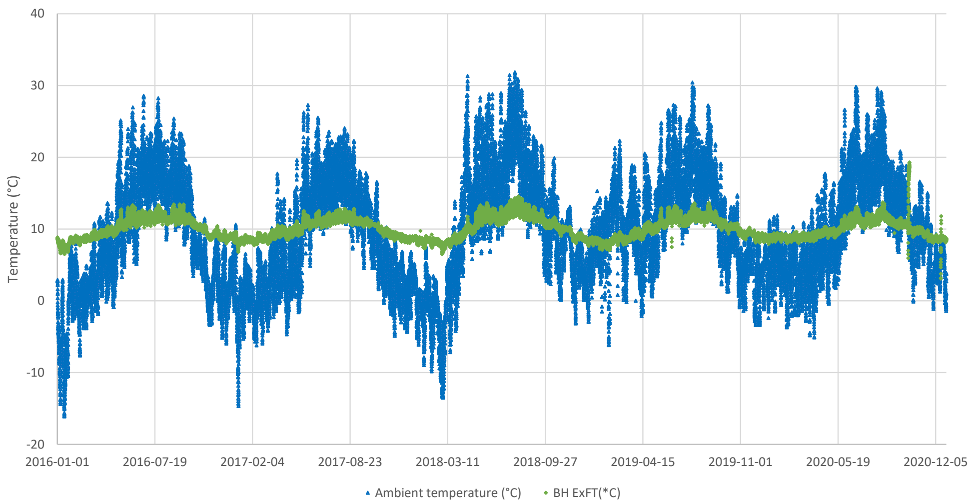

Figure 10. Ground heat exchanger entering fluid temperature and ambient temperature over the five years of measurement (2016-2020).

Heat pump performance

Figures 11 and 12 show monthly performance factors for the heat pump (MPFH1*) with error bars over the five-year measurement period, for each month and as binned months. The heat pump performance is rather flat, around 3.8 for most of the heating periods, but drops significantly in the shoulder seasons and summer period. Counter to the expectation that the heating performance factors will be higher when the heat pump entering fluid temperatures are higher, the monthly performance factors are highest in the winter months and lowest in the summer months. During those months, the building heating load is low and the heat pumps are mostly used for DHW production, with a lower efficiency due to the higher supply temperature required. In addition, parasitic losses (e.g. control boards and energized solenoid valves) and cycling losses decrease the performance of the heat pump under low-load conditions.

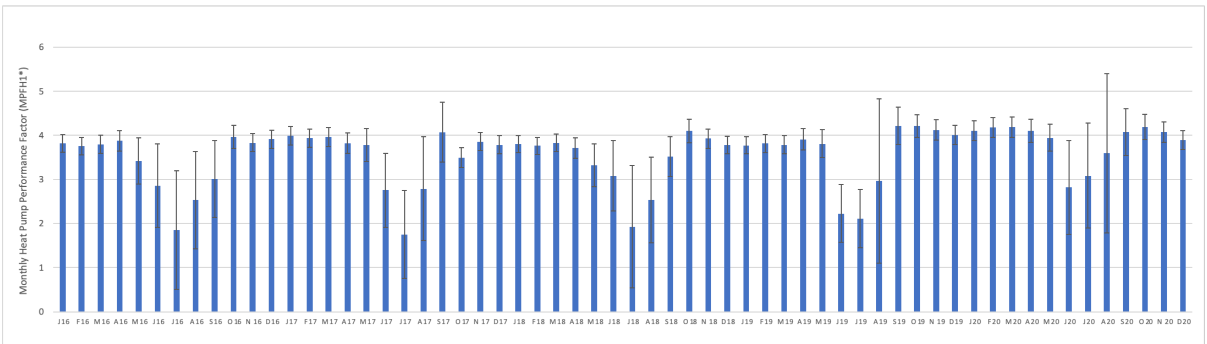

Figure 11. Monthly Heat Pump Performance Factors, MPFH1*, including internal electricity use, with error bars, for the measured period 2016-2020.

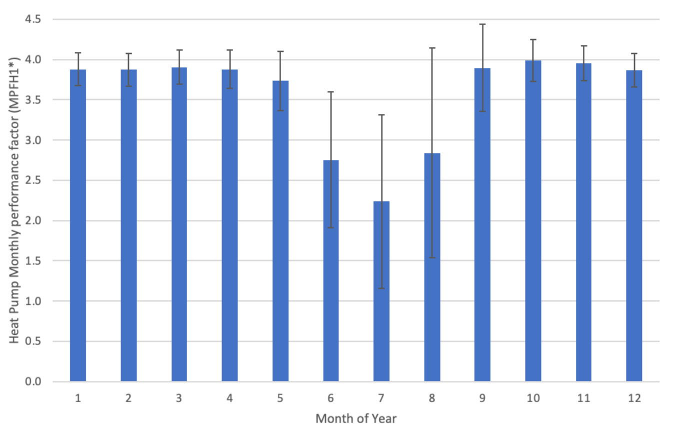

Figure 12. Binned Monthly Performance Factor for the heat pump including internal electricity use, with error bars, for the measurement period 2016-2020.

Overall system performance

Monthly heating performance factors for system boundaries 1* (which includes the heat pump internal electricity use), 2, 3+ and 5+ (where + indicates the inclusion of the electric booster heater) are shown in Figure 13. Accuracy is generally good when heating loads are high or when boundaries H3+ and H5+ are used. In addition to the effects of parasitic losses and cycling losses on the heat pumps, system performance is further degraded during low-load conditions due to the effects of pumping energy and the Legionella protection system, which become more important as the heating load is low. The decrease in performance from boundary 1 to boundary 2 is due to the source-side circulating pump. The decrease in performance from boundary 2 to 3+ is due to the Legionella protection system, and the decrease from boundary 3+ to 4+ is due to the load-side circulating pumps.

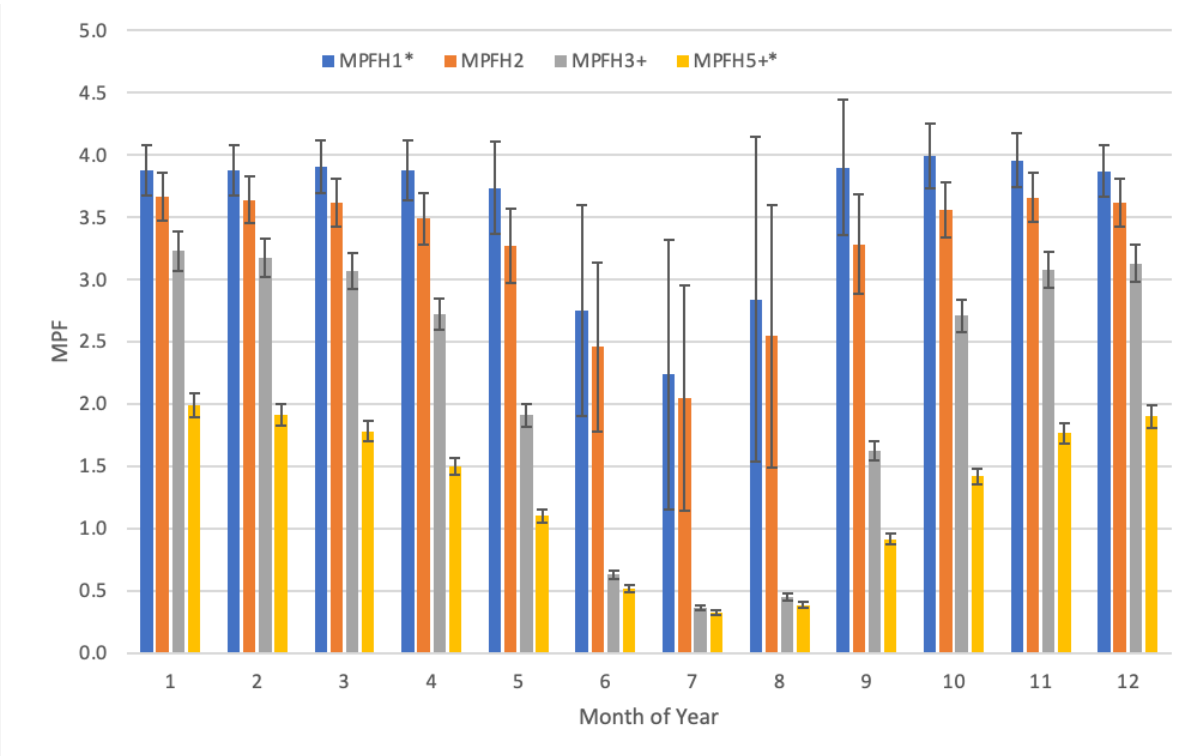

Figure 13. Binned monthly heating performance factors with uncertainty, 2016-2020. (The asterisk in MPF1* means that the heat pump internal electricity use is included).

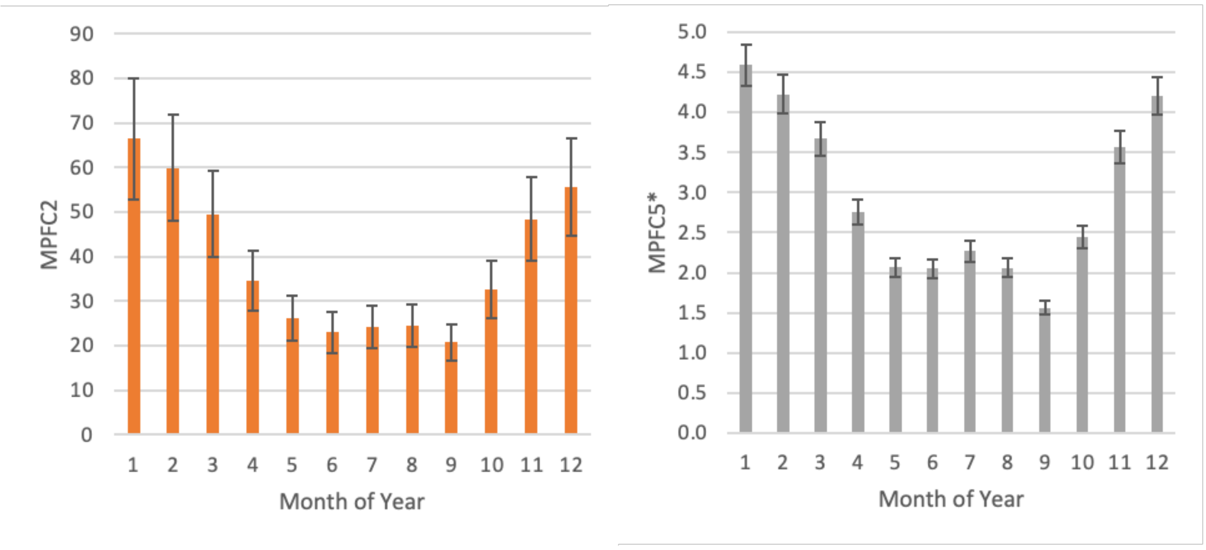

Figure 14. Binned monthly cooling performance factors with uncertainty, 2016-2020.

As expected, for the cooling operation (Figure 14), monthly performance factors are higher during the winter months, when return fluid temperatures from the ground are lower. MPF_{C2} (Left in Figure 14) are very high because the cooling is provided directly without a heat pump, and only the source-side circulation pump uses electricity. 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 MPF_{C2}.

The energy required to distribute the chilled water to the air handling units, accounted for in boundary C5* (Right in Figure 14), 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 and the pumping energy is mostly allocated to heating.

The overall seasonal performance factors (SPF_{CH}), evaluating the combined heating and cooling, for system boundaries 2 and 5+* are shown in Figure 15 together with the overall performance factor for the entire measured five-year period. Both SPF_{CH} are slightly higher for the year 2018, compared to the other years, due to the unusually warm summer, with a much higher cooling load. Legionella protection and electricity use for load side distribution cause a significant drop in the performance factors between level 2 and 5+*.

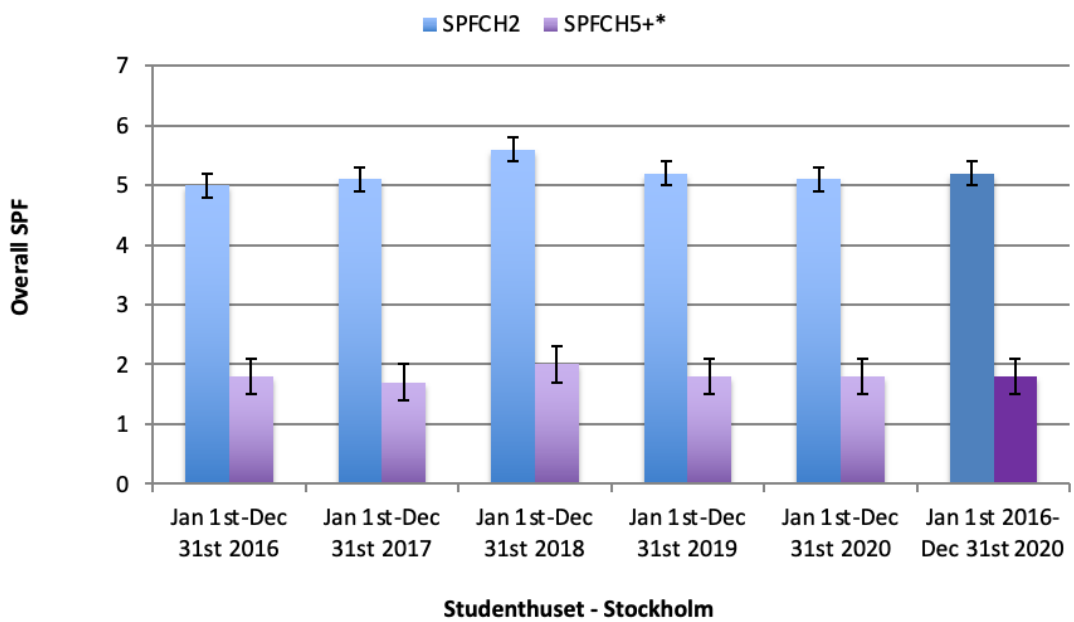

Figure 15. Overall performance factors for system boundaries 2 and 5+* for Studenthuset, 2016-2020.

Binned performance factors have been calculated for heating and cooling versus GHE exiting fluid temperature, as shown in Figures 16 and 17. Each symbol 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 over the five-year evaluation period.

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.

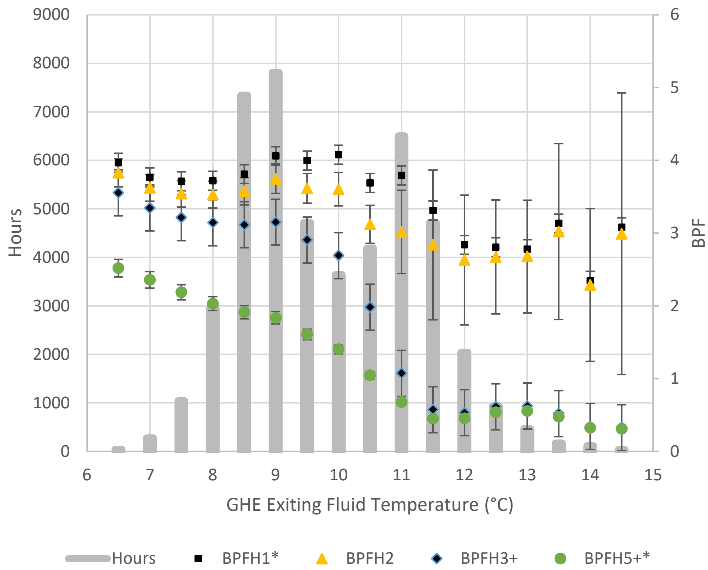

Figure 16. Binned performance factors for heating vs ground heat exchanger exiting fluid temperature.

For cooling (Figure 17), the performance factors show a V-shaped trend – highest at low or high temperatures, lowest at the middle point. The trend is the same for boundary 2 and 5. 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 red triangles in Figure 18. In this case, the performance increases with increasing fluid temperature. 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.

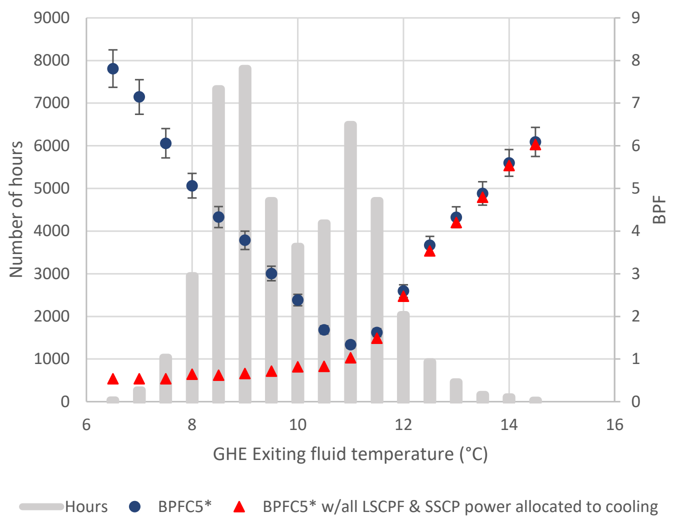

Figure 17. Binned performance factors for cooling vs ground heat exchanger exiting fluid temperature.

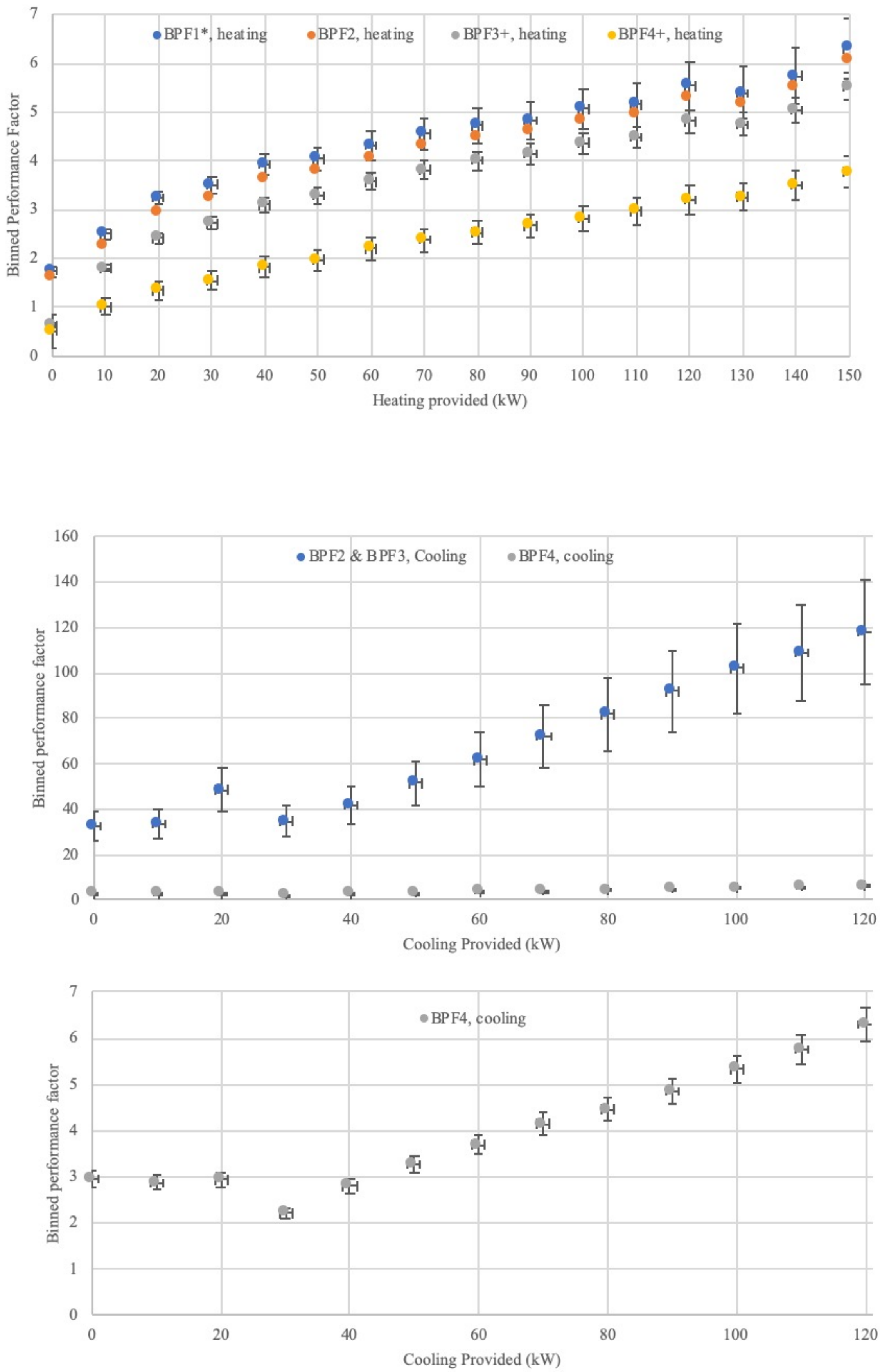

Figure 18. Binned performance factors vs heating and cooling load for Studenthuset 2016-2019.

The amount of heating and cooling being provided has a significant impact on the system performance, reducing the proportion of electrical energy used for pumping, blowing, and "parasitic" uses like control boards and solenoid valves. Figure 18 illustrates this by showing binned performance factors for heating and cooling at various system boundaries vs. the amount of heating or cooling being provided. For both heating and cooling at every system boundary, the performance factors increase with increasing load. Note the difference in scale in the graphs.

Another way to illustrate this load dependence is shown in Figure 19, where binned daily system performance factors (boundary HC5+*) for heating and cooling combined is plotted 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.

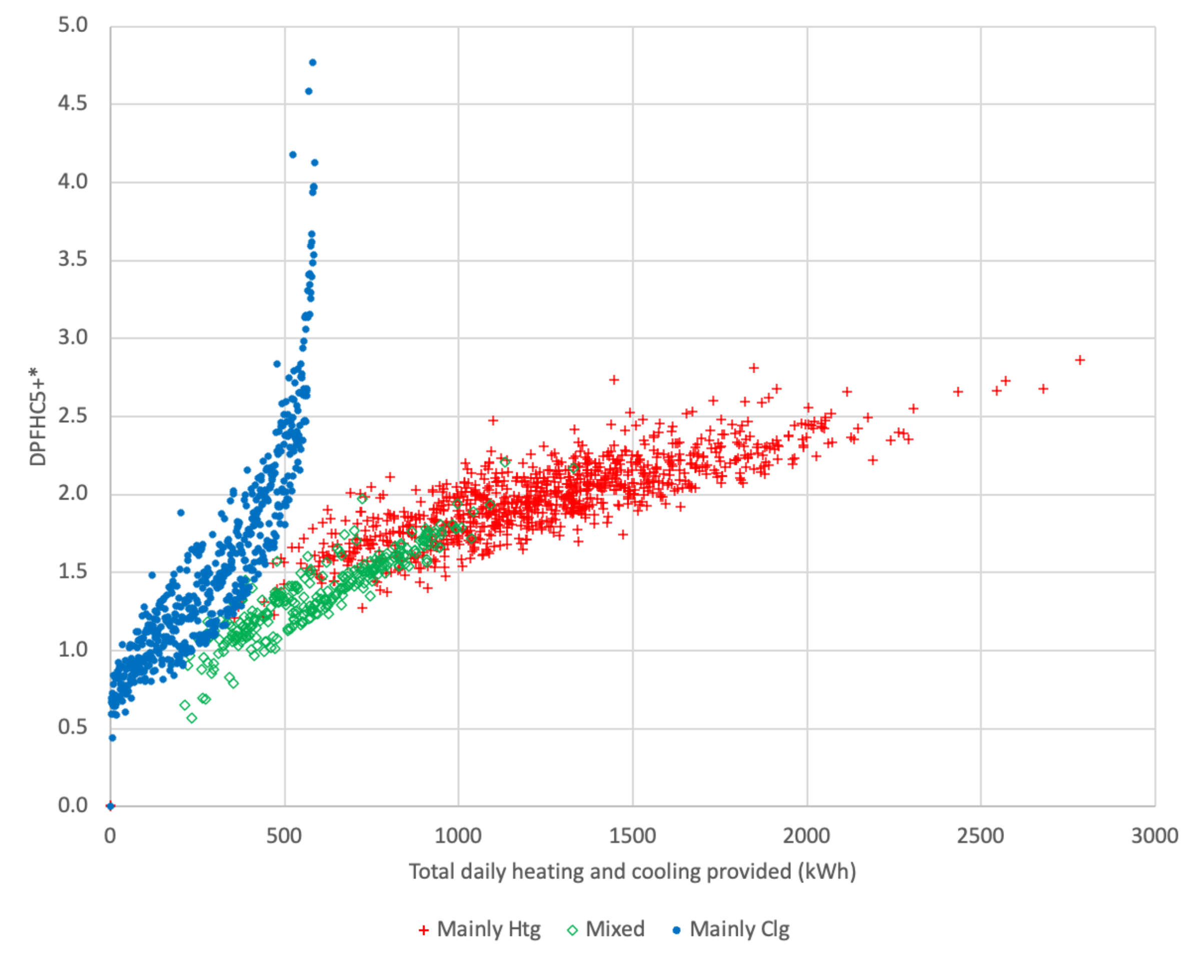

Figure 19. Binned daily total performance factors vs total heating and cooling provided at boundary 5+*.

Seasonal performance factors for heating are computed for each year in Figure 20. 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.

SPFs for the cooling system are given in Figure 21 for boundaries 2 and 5*. 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 significantly reduced.

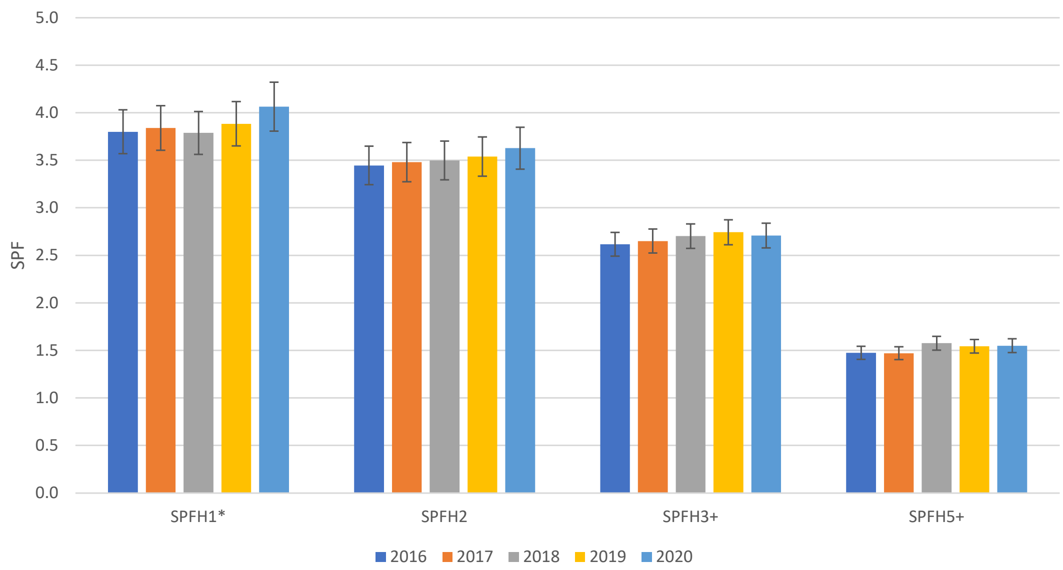

Figure 20. Heating SPF (2016-2020).

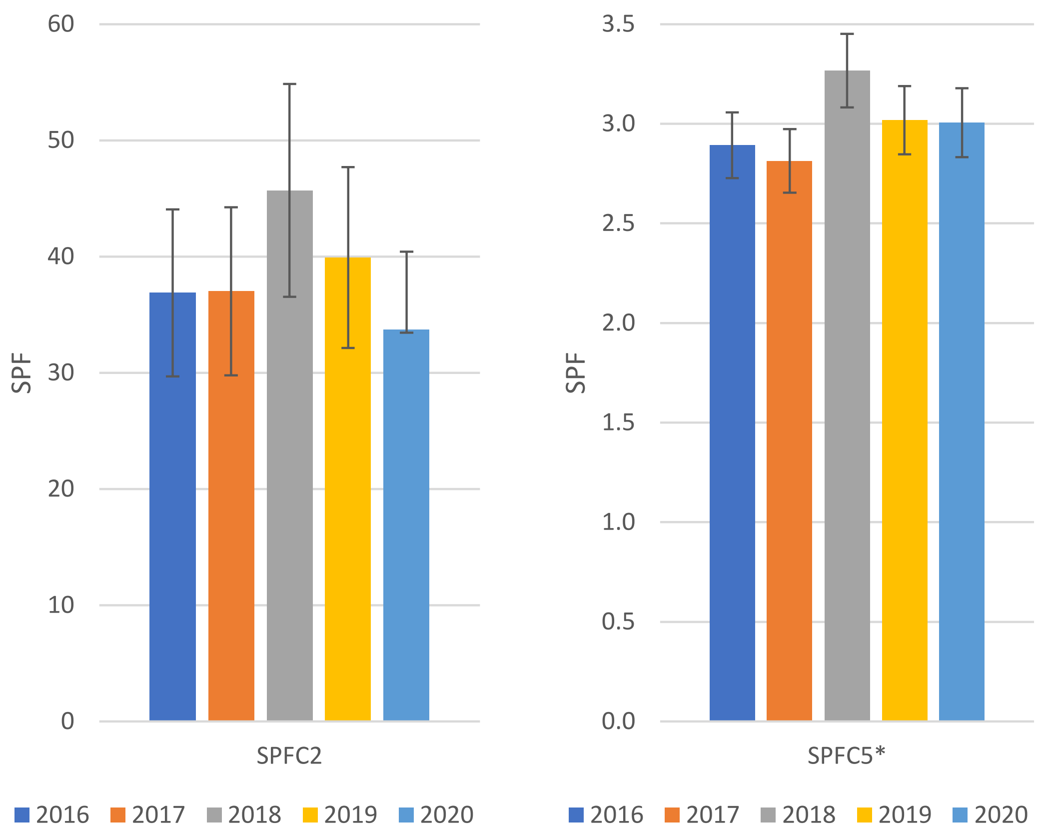

Figure 21 – Cooling SPF (2016-2020).

Table 7. Seasonal Performance factors over the monitoring period.

Start of evaluation period	January 1st 2016	January 1st 2017	January 1st 2018	January 1st 2019	January 1st 2020
End of evaluation period	December 31st 2016	December 31st 2017	December 31st 2018	December 31st 2019	December 31st 2020
SPFH1*	3.8±0.23	3.84±0.23	3.79±0.23	3.88±0.23	4.06±0.26
SPFH2	3.44±0.20	3.48±0.21	3.50±0.20	3.54±0.21	3.63±0.22
SPFH3+	2.62±0.13	2.65±0.13	2.70±0.13	2.74±0.13	2.71±0.13
SPFH4+	1.47±0.07	1.47±0.0.7	1.58±0.07	1.54±0.07	1.55±0.07
SPFC2(3)	36.88±7.20	37.02±7.22	45.69±9.16	39.91±7.78	33.72±6.70
SPFC4	2.89±0.16	2.81±0.16	3.27±0.19	3.02±0.17	3.01±0.17
SPFCH2	4.98±0.19	5.07±0.19	5.61±0.21	5.19±0.20	5.06±0.20
SPFCH4+	1.8±0.28	1.7±0.30	2.0±0.29	1.8±0.29	1.8±0.29

* Heat pump internal electricity use is included.

Table 7 summarizes the seasonal performance factors for each system boundary, including combined seasonal performance factors for heating and cooling taken together (SPF_{CH}) for system boundaries 2 and 4+. 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 seasonal performance factors for cooling and for SPF_{CH}. The impact of the internal heating and cooling distribution energy is substantial, decreasing the 5-year SPF from 5.06 at boundary HC2 to 1.8 at boundary HC4+*.

LESSONS LEARNT

The GSHP system has been analyzed with data from one year by Spitler and Gehlin (2018, 2020) and three years (Spitler and Gehlin 2021) 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, as well as the shorter data series, show that the performance factors increase with increasing heating and cooling load. 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 decreases when energy provided increases. The Studenthuset GSHP system performance factors are highest when the building heating and cooling loads are highest, whether due to occupant effects or weather, and the lowest performance factors appear during those periods when loads are lowest. During those periods standby circulation, DHW and Legionella protection are dominant.

The results pinpoint 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.

Improvement measures

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 in a more optimal way. Such improvements of the distribution system should significantly decrease the energy consumption at low heating and cooling loads and thus 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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Other project publications and presentations

Gehlin, S. Measured performance of the University of Stockholm Studenthuset ground source heat pump system. Paper presentation at the 14th International Conference on Energy Storage-EnerSTOCK2018, Adana, Turkey. April 26th 2018.

Spitler, J.D. GSHP System Performance Research at the University of Stockholm Studenthuset. Online presentation at the ASHRAE Digital Annual Meeting, June 30th 2020.

Project data access

Open access data from one year of measurements from Studenthuset is available at:

https://www.mdpi.com/1996-1073/12/10/2020 (3 years of data)

https://doi.org/10.22488/okstate.22.000005 (5 years of data)

Project participants and their contribution

Dr. Signhild Gehlin at the Swedish Geoenergy Center (Svenskt Geoenergicentrum) has been project manager and performed the data analysis and publication of results from the case study. The Swedish Geoenergy Center has provided part of the in-kind funding.

Professor Jeffrey D. Spitler at Oklahoma State University (OSU) has performed the data analysis and publication of results from the case study.

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