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Measured performance of the University of Stockholm Studenthuset ground source heat pump system

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Abstract

When the new student center at Stockholm University in Sweden was completed in the fall of 2013 it was thoroughly instrumented. The 6300 m^2 four-story building with offices, a restaurant, study lounges and meeting rooms was designed to be energy efficient with a planned total energy use of 25 kWh/m^2/year. 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. This paper uses measured performance data from Studenthuset to calculate the actual thermal performance of the GSHP system during one of its early years of operation. Monthly system coefficients-of-performance for both heating and cooling operation are presented. In the first months of operation, several problems were corrected, leading to improved performance. This paper provides long-term measured system performance data from a recently installed GSHP system, shows how the various system components affect the performance, and describes how some unanticipated consequences of the design may be ameliorated.

Keywords: Ground source heat pumps, GSHP, ground heat exchangers, GHE, office building, long-term system performance, BTES, Sweden

1. Introduction

Long-term system performance data from well-instrumented ground source heat pump (GSHP) systems are rare but highly valuable tools for researchers, practitioners and buildings owners. Such measurements help to show how the various system components and control strategies affect the overall performance, identify best practices, identify design and installation issues that lead to poor performance, provide benchmarking of GSHP system performance, and give guidance to how unanticipated consequences of the design be ameliorated.

It is of great importance to clearly state system boundaries as well as time boundaries when monitoring and analyzing system performance. Performance measures will serve different purposes when they are evaluated for the heat pump only, and when circulation pumps and fans on the source side and on the distribution side are included. Performance factors will also provide different information when evaluated over either a very short period of time, e.g. one hour, or over a longer period of time, such as a month, or a full year (seasonal performance). In this paper we use Seasonal Performance Factor (SPF) as term for seasonal performance factors, i.e. calculated over a period of 365 subsequent days, and Coefficient of performance (COP) for performance factors calculated over shorter periods of time, such as monthly performance.

The EU project SEPEMO (Nordman 2012) defined heating and cooling SPFs for a range of boundaries, in heat pump systems and cooling systems, mainly for residential buildings (see Table 1). We use this set of boundaries both for SPFs and COPs. The final report noted that heat pump system performance depends not only on the heat pump, but also on the climate and quality of installation. The SEPEMO project guidelines work well for smaller residential GSHP systems, but do not fully address all of the features that may be found in GSHP systems serving larger and more complex GSHP systems, such as commercial, institutional and multi-family buildings.

Table 1. System boundaries for SPF according to the SEPEMO model (Nordman 2012)

SPF_{H1}	Heat pump only
SPF_{H2}	Heat pump and circulation pumps/fans on source side
SPF_{H3}	Heat pump, circulation pumps/fans on source side and auxiliary heating
SPF_{H4}	Heat pump, circulation pumps/fans on source side, auxiliary heating and circulation pumps/fans on load side
SPF_{C1}	Cooling unit only
SPF_{C2}	Cooling unit and circulation pumps/fans on source side
SPF_{C3}	Cooling unit, circulation pumps/fans on source side and load side
SPF_{C4}	Cooling unit, circulation pumps/fans on source side and load side, and supplementary cooling unit

Note that the SEPEMO system boundaries for SPF_{H1} and SPF_{H2} correspond to SPF_{C1} and SPF_{C2}, while the boundaries for SPF_{H3} do not correspond directly to those for SPF_{C3}. SPF_{H3} includes auxiliary heating but not distribution pumps/fans, whereas SPF_{C3} includes distribution pumps/fans, but not supplementary cooling units. Hence if there is no auxiliary heating in the heating system, $SPF_{H2} = SPF_{H3}$, while $SPF_{C3} = SPF_{C4}$ for systems without supplementary cooling.

One example of thoroughly measured long-term performance of an office-building GSHP system is found in Southard et al. (2014a, 2014b) and Spitler et al. (2017). System performance factors were calculated over two years of measurements for heating and cooling respectively, and presented as monthly average performance with quantified uncertainty of the performance. The study involved a detailed analysis of two *distributed* heat pump systems at the ASHRAE Headquarters building in Atlanta – an air-source variable-refrigerant flow heat pump system and a ground-source heat pump system. It shows some complexities in monitoring system performance and points out how standby-losses, cycling, pumping, and running fans for ventilation purposes only may degrade the overall system performance.

This paper provides long-term measured system performance data from a recently installed *centralised* GSHP system for a new-built office building in the Swedish capital Stockholm. It shows how the various system components affect the performance, and describes how some unanticipated consequences of the design may be ameliorated.

2. System description

Stockholm University is located within the large campus area Frescati in central Stockholm. In 2011 the government-owned real-estate owner Akademiska Hus, responsible for management and development of buildings for research and higher education in Sweden, built a new student center at the campus (Figure 1). The new building was completed in the fall of 2013. Ambitions were high for the student center building to be a model building regarding sustainability, ecologic footprint, and energy use. The 6300 m^2 four-storey building contains office area for 130 staff, small meeting rooms, 200 study-booths for students and a café, and was designed to be highly energy efficient with a planned total use of 25 kWh/m^2/year (< 160 MWh/year) bought energy (electricity).

The building services are 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 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. The bore field 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, and the boreholes are drilled at an angle so that they reach under the surrounding building.

Figure 1. View of Studenthuset. Photo credit: Jeffrey D Spitler

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. A schematic of the Studenthuset heating and cooling system is seen in Figure 2.

Prior to building operation, total annual energy loads were anticipated to be 200 MWh heating and 34 MWh cooling. The installed capacity is 200 kW heating and 120 kW cooling from the boreholes. No auxiliary heating or cooling is installed, except for an electric resistance heater that boosts the hot water temperature to protect against Legionella. The anticipated electricity use for the building installations was approximately 14 kWh/m^2/year. Distribution losses in the heating system were estimated to be 2 kWh/m^2/year. Heat pump SPF was expected to be 4.5 according to the design documents, though the SPF boundaries were not defined.

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.

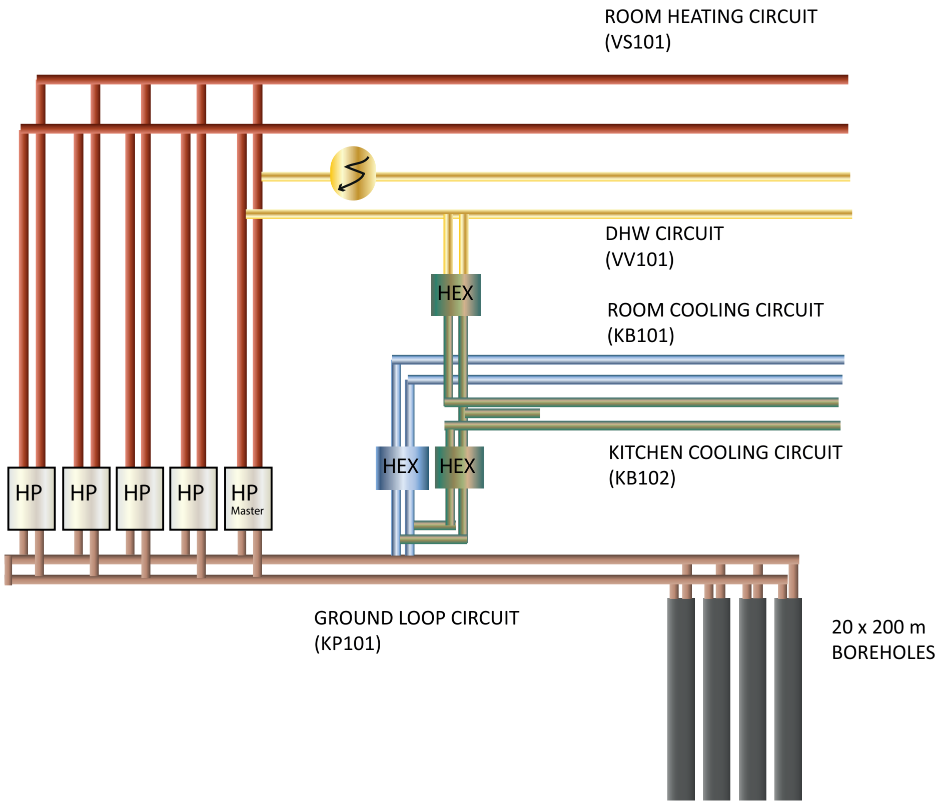

Figure 2. Schematic of the Studenthuset heating and cooling system. Illustration: S. Gehlin

3. Measurements and system characteristics

This paper uses measured performance data from Studenthuset to characterize the actual thermal performance of the GSHP system during its third year of operation. Measured data from the period April 1, 2016 through March 31, 2017, are used. Monthly energy loads for this period are shown in Figure 3. This period was chosen because some additional instrumentation was added at the beginning of the period, allowing more accurate measurement of the cooling provided.

3.1 Instrumentation

Heat transfer rates to/from the ground and to/from the building are measured both with "energy meters" and with thermodynamic analysis of the fluid mass flow rates and entering/exiting fluid temperatures. DHW energy consumption is calculated based on measured water usage, the estimated inlet temperature to the building (i.e. from the water mains) and the temperature set-point for hot water provided to the building. Heat is recovered from the ventilation air in the kitchen through one flat plate heat exchanger and one rotary heat exchanger. Heat recovery is also obtained from room ventilation air in the rest of the building through three rotary heat exchangers. Unfortunately, there are 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. This limits the possibilities for calculating SPFs and COPs with the H4, C3, and C4 boundaries.

The system electrical energy consumption is monitored continuously and recorded on an hourly basis. One measurement point logs electricity use for the five heat pumps (compressors and built-in circulation pumps), including the heat pump that is dedicated to DHW heating. It also includes electricity consumed by the "Legionella protection system" (LPS) - an electric resistance heater used to raise the domestic hot water temperature from 55°C provided by the heat pump to 60°C and a circulation pump that continuously circulates hot water through the piping system. The LPS consumes a minimum of 3 kW throughout the year. Another measurement point records electricity 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, but not DHW production or heat pumps. A separate set of measurements was made to allow estimation of the electricity used by the source-side circulation pump as a function of flow rate (which was measured).

3.2 Load Characteristics

The total energy loads for the selected period were 194 MWh space heating, 130 MWh space cooling, and 33 MWh domestic hot water (DHW) including the Legionella protection system (LPS).

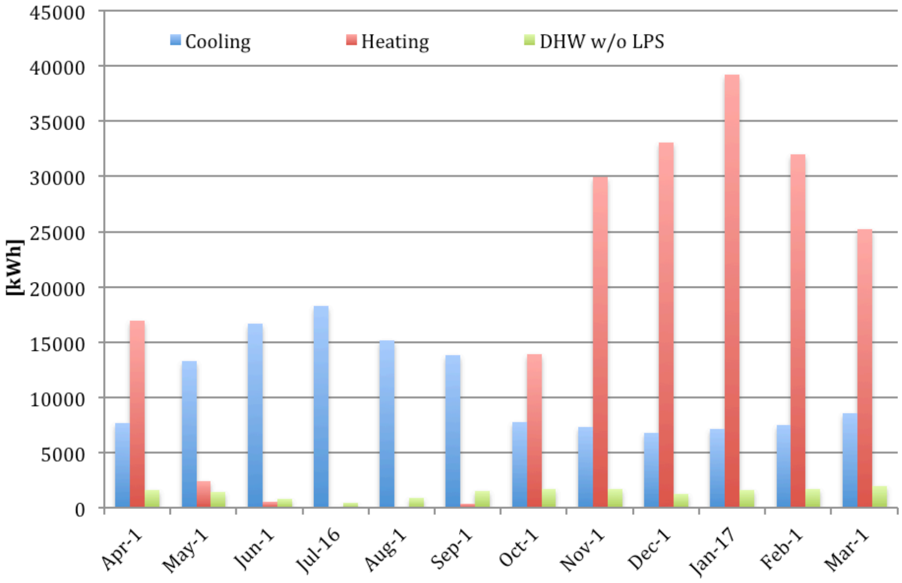

Figure 3. Monthly heating, cooling and DHW load. April 1 2016 - March 31 2017.

As can be inferred from Figure 3, heating and cooling is provided simultaneously over a substantial part of the year. A complicating problem in determining the performance factors of the system is that there is no standard way to allocate electrical energy usage to cooling and heating respectively, when the system is doing both simultaneously. There are many hours for which the Studenthuset system is simultaneously providing building heating and DHW from the heat pumps while also providing cooling somewhere in the building. In this study, we have calculated a heating fraction as the ratio of heating provided in an hour to heating and cooling provided in an hour. We then allocate the electricity used by the source-side circulation pump based on the heating fraction. Figure 4 shows the heating fraction as a function of outdoor air temperature. Each point on the plot represents the average heating fractions for a particular temperature bin of width 1°C.

The heating system has a maximum capacity of 200 kW, but as seen in the duration curve in Figure 5, heating is mostly provided at 20-60 kW. Maximum capacity of the borehole free-cooling system is 120 kW.

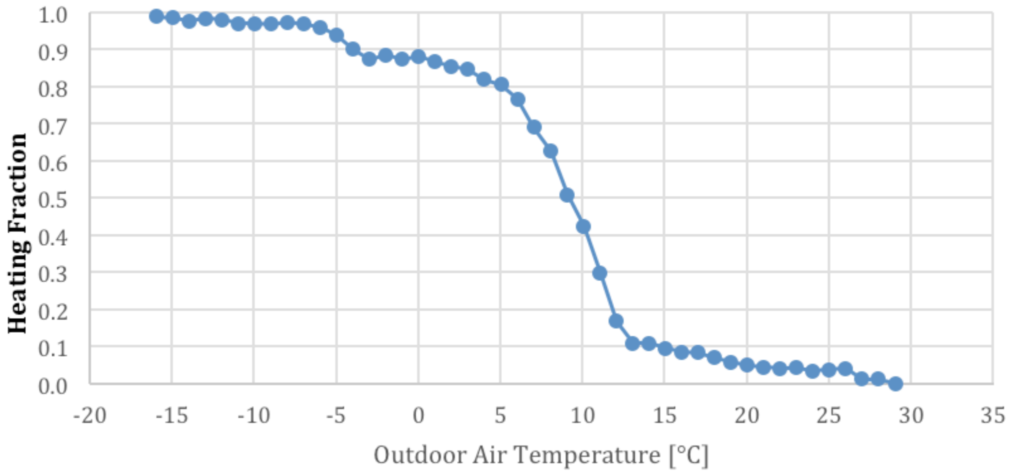

Figure 4. Heating fraction

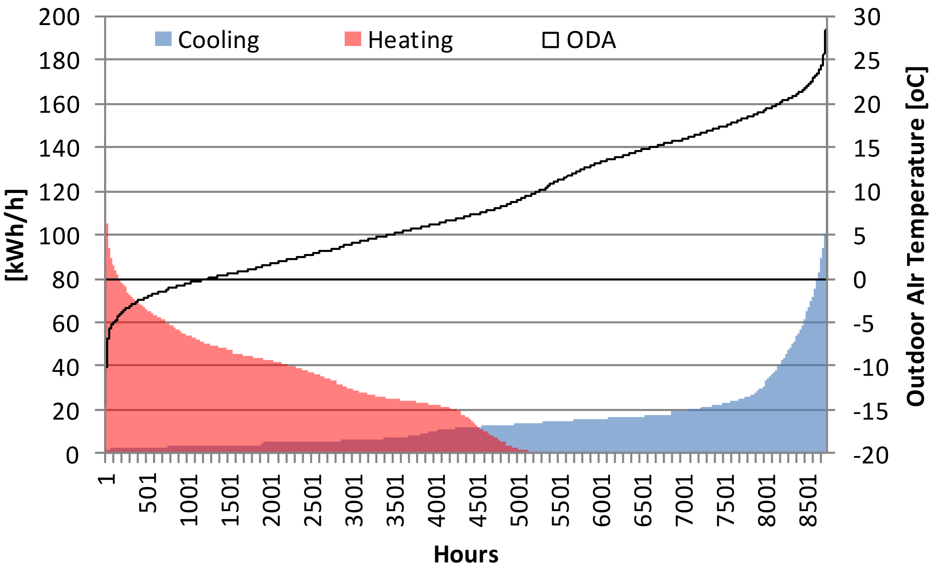

Figure 5. Duration curve for heating, cooling and outdoor temperature (ODA). April 1 2016 - March 31 2017.

3.3 System Boundaries

In this paper we have used the system boundaries for calculating system performance for heating and cooling, as suggested by the EU-project SEPEMO (Nordman 2012). The SEPEMO project was mainly focused on single family houses with heat pumps for heating or cooling, while Studenthuset is an office building with both heating and cooling, and thus has a higher degree of system complexity. Figure 6 shows the SEPEMO system boundaries applied to Studenthuset.

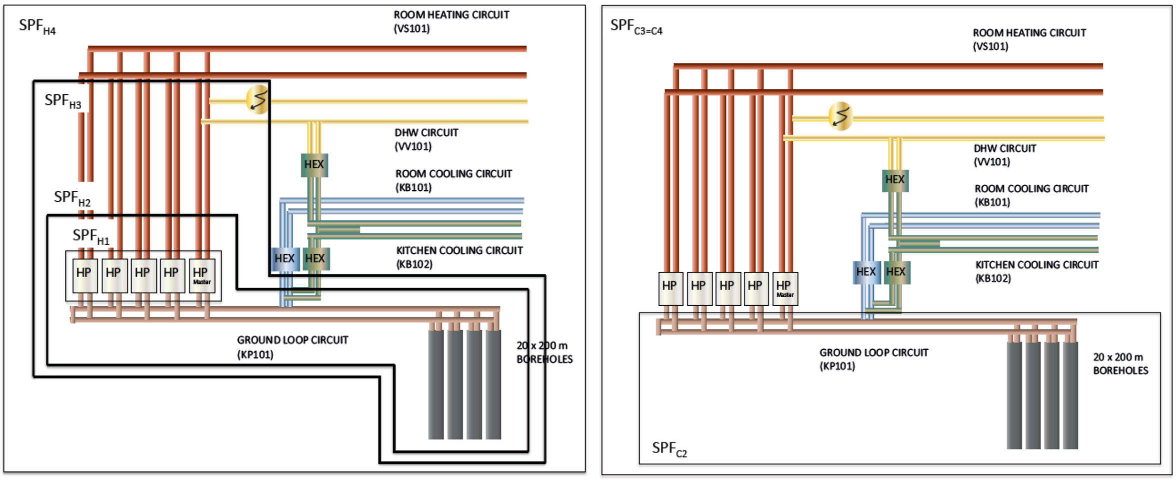

Figure 6. SEPEMO system boundaries (Nordman 2012) for heating SPF (left) and cooling SPF (right) for Studenthuset. SPF_{C1} cannot be calculated, as the system has no cooling unit.

Tables 2 and 3 summarize the energy delivered, and the allocated electricity usage for calculation of the various SPFs for heating and cooling respectively as defined by the SEPEMO system boundaries. SPF_{H1} cannot be calculated for Studenthuset as there is no instrumentation to measure heat pump compressor electricity separately from the built-in circulation pumps.

Table 2. Studenthuset heating SPF with SEPEMO system boundaries

Component	Annual (kWh)	**SPF_{H1}**	**SPF_{H2}**	**SPF_{H3}**	**SPF_{H4}**
Delivered space heating from HP	193832	x	x	x	x
Delivered DHW heating from HP	16769	x	x	x	x
Delivered DHW heating from LPS.	1784	---	---	x	x
Useful heat dissipated from LPS	26280*	---	---	x	x
Useful heat dissipated - internal pumps and fans	65962*	---	---	---	x
Delivered heating to building from EAHR	N/A	---	---	**	x
Electricity HP compressor w/o int. circ. pump	N/A	x	---	---	---
Electricity HP compressor + int. circ. pump	52208	---	x	x	x
Electricity source side circ. pump for heating	4380*	---	x	x	x
Electricity LPS	28064	---	---	x	x
Electricity load side circ. pumps+fans	N/A	---	---	---	x
Electricity load side circ. pumps+fans+EAHR	54343*	---	---	---	x
		N/A	3.72	3.46	N/A

Table 3. Studenthuset cooling SPF with SEPEMO system boundaries

Component included	Annual (kWh)	**SPF$_{C1}$**	**SPF$_{C2}$**	**SPF$_{C3}$**	**SPF$_{C4}$**
Delivered space cooling	130137	x	x	x	x
Delivered space cooling - supplemental cooling	0	---	---	---	x
Delivered space cooling from ventilation	N/A	---	---	x	x
Electricity - cooling unit compressor	0	x	x	x	x
Electricity - source side circ. pump for cooling	4495*	---	x	x	x
Electricity load side circulation pumps+fans	51097	---	---	x	x
Electricity suppl. cooling units	0	---	---	---	x
		N/A	28.95	N/A	N/A

Part of the energy used by the Legionella protection system will be transferred to the building as heat. We treated this as "useful heat" for every hour for which the heat pumps were delivering heat to the building. In hours when no heating was otherwise being provided, it was assumed to be not useful and was not counted as delivered heating. In Tables 2 and 3 an asterisk (*) added to the annual kWh denotes that the number has been estimated by allocating between heating and cooling and, for components that start with "Useful heat dissipated", the heating is only considered useful if there is space heating being delivered by the heat pumps during the hour. "N/A" means that the data is not available. Exhaust air heat recovery (EAHR) contributes to the heat delivered on the load side, though it cannot be quantified. Double asterisks (**) in Table 2 indicate that the SEPEMO guidelines don't clearly speak to the question of whether or not heating provided by the EAHR system should be considered "auxiliary heating". In this study, we account for EAHR as part of SPF$_{H4}$, where the ventilation systems fans are included, since EAHR is part of the ventilation system.

As the Studenthuset cooling system does not include a cooling unit, there is no SPF$_{C1}$. Also, there is no supplementary cooling for Studenthuset, hence SPF$_{C3}$ = SPF$_{C4}$.

3.4 Annual performance

Annual delivered space heating, space cooling and DHW heating from the GSHP system is shown in Figure 7. Heat recovered from the ventilation air rotary heat exchangers is not included in the figure, as this energy could not be estimated from available data. Nor is the amount of cooling provided directly from the ventilation system.

Annual electricity used on source side and load side is shown to the right in Figure 7. This electricity includes the amount used for the heat recovery, and cannot be quantified separately. Without accounting for the recovered heat in the ventilation air or the "free" cooling sometimes provided by the ventilation air, the overall SPF$_4$ will be unfairly low, as this energy significantly improves the building energy performance. Figure 7 shows that electricity use for distribution of heating and cooling, ventilation, and heat recovery accounts for about twice as much electricity as the heat pumps and source-side circulating pump together. In a centralised system such as this, distribution energy on the load side may be similar regardless of the chosen energy source. That is, the distribution energy may be approximately the same whether the heating is provided by centralised GSHPs, district heating or a gas boiler. Therefore, SPF and COP H3 and C2 may still be useful for comparison to other heating and cooling system types. However, for comparison to distributed GSHP systems, it is desirable to make comparisons using the H4 or C3 boundaries, because the distributed GSHP energy necessarily includes fan power.

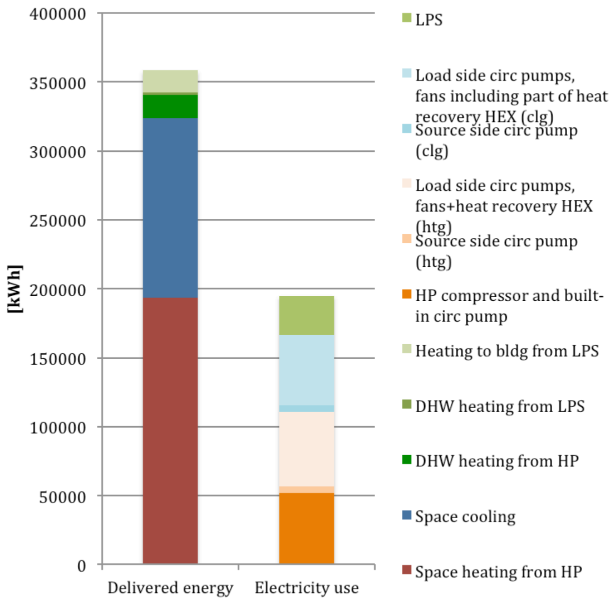

Figure 7. Annual delivered heating, cooling and DHW provided (left), and electricity used (right). Note that delivered heating from exhaust air heat recovery is not included.

3.4.1 Heating

Delivered space heating, electricity consumption for heating and seasonal performance factors for the heating system are shown in Table 2. As discussed above, the electricity used by the source-side circulation pump had to be allocated between heating and cooling based on the heating fraction. The total annual space heating delivered to the building, excluding heat recovery, was 194 MWh which is consistent with the anticipated annual space heat load (200 MWh) for the building.

According to the building design documents, the SPF for the heat pumps was expected to be 4.5. As mentioned above, the design documents are silent on the point of which boundary conditions correspond to the stated SPF. Annual SPF for the heat pumps including electricity for the internal circulation pumps was 4.0. Annual SPF_{H2} (which includes both the internal and external circulation pumps was 3.72.

3.4.2 Cooling

Seasonal performance factors for the cooling system are shown in Table 3. Studenthuset does not have a cooling unit, hence SPF_{C1} does not exist, but SPF_{C2} which includes the source and source side circulation pump is estimated as 28.95. Electricity used by source side circulation pumps for cooling is allocated using the heating fraction (as described for heating in section 3.4.1) to calculate the fraction of cooling. As the amount of cooling provided by the ventilation system is not measured, SPF_{C3} and SPF_{C4} cannot be estimated.

Measured annual cooling amounts to approximately 130 MWh, which is about four times as much as the anticipated annual design cooling load of 34 MWh. The reason for this difference has not yet been determined.

3.5 Monthly performance

3.5.1 Heating

Monthly performance factors for heating were calculated using the system boundaries in Figure 6. Figure 8 shows monthly COP_{H2} and COP_{H3} for the evaluated period.

Somewhat counter-intuitively, the monthly heating COPs are as highest during the colder months and lowest in the summer. The explanation lies partly in the source side circulation pumps providing a minimum of 8 L/s throughout the year, regardless of whether or not there is a heating load. COP_{H3} is largely affected by the Legionella protection system (LPS), which runs all the time. Much of the electricity consumed by the LPS is eventually dissipated to the building, so during the heating season, this is counted as “useful heating delivered”, increasing COP_{H3}. However, during the warmer months, the heat dissipated is not useful and it significantly decreases COP_{H3} to the point that it falls below 1 for some months.

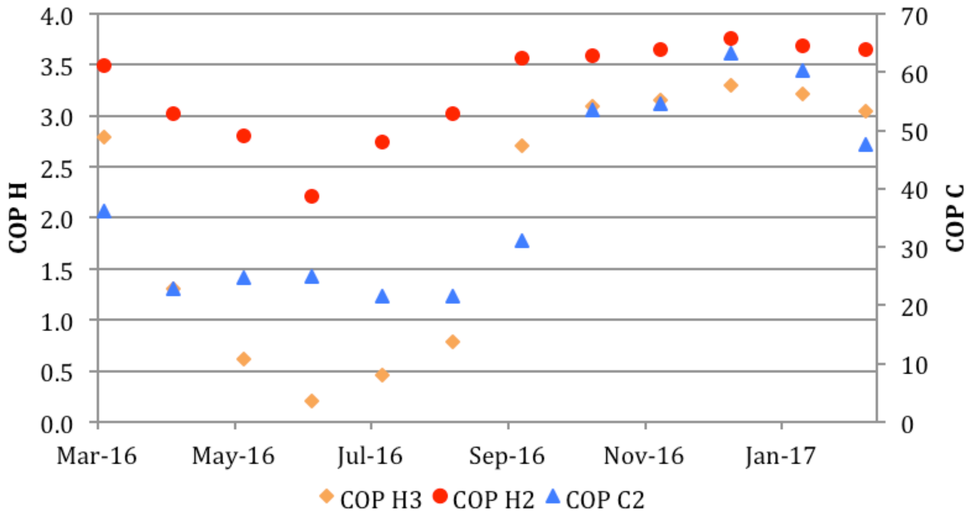

Figure 8. Monthly COP_{H2}, COP_{H3} and COP_{C2}, April 1 2016 - March 31 2017.

3.5.2 Cooling

Monthly performance factor for cooling is presented for COP_{C2} in Figure 8. The COP varies between around 20 in the summer and up to above 60 in mid-winter times, when the heat pumps are lowering the heat carrier fluid temperature. The amount of cooling used in the winter months is however quite small. These COPs do not account for distribution energy (as in COP C3 and C4), and although we cannot calculate COP_{C3} due to lack of data from the ventilation system, we expect COP_{C3} to be significantly reduced compared to COP_{C2}.

3.6 Performance vs temperature and load

In Figure 9 COP H3, H2 and C2, binned at half-degree intervals, are plotted versus entering fluid temperature (EFT) to the system from the borehole field. (By “binned” we mean that average values are taken for all hours with heat pump EFT that fall within a half-degree bin, e.g. the points shown at 10°C are averages for all hours with heat pump EFT between 9.75°C and 10.25°C.) COP_{C2} and COP_{H2} have minimums at 11°C and COP_{H3} drops significantly between 10-11.5°C. As shown in Figure 10 the overall daily load is as lowest at those EFTs. This correlation between low part loads and low performance is consistent with measured performance of the distributed GSHP system (Spitler, et al. 2017) serving an office building in Atlanta. This may seem counterintuitive, compared to thermodynamic theory, which might lead us to expect that the highest heating COP should occur at the highest heat pump EFT. But the effects of "parasitic" loads – e.g. pumping and control boards – and heat pump cycling losses seem to dominate the actual field-measured COP.

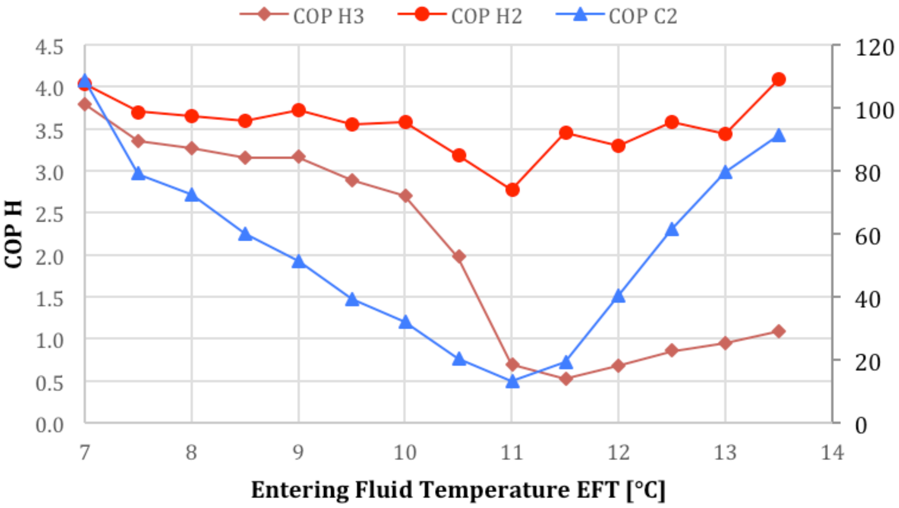

Figure 9. COP vs EFT.

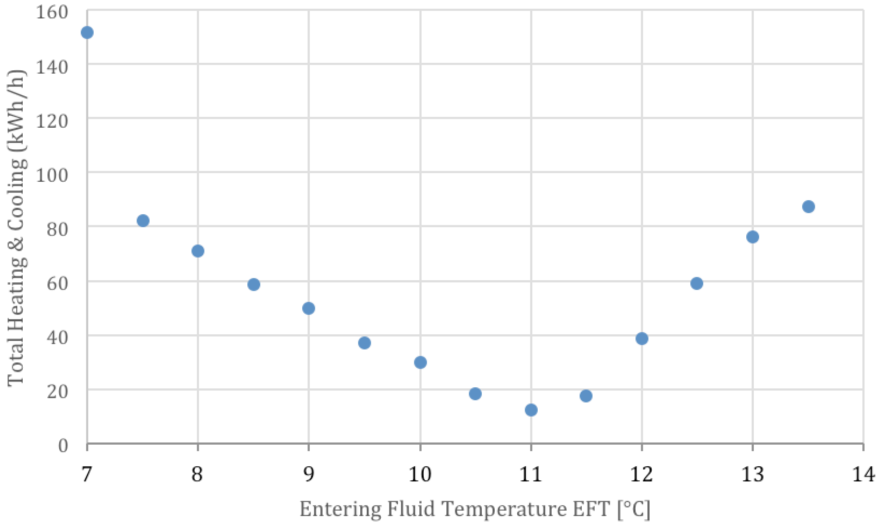

Figure 10. Overall Daily Load vs EFT.

Figure 11 shows daily overall COP plotted versus overall energy load. Loads include building heating and DHW heated by the heat pumps and legionella protection system (LPS), while for cooling only the chilled water provided by the boreholes is included. The electricity use includes heat pump operation, LPS and source-side circulating pump. Days with mainly cooling load (heating fraction ≤0.25), mainly heating load (heating fraction

≥0.67), and mixed heating and cooling load are colour coded to illustrate the different correlations between COP and heating and cooling load respectively.

The figure raises some interesting questions. Firstly, why is there such a discrepancy between COP_{C2} in Figures 8 and 9, and the overall COP for the mainly cooling cases? The explanation would be that for days when the heating fraction is very small, there is still a DHW load, and the LPS is still running. For a bin temperature of 20°C, the cooling provided is about 40 kW and the DHW provided is about 2.3 kW, but the LPS is using 3.2 kW and the circulating pump is about 1 kW. This means that even though COP_{C2} at those conditions is 42, adding the DHW heating gives about 44.3/4.2 kW, which gives an overall COP of only 10.5.

Second, we don't see nearly as strong a trend for the heating loads as for the cooling loads. COPs for cooling dominated conditions increase about 10 units over 1000 kWh increased daily energy load, whereas the increase in heating dominated COPs is only 1 unit over 2500 kWh load increase. While an increased cooling load only requires a small increase in electricity use for the circulation pump to increase the flow rate, it also means that the relative influence on the COP from the Legionella protection system and DHW circulation decreases. For heating dominated conditions, the Legionella protection system and DHW circulation are small contributions to the overall load and electricity use. Also, since there are five heat pumps that are staged, individual heat pumps tend to work at close to full load conditions.

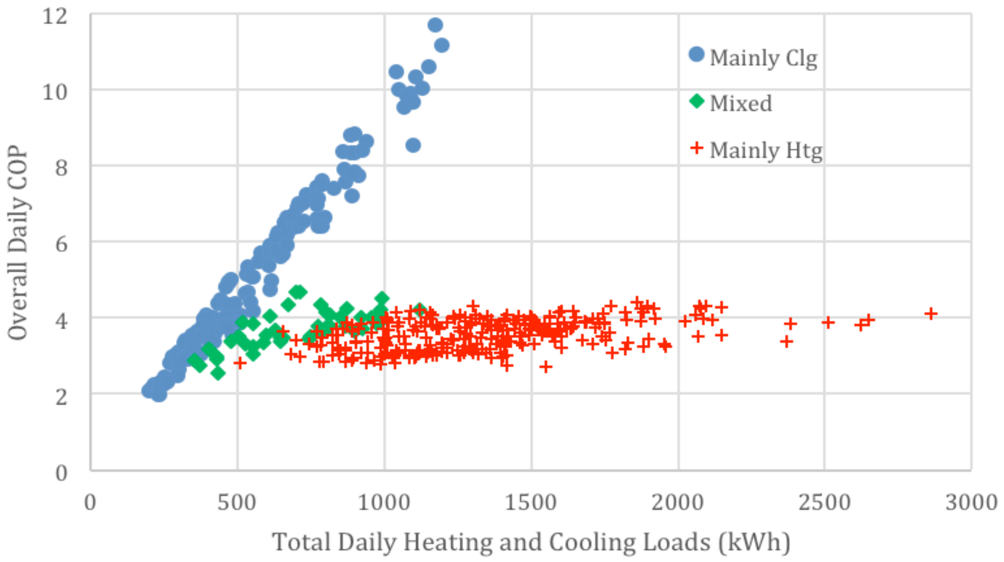

Figure 11. Overall Daily COP vs Overall Daily Load.

4. Discussion

System performance has been analysed based on a range of boundary conditions – H2, H3, H4, C2, C3, C4 shown in Tables 2 and 3. The results have been presented for a one-year period, monthly periods, daily periods, hourly periods and binned hourly periods.

For the situation in Sweden, the annual SPFs H2 or H3 are commonly used as a basis for comparison, because other systems to which GSHP systems may be compared are also centralized systems. That is, they also provide hot water and chilled water to panel radiators, fan coil units and other heating/cooling distribution devices. In this case, it makes sense to compare the “central plant” equipment using the H2 and H3 boundary conditions. For cooling, the C2 boundary conditions would be commonly used.

However, if we wish to compare to distributed GSHP systems or other distributed systems where the heating and cooling equipment has integrated distribution fans and, likely, ventilation provided using these same fans, it is necessary to compare using boundary conditions that include the heating and cooling distribution and even the ventilation. In our results for the Studenthuset system, these correspond to the H4 and C4 results.

This, however, raises a further complication. The ventilation system does provide heating and cooling because outdoor air is at least tempered using hot water or chilled water from the heat pumps. Therefore, the ventilation system electricity consumption is included in the H4 and C4 boundary conditions. On the other hand, the ventilation system consumes electricity primarily for the purpose of providing fresh air to the space, not for heating and cooling purposes. So, when calculating heating and cooling COPs with the H4 and C4 boundary conditions, is there a fair way to divide the electricity consumption between heating/cooling and provision of fresh air? It seems that it might be possible to calculate the pressure drop due to heating and cooling coils, the pressure drop due to the rest of the ventilation system and apportion the electricity consumption accordingly. This remains a topic for further investigation.

Beyond the question of the comingling of electricity for ventilation and heating/cooling, several other problematic issues have arisen during the performance analysis of the Studenthuset system. These include:

- Division of electricity consumption between heating and cooling when both are being provided simultaneously. For the Studenthuset building, this arises when accounting for the electricity used by the source-side circulating pump under conditions when one or more heat pumps are being operated to provide heating and “free” cooling is being provided at the same time directly from the boreholes. It also arises with respect to the fans and pumps of the heating/cooling distribution system and ventilation system, for which we only have a single energy meter. In these cases, we divided the electricity proportionally to the amount of heating and cooling provided.
- The Studenthuset system utilizes an electric resistance heater to raise the domestic hot water temperature in order to protect against Legionella. The required hot water temperature is 60°C, but in practice the electric resistance heater is operated continuously and excess heat is dissipated into the building. A pump is used to continuously circulate this hot water around the building. This continuous circulation is used both to protect against Legionella (by insuring that temperatures remain high through the domestic hot water piping) and to significantly reduce the amount of waiting time for hot water at any tap. Treatment of this subsystem is perplexing. Should the heating provided by the electric resistance heater all be treated as providing useful heating to the building? Clearly, when domestic hot water is being utilized, the Legionella protection system is providing some of the required heating. The energy expended to heat the domestic hot water to 60°C can certainly be considered as part of the heating load. But what about that dissipated to the building? It could either be providing useful heating or merely increasing the cooling

load. So, it seems that it should be treated on the basis as to whether or not the building has a heating load at that time. In this analysis, we took this into account by treating the heat provided by the Legionella protection system as useful for any hours where the heat pumps were providing any building heating. However, as this includes hours when the building was simultaneously being heated and cooled, this approach should be refined.

- The fact that the Legionella protection system ran every single hour did, however, alleviate one other problem encountered in other system performance studies – how to treat energy consumed by pumps, fans, control boards, etc. when neither heating nor cooling are provided by the system.
- It may always be the case that additional instrumentation is desirable. In this case, we could not calculate COP_{H1} because the heat pumps had integrated circulating pumps and we did not have independent measurements of the compressor energy consumption.
- Another limitation in the instrumentation is that heating supplied and cooling supplied are determined solely from water-side measurements made near the central plant. As shown in Figure 7, the internal circulation pumps and fans use a little over half of all system electricity. This electricity usage would be accounted for in the input electricity used to calculate COP and SPF for boundaries H4, C3, and C4. However, all of this electricity is eventually dissipated as heat somewhere. Treatment of this dissipated heat faces the same complications as the treatment of heat from the Legionella protection system. Furthermore, the fan energy is used to provide heating and cooling to the ventilation air and cooling to the building space. But without suitable instrumentation, it is not possible to quantify this. Therefore, we demurred from calculating COP and SPF for boundaries H4, C3, and C4. Further instrumentation here would be particularly helpful.

Finally, one of the most important uses of this kind of performance investigation is identification of possible system improvements. We have identified several possibilities, though their impacts have not yet been fully evaluated:

- The scheduled run time of the electric resistance heater providing Legionella protection could be reduced. It currently runs 24 hours per day, seven days per week. Many heat pump systems run a heating cycle for Legionella protection on a once-per-week schedule.
- The continuous circulation pump could also be scheduled to run at a reduced run time, more closely matching the operating hours of the building. Merely limiting the circulation pump and electric resistance heating to run during office hours only would save about 12,000 kWh year in electricity consumption. Some of the heating provided by the Legionella protection system would then be replaced with heat provided by heat pumps at a higher COP.
- The minimum flow rate through the ground heat exchanger is set to be 8 L/s year-round. This often results in very low ΔT across the boreholes. It seems likely that the

setpoint could be reduced significantly for portions of the year and/or a reset control could be utilized that reduces the flow when allowable.

5. Conclusions

The Studenthuset in Stockholm, Sweden, and its GSHP system were designed with high ambitions for both energy efficiency and indoor comfort. The owner has long experience with GSHP systems in buildings and the system is thoroughly instrumented and monitored by experienced staff. This study shows that the system provides space heating consistent with the design values, and that the cooling provided is about four times higher than anticipated from the design. The system provides sufficient heating, cooling and DHW, but there is room for improvement of the performance. Potential improvements include scheduling of the Legionella protection system and DHW circulation, and allowing reduced flow rates in the boreholes circuit. These actions have the potential of significantly decreasing parasitic losses and hence improve the performance.

A key finding is that the measured COPs are more affected by the amount of heating and cooling and provided than by the entering fluid temperature to the heat pumps. In general, this corresponds to higher run time fractions for equipment and less influence of “parasitic” loads such as pumps and unit control boards. This is consistent with findings for a distributed GSHP system (Spitler, et al. 2017) in Atlanta.

Despite the thorough instrumentation and monitoring, several additional measurement points are needed in order to provide a complete analysis of the system performance. Additional instrumentation and data logging would be needed for estimating the amount of heat recovery and cooling provided from the ventilation air, as well as allocating the electricity used for this. This would make possible estimation of SPF H4 and C3 and C4.

Other desirable additional instrumentation would be electricity measurements for the heat pump compressors to enable estimation of SPF_{H1}, separate electricity measurement for the circulation pump on the source side, and separate electricity measurement for the different parts of the Legionella protection system.

For a Swedish centralized GSHP system like Studenthuset, it makes sense to evaluate SPF H2 H3, C2 and an overall SPF including only the ground source, heat pumps and DHW heating, and leaving out the load side energy and electricity. However, since SPF H4 and C3 (= C4) could not be calculated for Studenthuset, it is not possible to compare this centralized system with a decentralized system such as the ASHRAE HQ in Atlanta.

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