Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Studies

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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for GRAHAM Energy Management

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These case studies have not considered the detailed design of the heat sources or ground loops, sizing of the buffer vessels nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 01

Prepared by GRAHAM Energy Management
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Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 01 and performance results from 12 consecutive months of monitoring data.

Site 01 is a 3-storey office building, converted from an 18th-century mill and extended in 2010.

The open-loop water-source heat pump of 26 kWTH capacity, located in an adjacent factory building, extracts heat from groundwater, pumped from a 120m borehole directly to the evaporator. It provides space heating via underfloor coils.

During warm summer weather, water from the borehole is circulated through the underfloor pipes to provide cooling. The heat pump itself is not used for cooling.

The seasonal heating performance factors measured over a year of operation
(1st January 2015 to 31st December 2015) were:

SPFH2	[Total heat delivered by the heat pump] – [heat added by the buffer pump] --- Electricity used by [heat pump] – [buffer pump] + [source pump]	4.47
SPFH4	[Total heat from heat pump] – [heat loss from buffer tank] + [heat added by SH circ pump] --- Electricity used by [heat pump] + [source pump] + [SH circulation pump]	4.10

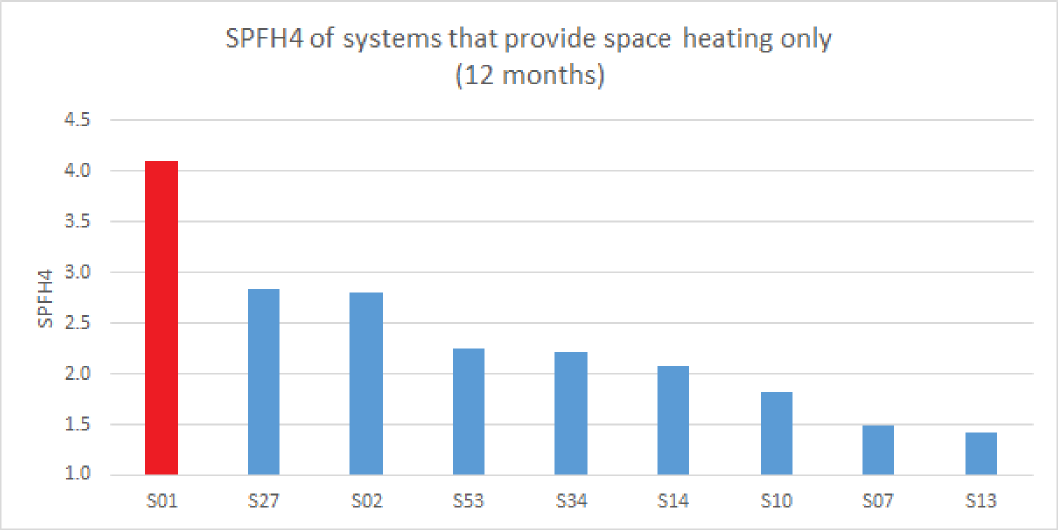

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

Aspects of this system that positively influenced its performance are:

- The temperature of the water from the source was always above 10 °C. During the winter months, this was the highest of all systems monitored.
- The source water is pumped directly to the evaporator, without an intermediate heat exchanger which would introduce temperature loss.
- The heat pump output temperature was always below 40 °C. This was lower than on most other systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump run times were sometimes shorter than the minimum recommended by previous research [1].
- The heat pump was run during the night, although the building is presumably not occupied at night.
- Weather compensation was not used.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	01
Survey date	27/02/2014
Monitoring installed	10/07/2014
G/WSHP	WSHP[1]
Building type	Offices in a converted and extended 3-storey 18th-century mill. The offices were designed to be heated by a heat pump, and the building has an EPC rating of A+.
Location	Rural
Heat pump capacity kWTH	26
Number of heat pumps	1
Heat source	Ground water from 120m borehole; pumped directly to the heat pump evaporator; returned to an adjacent river
Heat emitter	Underfloor heating pipes
Cooling	Water from borehole can be pumped to the underfloor pipes
DHW	No
Auxiliary heat sources	None
Source pump	Down-hole pump: 220 W fixed speed
Buffer tank	400 litre 4-pipe
Buffer tank shunt pump	Incorporated into the heat pump: 100 W fixed speed
SH circulating pump	External to heat pump: 200 W variable speed
DHW cylinders	N/A
DHW cylinder coil shunt pump	N/A
DHW distribution pump	N/A
Control	Heat pump controller + buffer tank thermostat + room thermostats and timeswitch for night setback.
Weather compensation	Disabled (because the sensor is located inside the heat pump)
Heat meter type	Vortex
No. of heat meters	1
Heat meter interface	Pulse (1 kWh / pulse)
Building operation and use	Assumed use as offices open during normal office hours
Comments	The heat pump is installed in the corner of a factory immediately adjacent to the office building. No heat is supplied to the factory. Water from the borehole can be diverted to the underfloor pipes during warm weather to provide cooling.

Table 1 – System details

This site is a converted 18th century mill in a moderately exposed rural location. It was completely refurbished and extended in 2010 to create a 3-storey office building. It has been insulated to a high standard, and has an Energy Performance Certificate (EPC) rating of A+. The building is understood to be occupied by a number of businesses and is in use during normal office hours.

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[1] This system is classified in the RHI database as a water-source heat pump. However, the heat source is groundwater, so it could also be considered to be a ground-source heat pump (see MIS 3005 [3]).

This application entails extracting heat from groundwater to provide space heating only to offices. The source water is pumped directly to the heat pump without any intermediate heat exchanger, so the heat pump input temperature should be relatively high. The heat emitters are underfloor heating pipes, so the heat pump output temperature should be relatively low. No auxiliary heat is used. The building is located in an area with below-average outdoor temperatures – estimated annual mean 9.4 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The system performance would be expected to be above average.

Heat pump and monitoring systems

A single heat pump (thermal capacity 26 kW) is installed in the corner of a production facility that is immediately adjacent to the office building. Water is pumped from a 120-metre borehole below the car park, using a down-hole pump, directly to the evaporator of the heat pump (i.e. without an intermediate heat exchanger). The water is returned to the river that runs through the site.

Heat is provided to underfloor heating pipes in the offices, via a 400-litre 4-pipe buffer tank.

The system is controlled by the heat pump controller, with a thermostat in the buffer tank, room thermostats in the offices and a night setback timeswitch.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating (SH), and temperatures at key points in the system. The system boundaries for calculation of the seasonal performance factors SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. The existing heat meter (“H”) is monitored via its pulse interface. Temperatures (“T”) are monitored at key points in the system using surface-mounted probes[2].

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[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

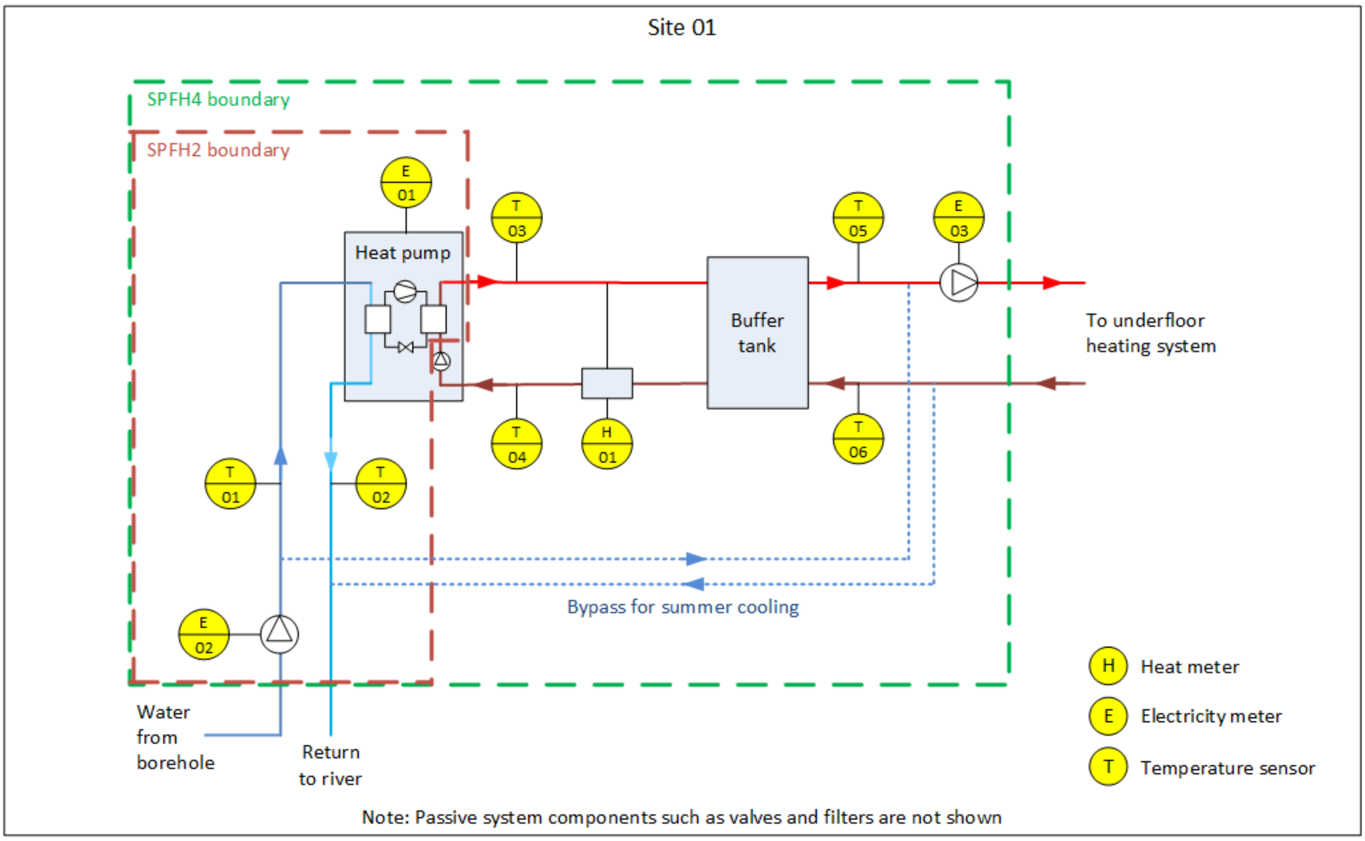

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses a vortex flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is mains-powered.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPFH1, SPFH2, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPFH2 represents the performance of the heat pump together with the source pump.
- SPFH4 represents the performance of the complete system, including the heating circulating pump and excluding heat losses from the buffer tank.

Heat pumps achieving an SPFH2 of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [2].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a “raw data” database. The raw data was subsequently processed by custom software to generate a “clean” database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump] – [heat added by buffer pump]}}{\text{Electricity used by: [heat pump] – [buffer pump] + [source pump]}}$$

- This calculation required the electrical energy used by the buffer pump inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running.

- The heat added by the buffer pump was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pump.

$$SPF_{H4} = \frac{\text{[Heat output of heat pump] – [heat loss from buffer tank] + [heat added by SH circ pump]}}{\text{Electricity used by: [heat pump] + [source pump] + [SH circulating pump]}}$$

- The heat added by the heating circulating pump was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pump.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

The SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	4.47
SPF_{H4}	4.10

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 4.10 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

The number of 1-minute intervals selected as valid for analysis was 414 222 which represents 79% of the 12-month period. Some of the intervals excluded were for times when the heat pump was switched off.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system, for the period 1st January to 31st December 2015. The changes in SPF values during the year are most likely explained by changes in the heat pump output temperature. See the notes on page 15 for a further discussion of this.

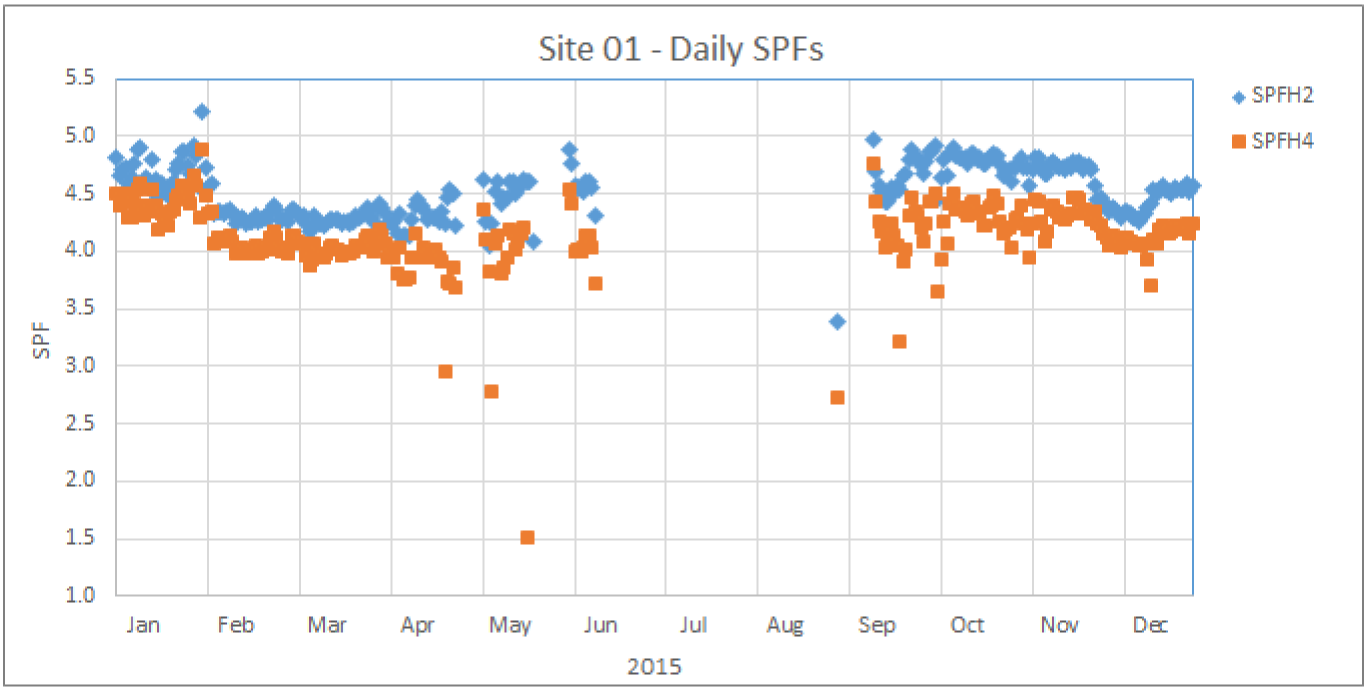

Figure 3 – Seasonal performance factors SPF_{H2} and SPF_{H4} calculated daily (excluding days when in cooling mode)

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source is the groundwater from which heat is being extracted and the sink is the space being heated.

Heat extraction from the source to the heat pump is direct: the groundwater is pumped through the evaporator.

Heat delivery from the heat pump to the heated space is via a hot water circuit. This water will always be warmer than the space because of the need for a temperature difference between the water and the space to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the source water at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump water from the source, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [1] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, in order to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the heat output to the underfloor heating. The daily mean outdoor temperature[5] and the electricity use by the total heat pump system are shown for reference, and it can be seen that, in general, the heat demand increased when the outdoor temperature was lower, as would be expected.

There was no heat demand during the summer months.

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[5] The outdoor temperature was not monitored at this site. Temperature data has been derived from the data recorded at other sites and adjusted for altitude.

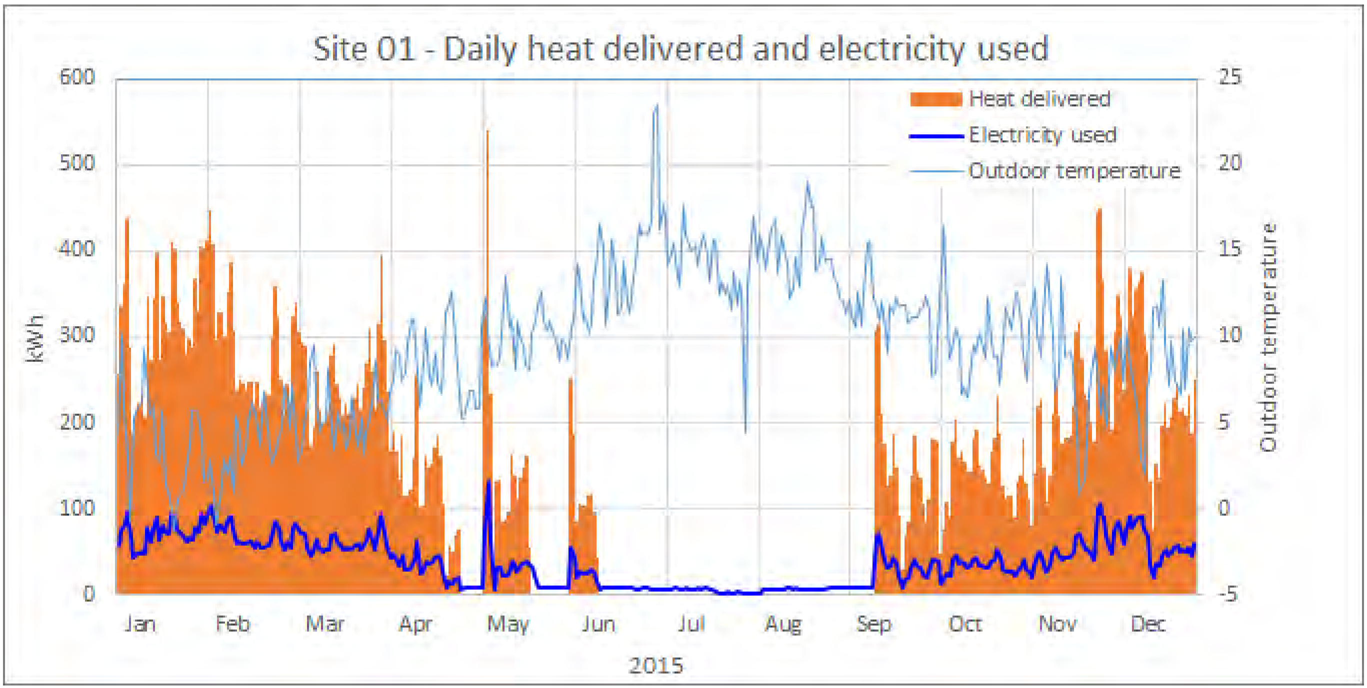

Figure 4 – Daily heat output and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The use during the summer cooling period was still quite significant. This is explored in more detail below.

The source pump used 4.4% of the total electricity used by the heat pump system while it was operating in heating mode. This was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%) and would have had a positive influence on the system performance.

The buffer pump and the heating circulating pump together used 7.4% of the total electricity in heating mode. This was also below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%) and would have had a positive influence on the system performance.

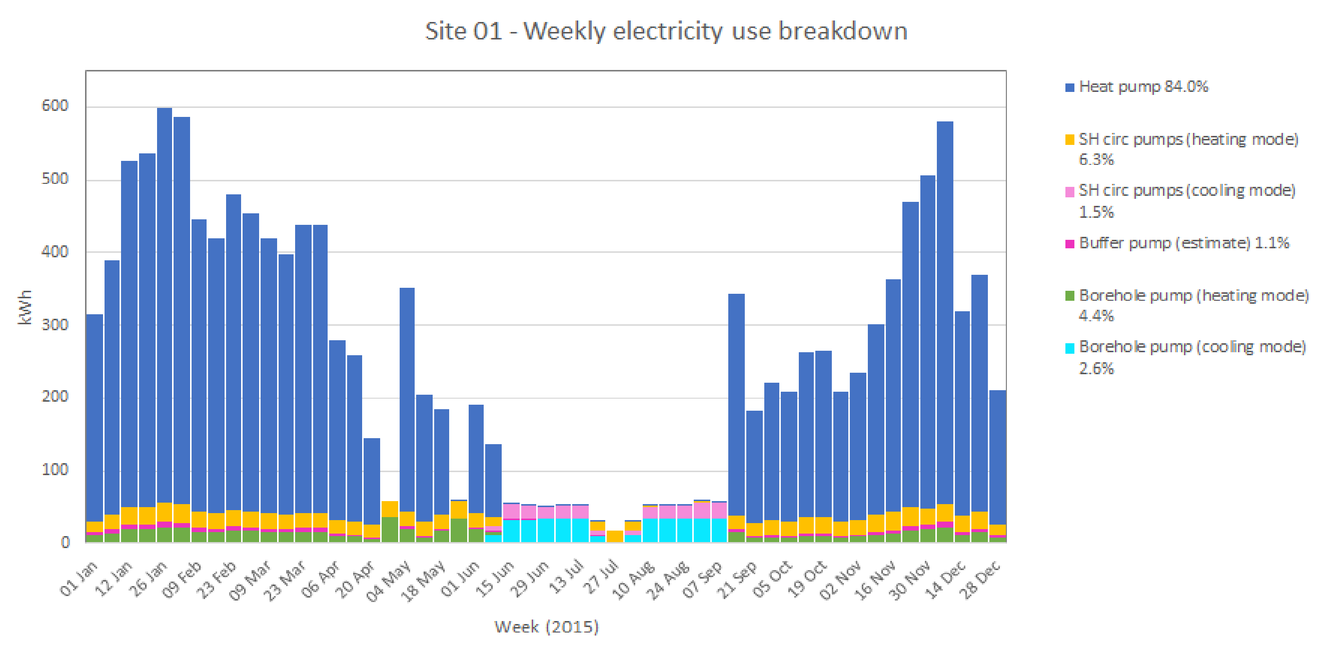

Figure 5 – Weekly electricity use breakdown

Cooling mode

During the warm summer months, the system was used in cooling mode, with water from the borehole being pumped directly to the underfloor pipes. In this mode, the borehole pump and the underfloor circulating pump continued to be used – as shown in Figure 6.

The system was shut down for a 2-week period at the end of July/start of August, although the underfloor circulating pump continued to run. The reason for this is unknown. It may have been due to an error in the control settings or, if the pump was controlled manually, it may have been due to an oversight. Although the effect on overall performance was small (0.3% reduction in SPF$_{H4}$), wasteful operation like this should be avoided.

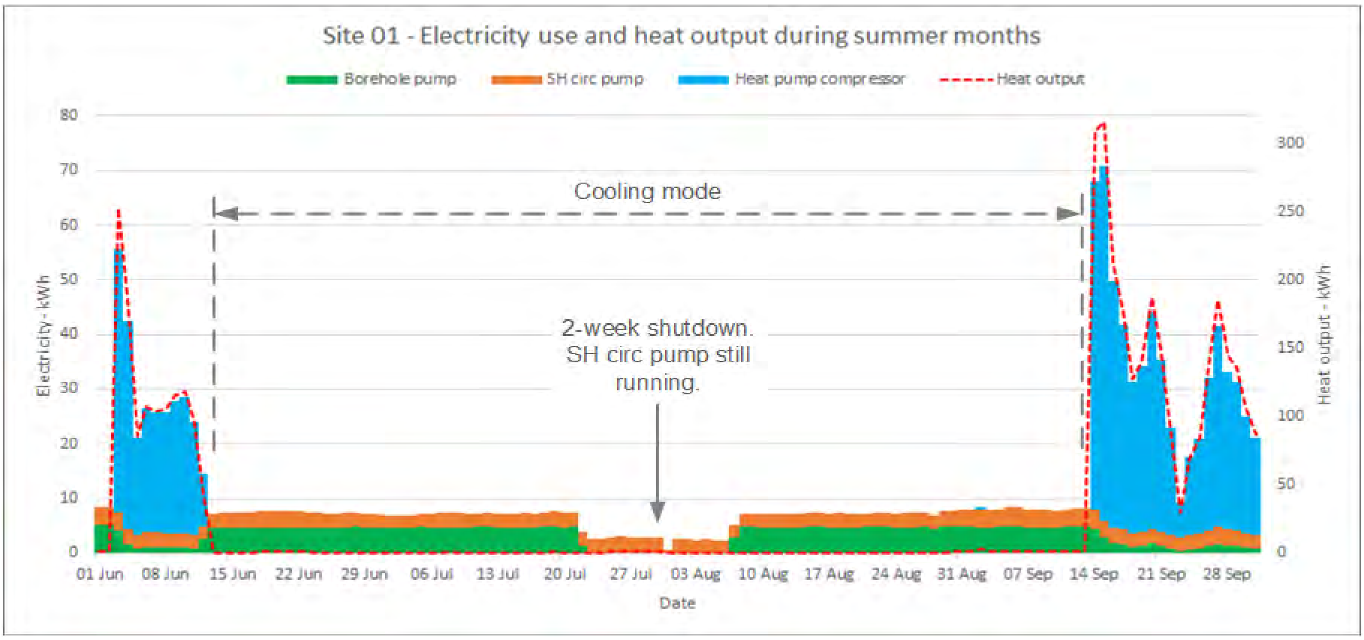

Figure 6 – Electricity use and heat output during the summer months

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 7 shows the pattern of operation on 5th January when the outdoor temperature was between 2 and 4 °C. The heat pump ran approximately four times every hour for periods of 8 to 15 minutes. This is within the limits recommended by previous research on cycling [1]. The source pump operated at the same time as the heat pump. The heating circulating pump ran continuously.

The temperature of the source water flow to the heat pump was between 10.5 and 11.0 °C, with the return to the river between 5.5 and 6.0 °C. The temperature drop of 5 °C through the evaporator indicates an appropriately sized source pump.

The temperature of the output from the heat pump was between 31 and 35 °C, with the return between 27 and 28 °C. The output from the buffer tank to the heating system was between 29 and 33 °C, with the return between 25.5 and 26.5 °C.

There was a loss of temperature through the 4-pipe buffer tank (between the heat pump output and the flow to the heating circuit) of 2 to 5 °C. The return to the heat pump was also 1 to 2 °C higher than the return from the heating circuit.

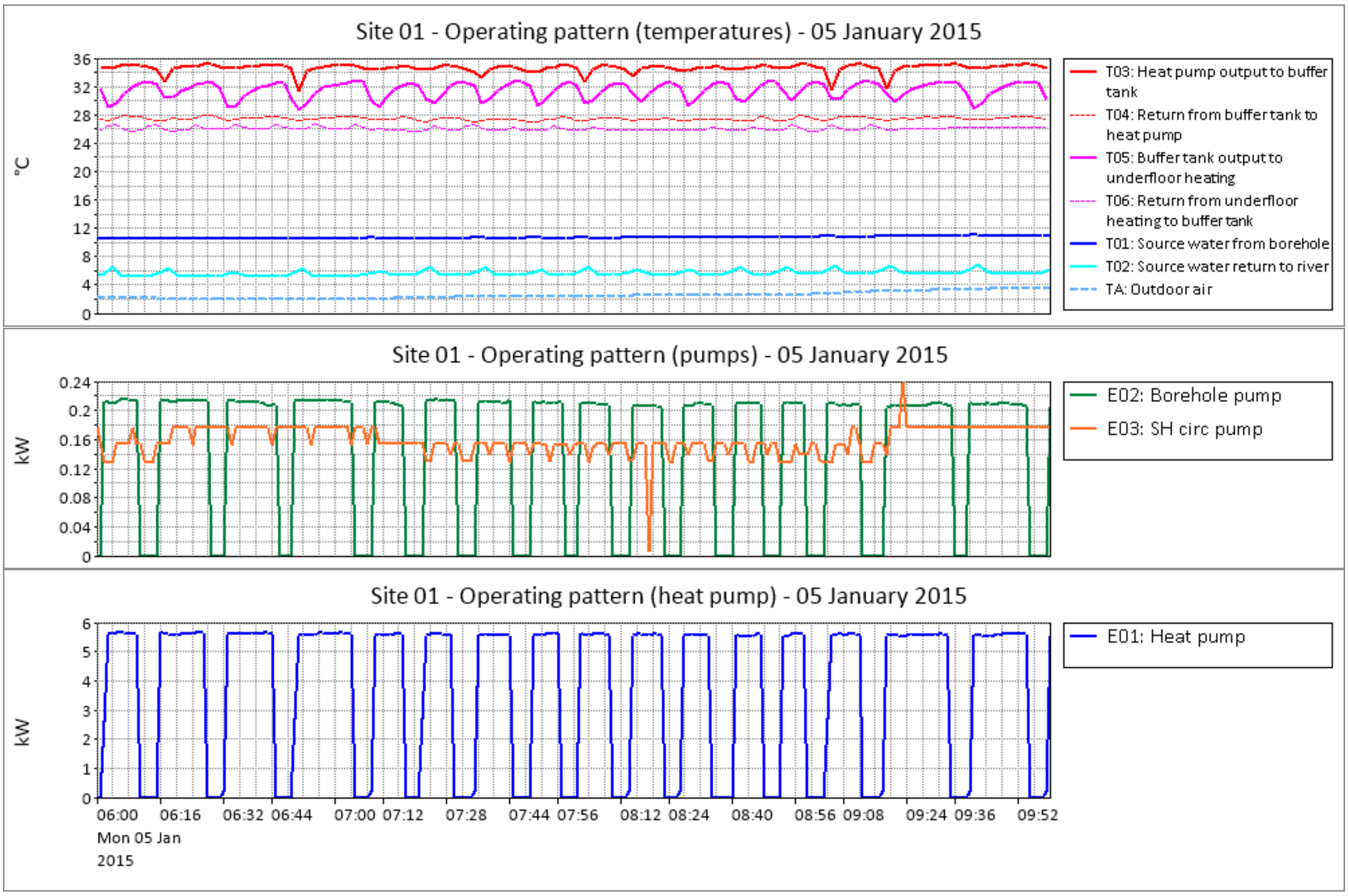

Figure 7 – Operating pattern on 5th January 2015

Figure 8 shows how the operating pattern on 4th June, when the outdoor temperature was between 8 and 19 °C. The pattern was very similar to that in January, but with heat pump run times of 4 to 7 minutes – shorter than recommended. The need for heating during June probably reflects the location of this site.

The temperature of the source water flow to the heat pump was between 11.0 and 12.5 °C, with the return to the river between 5.0 and 9.0 °C. The temperature of the output from the heat pump was between 28.5 and 33.5 °C, with the return between 24 and 26 °C. The output from the buffer tank to the heating system was between 26.5 and 29.5 °C, with the return between 22.5 and 24.5 °C. As in January, there was a loss of temperature through the buffer tank of between 2 and 5 °C.

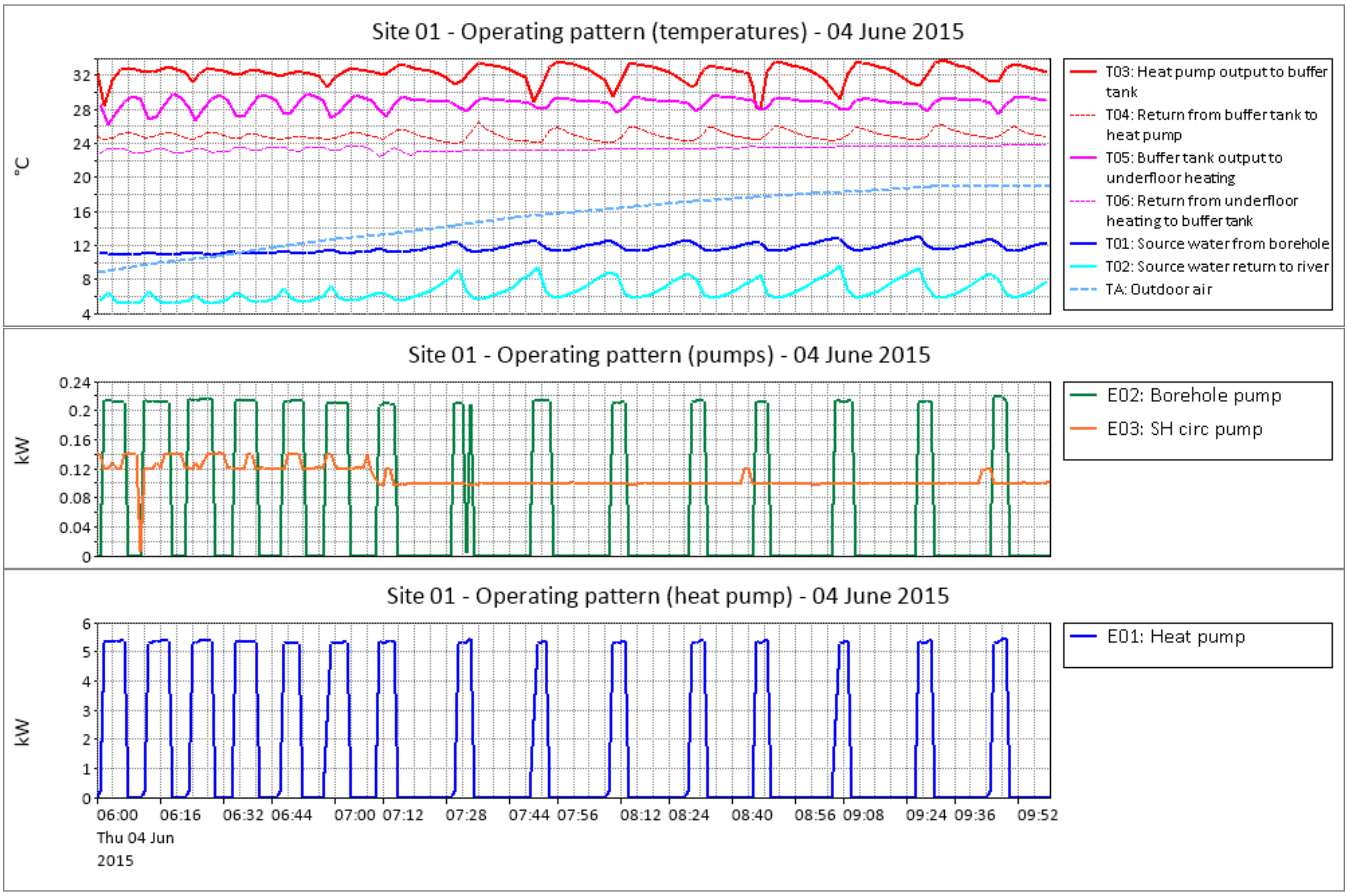

Figure 8 – Operating pattern on 4th June 2015

Source and sink temperatures

Figure 9 shows the principal temperatures of the source and the outputs from the heat pump, plotted over the year[6]. Note that the temperatures of the heat pump output and the flow to the underfloor pipes are shown only for times when the heat pump was running or when cooling was active.

It can be seen that the temperature of the heat pump output to the buffer tank (and of the output to the underfloor heating pipes) varied suddenly from time to time – on 22nd April when the output temperature dropped from 36 °C to 32 °C, 7th May (increase to 40 °C), 8th May (reduction to 33 °C), 14th September (increase to 36 °C), 23rd September (reduction to 32 °C), 28th November (increase to 35 °C) and finally on 17th December (reduction to 32 °C). The reason for these changes is unknown. The most likely explanation is that the thermostat on the buffer tank was adjusted for some reason. These changes in output temperature had a small effect on the daily SPF values, as can be seen by referring to Figure 3: the SPF$_{H2}$ and SPF$_{H4}$ values were lower when the output temperature was higher – as would be expected for a heat pump. This demonstrates how manual changes to system settings can have a negative impact on system performance.

The higher temperatures of the groundwater flow and return during cooling operation can be clearly seen during the summer months.

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[6] Temperatures of the heat pump system were recorded at 2-minute intervals.

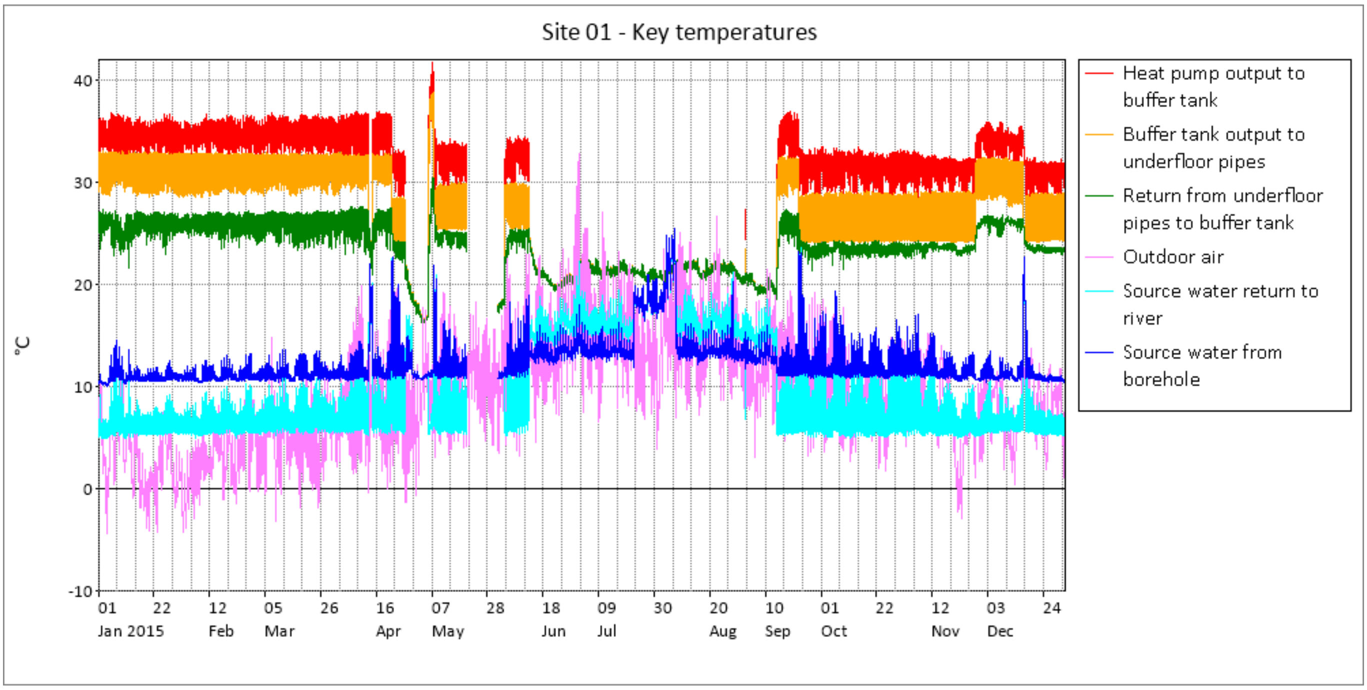

Figure 9 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 10 shows the daily mean source flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system are plotted in red. The gaps in the data correspond to periods when the heat pump was not in use.

It is also clear that this system benefits from a source temperature that is fairly constant throughout the year, and much higher than that of other systems during the winter. This would have had a positive influence on the system performance.

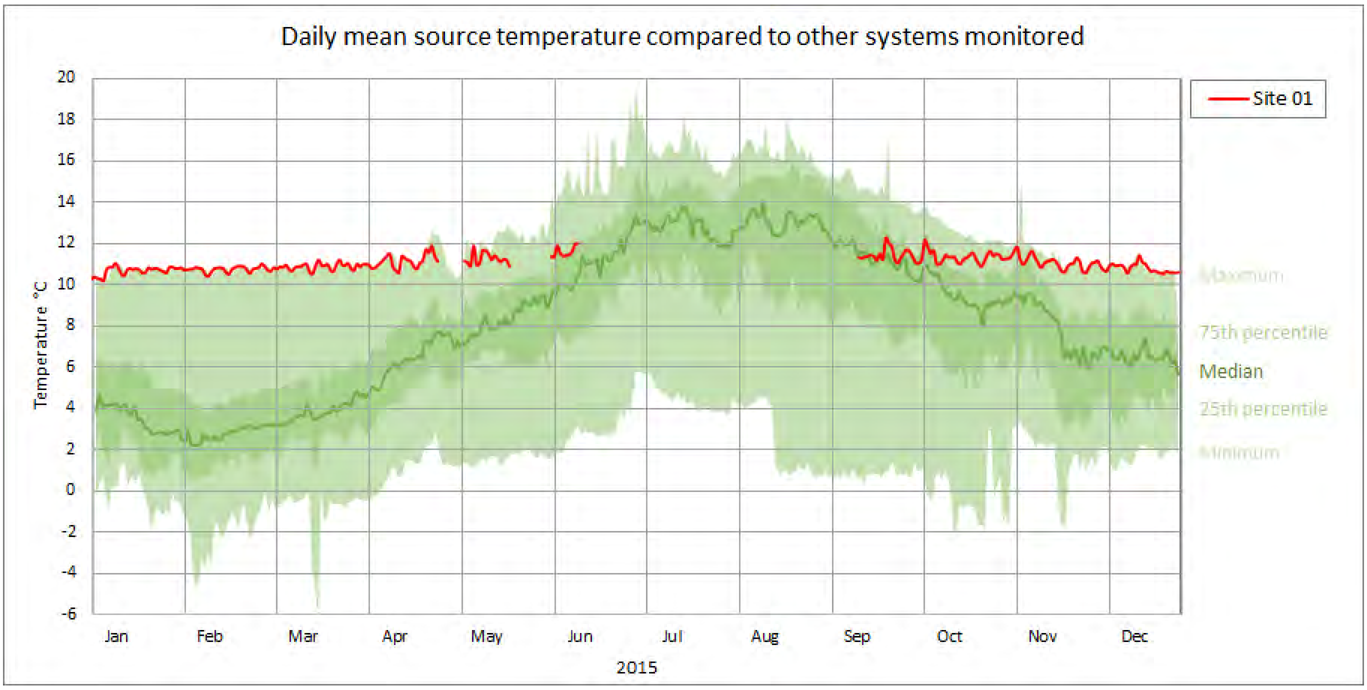

Figure 10 – Daily mean source flow temperature compared to the source temperatures of other systems monitored in this project (site 01 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were lower than for most other systems. This would have had a positive influence on the system performance.

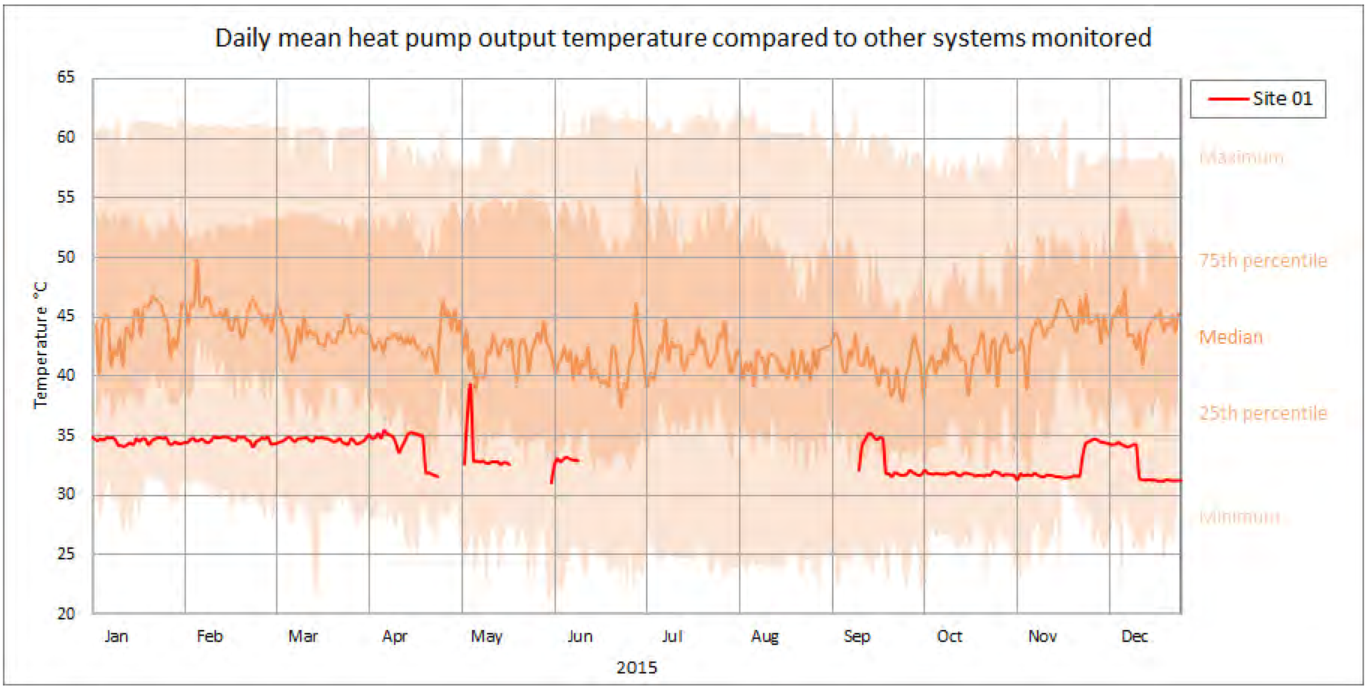

Figure 11 – Daily mean heat pump output temperature compared to those of other systems monitored in this project (site 01 is shown in red)

Weather compensation

Weather compensation was not used. It is understood from the system designer that the weather compensation function built into the heat pump was disabled because the sensor is located inside the heat pump casing and that it therefore would not operate correctly. Although weather compensation is used on many heat pump systems, it is not known whether its use on this system would yield any improvement in performance. Reducing the output temperature under low load conditions could exacerbate the short cycling behaviour and thereby negate any theoretical performance improvement.

Comments

The overall performance of this system (SPF_{H4} = 4.10) was high compared to other systems providing space heating only that were monitored in this project (SPF_{H4} range: 1.42 to 4.10, median value 2.23).

Aspects of this system that positively influenced its performance are:

- The temperature of the water from the source was always above 10 °C. This was the highest of all systems monitored during the winter months.
- The source water is pumped directly to the evaporator, without an intermediate heat exchanger which would introduce temperature loss.
- The heat pump output temperature was always below 40 °C. This was lower than on most other systems monitored.

These features provide very good operating conditions, by requiring a small temperature lift which yields good performance from the heat pump. There is nevertheless scope for improvement, as discussed below.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump run times were sometimes shorter than the minimum recommended by previous research [1]. Increasing the hysteresis of the buffer tank thermostat would allow the heat pump to run for longer and less frequently, giving a small increase in performance and reducing wear and tear on the equipment.
- The 4-pipe buffer tank introduced a temperature loss of up to 5 °C between the heat pump and the output to the heat emitters. It is possible that a different buffer tank arrangement would yield higher system performance. However, the design of buffer tank systems is a complex topic that is beyond the scope of this report.
- The heat pump was run during the night, although the building is presumably not occupied at night. (The night setback timeswitch did not seem to operate.) It would be worth altering the control strategy to inhibit operation of the heat pump at times when the building is unoccupied. A programmable thermostat would optimise the start and stop times according to the indoor and outdoor temperatures.
- Weather compensation was not used. It is not known whether the use of weather compensation would improve performance as reducing the heat pump output temperature under low load conditions would probably reduce the on time of each run cycle. If the run times were lengthened by other means, then weather compensation should give an improvement in performance.

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Case Study – Site 02

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Dr David Hughes asserts his moral right under the Copyright, Designs and Patents Act 1988 to be identified as the author of this work.

This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

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Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 02 and performance results from 12 consecutive months of monitoring data.

Site 02 is a grade A listed large house. A single heat pump (thermal capacity 93 kW) provides space heating only. Domestic hot water is provided separately using an immersion heater.

The heat source comprises 12 x 200 m horizontal loops at approximately 1.1 m depth, in a field near the house. The ground-collector manifold is approximately 150 m from the heat pump plant room.

The heat emitters are the radiators installed in 1999 for oil-fired central heating.

An oil-fired boiler (previously installed) is used for emergency back-up.

The seasonal heating performance factors measured over a year of operation
(1st January 2015 to 31st December 2015) were:

SPF_{H2}	[Heat delivered by the heat pump] --- [Electricity used by the heat pump + the brine pump]	3.43
SPF_{H4}	[Heat delivered by heat pump] + [heat added by buffer & SH circ pumps] – [buffer tank heat loss] --- [Electricity used by heat pump + brine and SH circulation pumps]	2.81

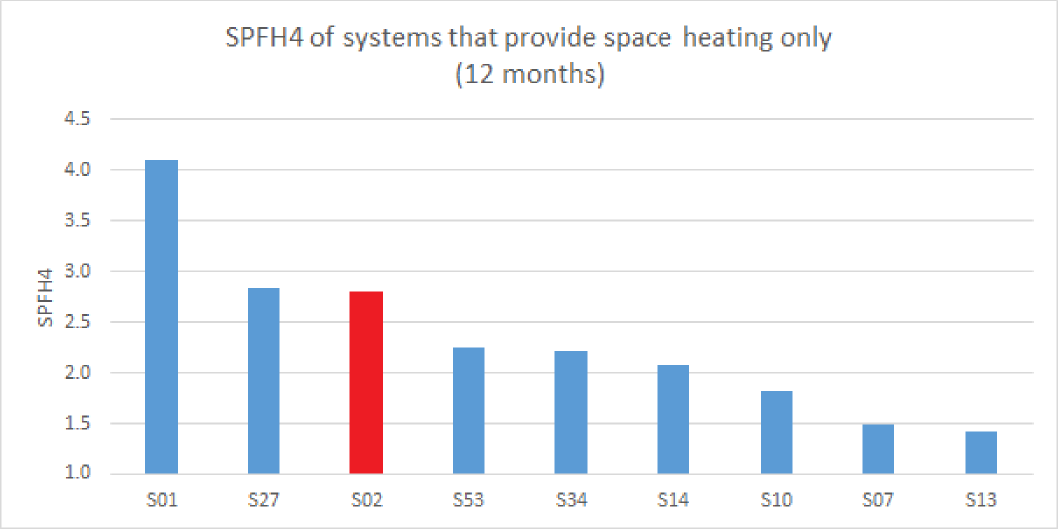


Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature when the outdoor temperature increased.
- No electric auxiliary heat was used.

Aspects of the system that may have negatively influenced its performance include:

- The brine pump used nearly 12% of the total electricity. (The median for other systems monitored in this project of 7.6%.)
- The heating circulating pumps accounted for 19% of the total electricity used. (The median figure for other systems monitored in this project was 8.8%.)

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	02
Survey date	08/04/2014
Monitoring installed	27/06/2014
G/WSHP	GSHP
Building type	Large house
Location	Rural
Heat pump capacity kWTH	93
Number of heat pumps	1
Heat source	Horizontal ground loops. 12 x 200m at 1.1m depth. Manifolds approx. 150m from the heat pump plant room.
Heat emitter	Radiators
DHW	No (provided by separate system)
Auxiliary heat	None (oil-fired boiler used for backup only)
Source pump	External to heat pump. 2.2kW
Buffer pump	External to heat pump. 390 W max
Buffer tank	1000 litre 2-pipe in flow
SH circulating pumps	External to heat pump. Total rating approx. 550W.
DHW cylinders	N/A
DHW cylinder coil shunt pump	N/A
DHW distribution pump	N/A
Control	Heat pump controller
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	1
Heat meter interface	Pulse (10 kWh / pulse)
Comments	Oil-fired boiler used for backup. This was used for a short period in January / February when there was a problem with the heat pump.

Table 1 – System details

The property is a grade A listed building. It has been insulated as best possible, with loft insulation and chimneys closed off with balloons. The sash windows have been draught-proofed and shutters and curtains have also been installed. Double-glazing is not permitted.

This application comprises a ground-source heat pump, retro-fitted in a building that is far from well insulated by current standards and is in a location that is colder than most of the other sites monitored – the mean outdoor temperature during the period monitored was 8.3 °C (the range for all sites was 8.1 to 12.5 °C, median 10.3 °C). The heat emitters used are radiators that were previously installed for use with an oil-fired boiler, and the pipe runs from the heat pump to the ground collector and to the radiators are long compared to most other systems. The seasonal performance factor of this system would not be expected to be as high as for many other installations.

Heat pump and monitoring systems

The heat pump plant is installed in a room in the basement of the house. It provides space heating (SH) only. Domestic hot water (DHW) is provided separately using an immersion heater.

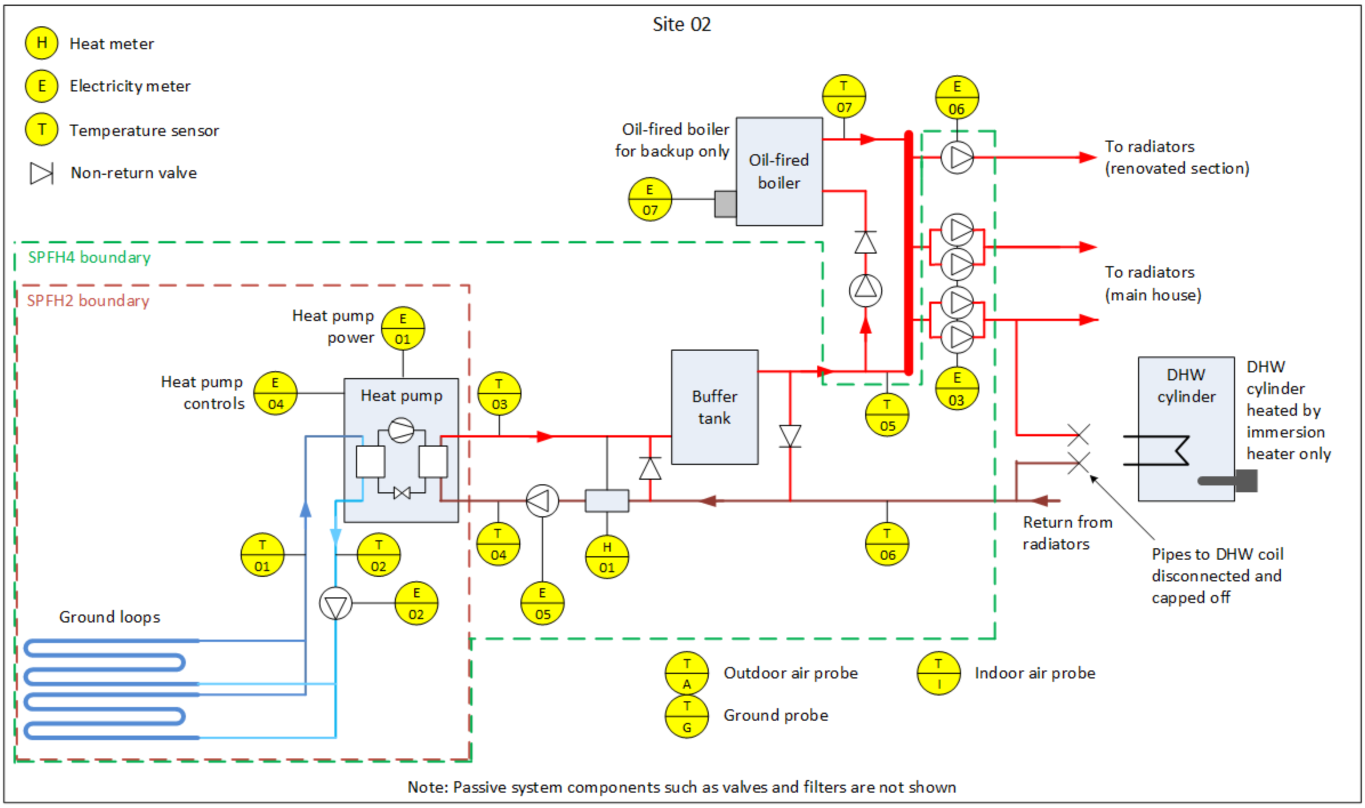
The heat pump supplies hot water via a 2-pipe buffer tank to a low-loss header, from where it is pumped to the heating circuits in the house.

One of the original 40 kW oil-fired boilers has been retained for backup duty.

The system is controlled by the heat pump controller, and was enabled 24 hours per day throughout the period monitored.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating (SH), and temperatures at key points in the system. The system boundaries for calculation of the seasonal performance factors SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1]. The outdoor air, ground and indoor temperatures are also monitored.



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses an ultrasonic flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is battery-powered, and monitoring was via the pulse interface.

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF$_{H1}$, SPF$_{H2}$, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF$_{H2}$ represents the performance of the heat pump together with the source pump.
- SPF$_{H4}$ represents the performance of the complete system, including the source pump, heating circulating pumps and excluding heat losses from the buffer tank.

Heat pumps achieving an SPF$_{H2}$ of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$\text{SPF}_{H2} = \frac{\text{[Heat measured by heat meter]} - \text{[heat added by buffer pump]}}{\text{Electricity used by: [heat pump]} + \text{[brine pump]}}$$

$$\text{SPF}_{H4} = \frac{\text{[Heat measured by heat meter]} - \text{[heat loss from buffer tank]} + \text{[heat added by SH circ pumps]}}{\text{Electricity used by: [heat pump]} + \text{[brine pump]} + \text{[buffer pump]} + \text{[SH circulating pumps]}}$$

---

[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer pump and SH circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 1:

SPF_{H2}	3.43
SPF_{H4}	2.81

Table 1 - SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 2.81 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

The number of 1-minute intervals selected as valid for analysis was 519 309, which represents 98.8% of the 12-month period.

The SPF_{H2} and SPF_{H4} values have been calculated on a daily basis. The daily performance of the system is shown in Figure 3.

The SPF_{H2} values increased from January to June as the ground temperature increased, and then decreased from September to December as the ground temperature reduced.

The SPF_{H4} values did not increase between January and June as much as the SPF_{H2} values. This can be explained by the SH circulating pumps running more or less continuously throughout the year, and thereby accounting for a higher proportion of the total electricity use during the warmer months when the heat demand was lower.

Both the SPF_{H2} and the SPF_{H4} values were low during the summer as a consequence of the heat pump running for only for very short periods. However, the heat demand during the summer was also low, so the effect on the overall annual performance was not very significant.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

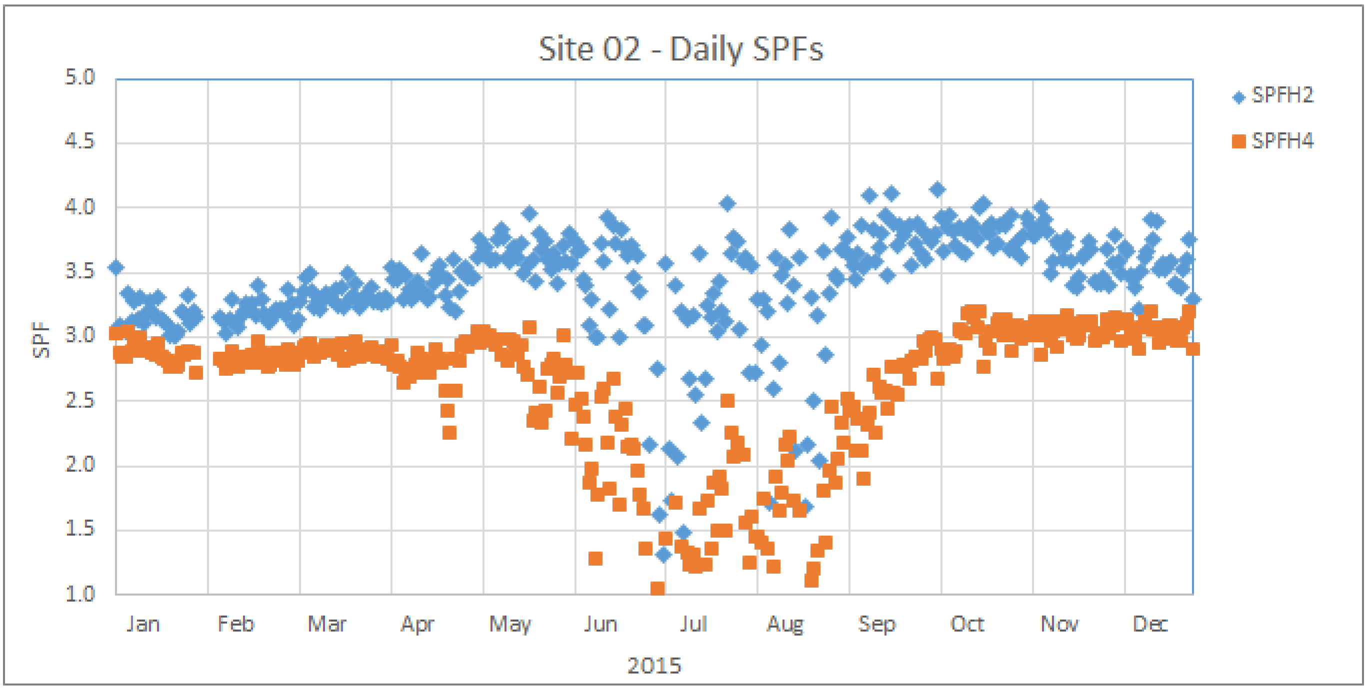

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source is the ground from which heat is being extracted and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the ground heat collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, in order to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output to space heating. The electricity used by the total heat pump system and the daily mean outdoor temperature are shown for reference.

It can be seen how the heat demand varied with outdoor temperature. There were only 3 days in 2015 when there was no demand for heat.

The gap in the heat demand curve from 28th January to 4th February was due to a fault[4] in the heat pump system. The backup oil-fired boiler was used during this period, and the heat output was not recorded by the heat meter.

The small amount of heat shown on the graph on the days when there was no output from the heat pump was from the circulating pumps which continued to run.

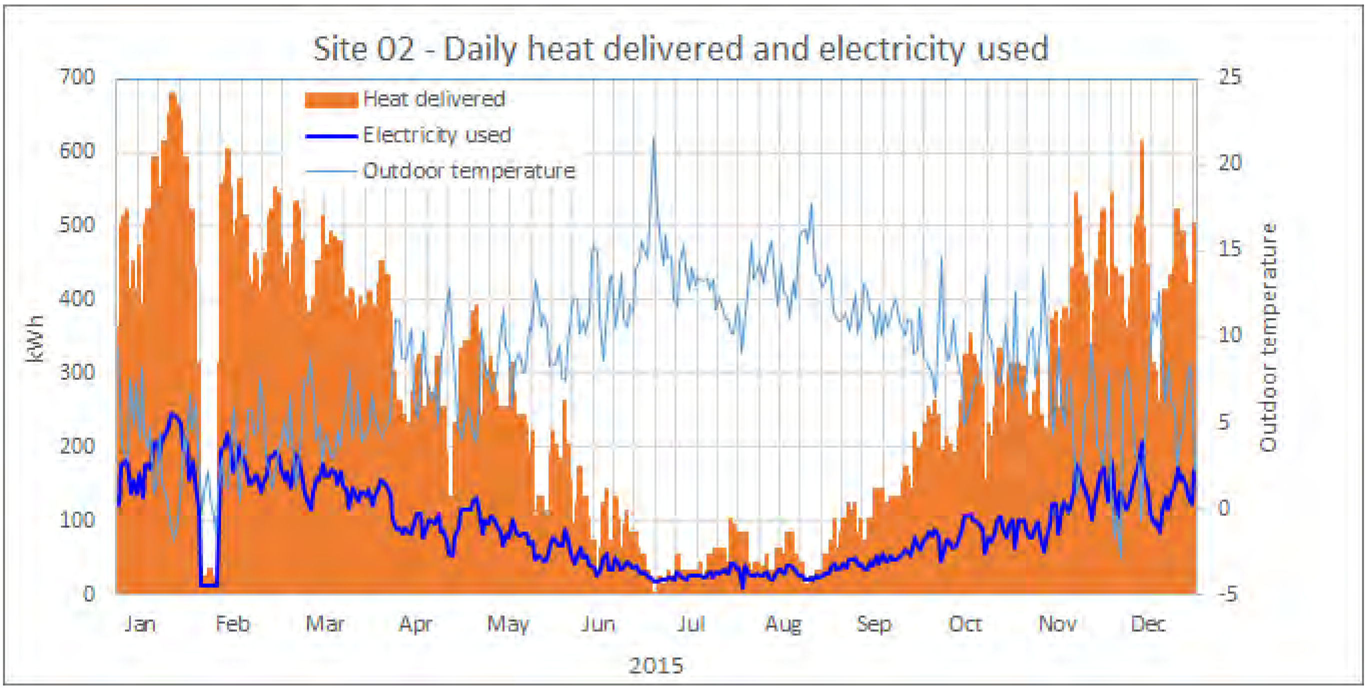

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The brine and heat circulating pumps account for relatively high proportions of the electricity used. This can be explained by the long pipe runs and large pumps consequentially needed.

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[4] The heat pump controller was inadvertently disturbed during maintenance of the monitoring equipment. The fault was easily rectified and apart from this incident the plant ran faultlessly.

The pipe run from the plant room to the manifold of the underground pipe loops is around 150 metres. The brine pump is rated at 2.2 kW and typically draws approximately 2.1 kW. It accounted for 11.7% of the total electricity use, which is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

The buffer pump and the heating circulating pumps have a combined power draw of approximately 950 W and accounted for 19.3% of total electricity. This is above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).

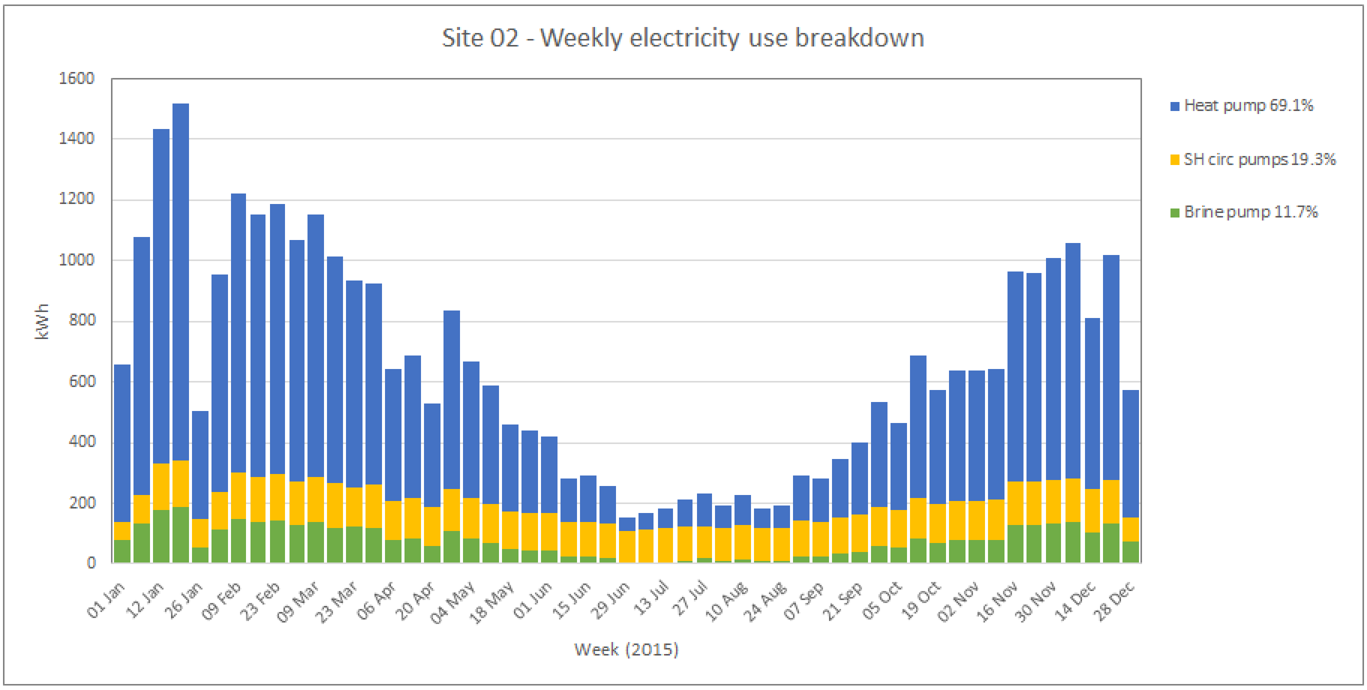


Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

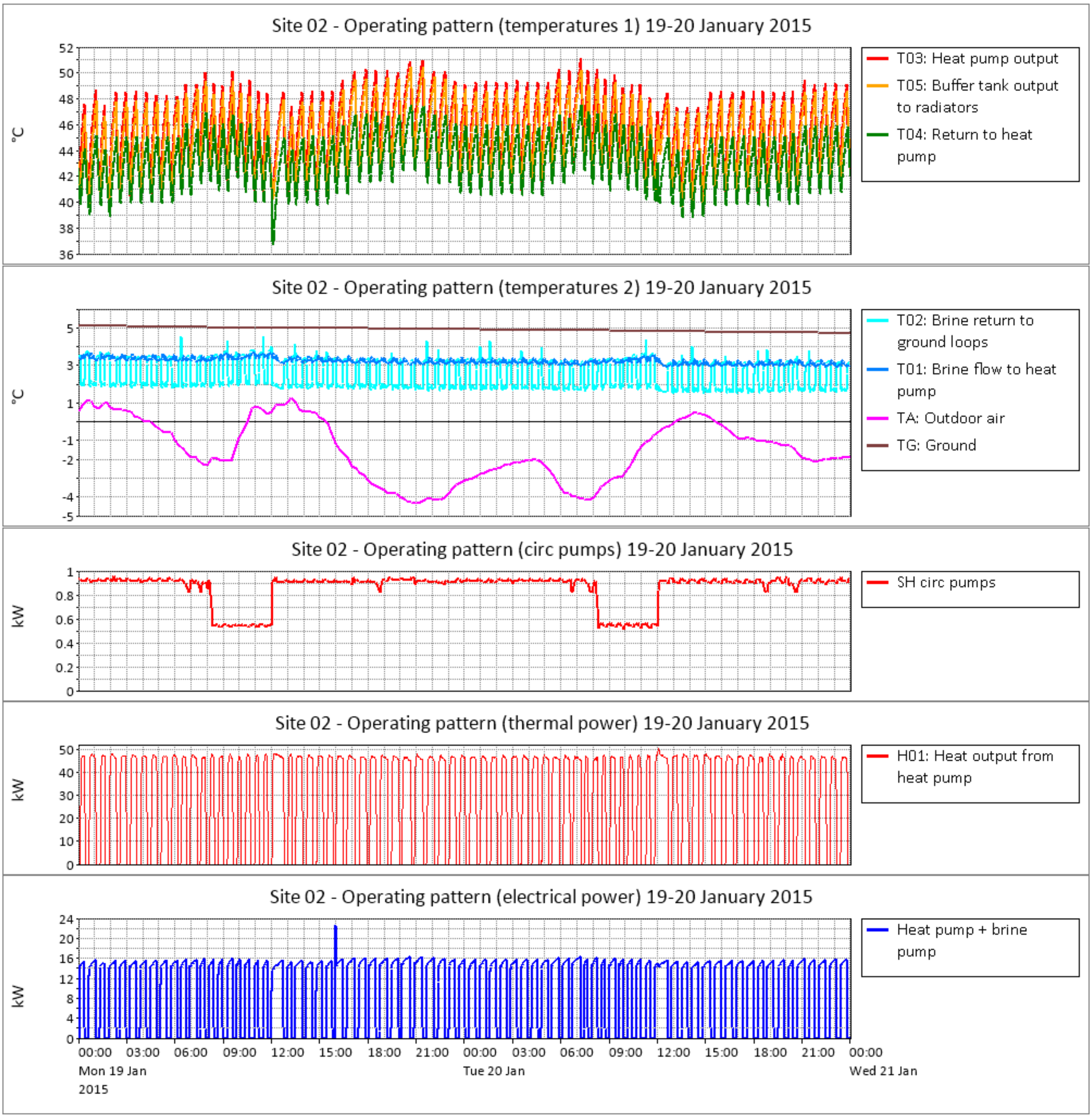
The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the typical pattern of operation during two days on 19th – 20th January 2015, when the outdoor air temperature was below zero for most of the time. The heat pump output temperature cycled between 40 and 51 °C. The temperature loss through the 2-pipe buffer tank was generally not more than 1 °C.

The temperature of the brine flow to the heat pump varied very little throughout the day – between 3.0 and 3.5 °C. The brine return temperature was between 1.9 and 2.1 °C while the heat pump was running. This is an unusually small temperature drop through the evaporator and suggests that a smaller brine pump could have been used.

The effect of the weather compensation can be seen: the heat pump output temperature was higher when the outdoor temperature was lower. This would have had a positive influence on the system performance. The influence of weather compensation on system performance is examined in more detail in the Final Report [3].

It is notable that one or more of the heating circulating pumps was switched off between 08:00 and 12:00 each day[5]. The heat pump run times were shorter during this period, with a reduction in heat output of approximately 20%. The reason for this reduction in space heating every morning is unknown.


Site 02 - Operating pattern (temperatures 1) 19-20 January 2015

Site 02 - Operating pattern (temperatures 2) 19-20 January 2015

Site 02 - Operating pattern (circ pumps) 19-20 January 2015

Site 02 - Operating pattern (thermal power) 19-20 January 2015

Site 02 - Operating pattern (electrical power) 19-20 January 2015

Figure 6 – Operating pattern on 19th – 20th January 2015

Figure 7 shows the pattern on 8th – 9th June when the outdoor temperature was between 4 and 17 °C.

The temperature of the brine flow to the heat pump was between 9.5 and 10.5 °C, with the brine return temperature generally just 2 °C lower.

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[5] This reduction in heating circulation between 08:00 and 12:00 occurred every day throughout the monitoring period.

The heat pump output temperature varied between 30 and 52 °C, with the effect of weather compensation being clearly seen: the output temperature was higher when the outdoor temperature was lower. The temperature loss through the buffer tank was not more than 1 °C.

The heat pump run times were relatively short: between 7 and 12 minutes. However, there was never more than one on/off cycle per hour so the system was generally operating within the cycling limits recommended by previous research [2].

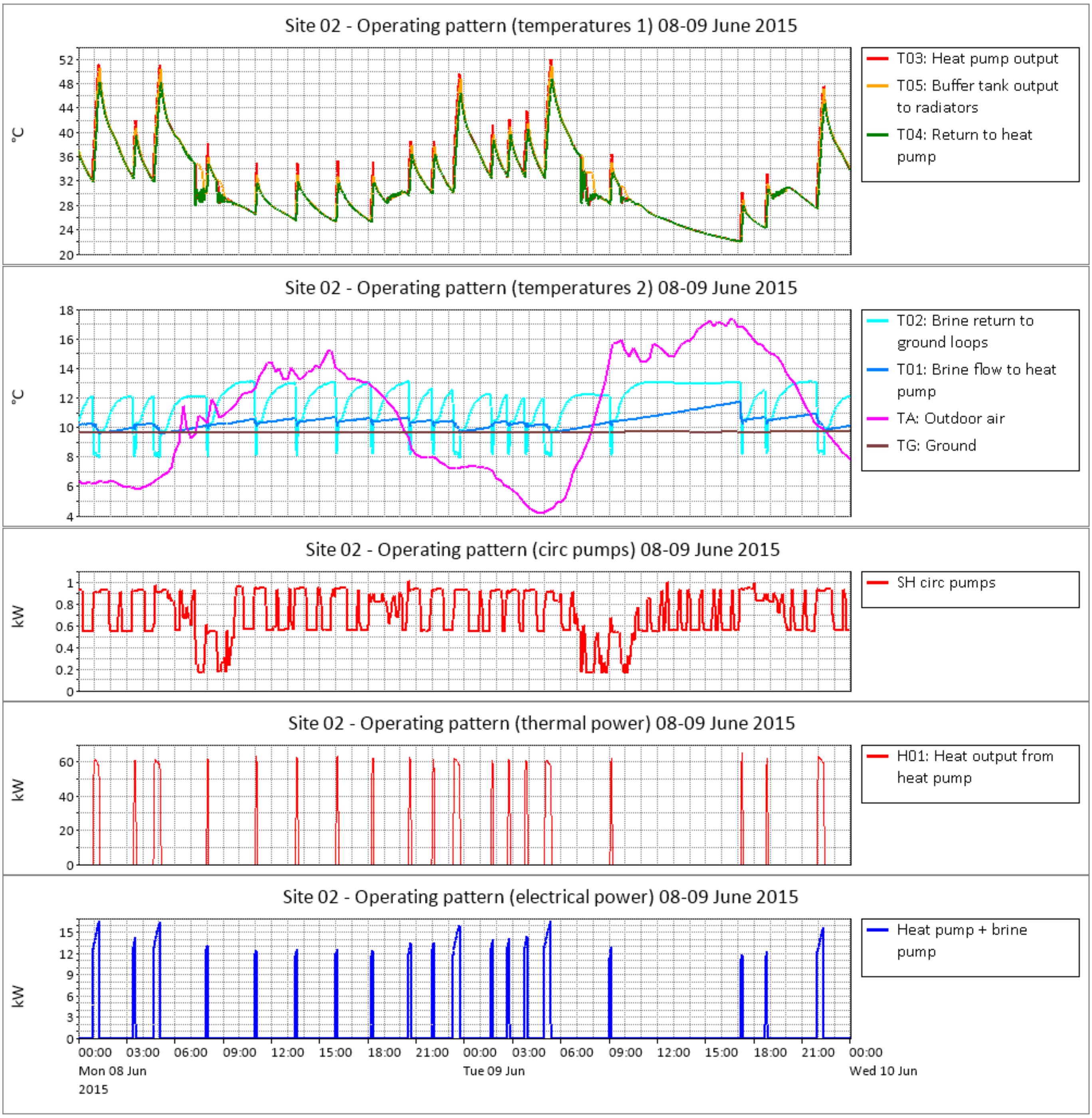

Figure 7 – Operating pattern on 8th – 9th June 2015

Source and sink temperatures

The principal temperatures of the outdoor air, ground, brine and the output from the heat pump are shown in Figure 8, plotted over the year[6]. The heat pump output temperature and the brine flow temperature are plotted only for times when the heat pump was running.

The ground collector appeared to work well, as the temperature of the brine at the input to the heat pump was rarely more than 2°C below the ground temperature[7] (although the brine pump may be oversized as noted above).

The output from the heat pump was rarely above 54 °C. Interestingly, the daily maximum output temperature often remained above 50 °C during warmer weather, because the night-time outdoor temperature was generally quite low – often below 5 °C. However, the weather compensation function reduced the output temperature during each day (as can be seen in Figure 7).

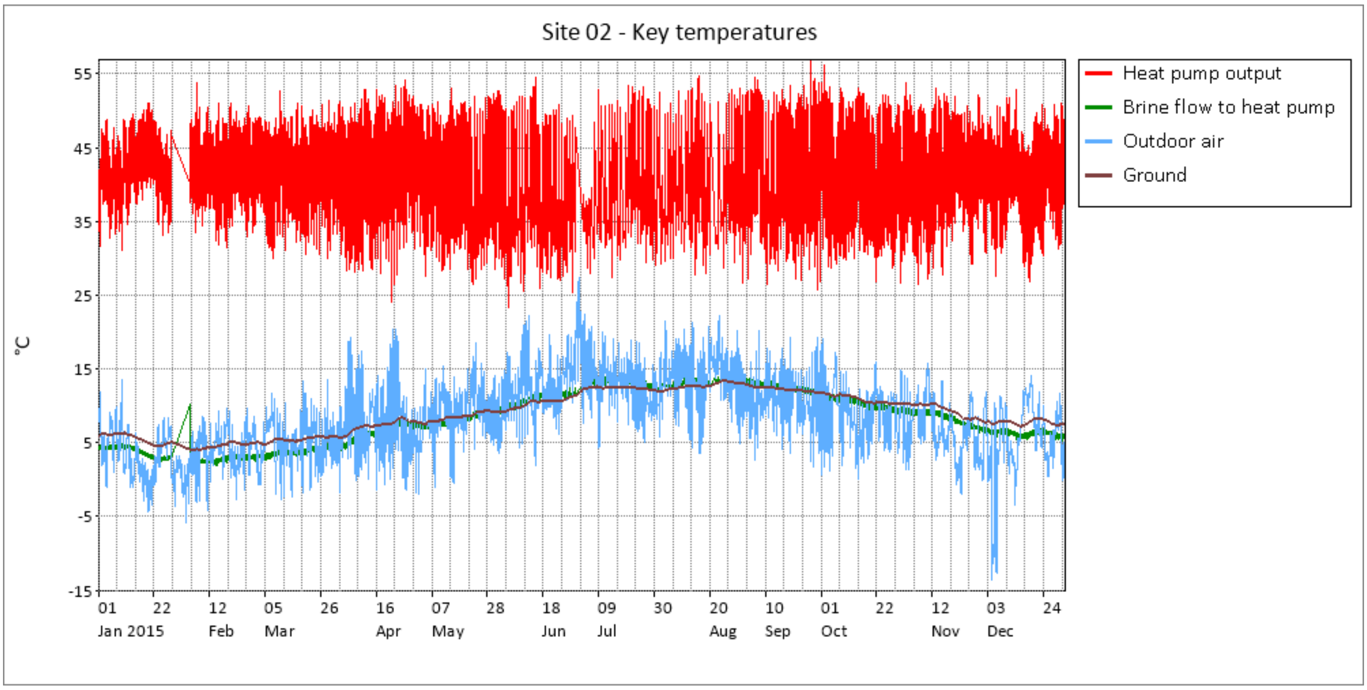

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were average compared to other systems.

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[6] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

[7] The ground temperature was measured 1m below the surface, in an area of the field remote from the ground collector loops

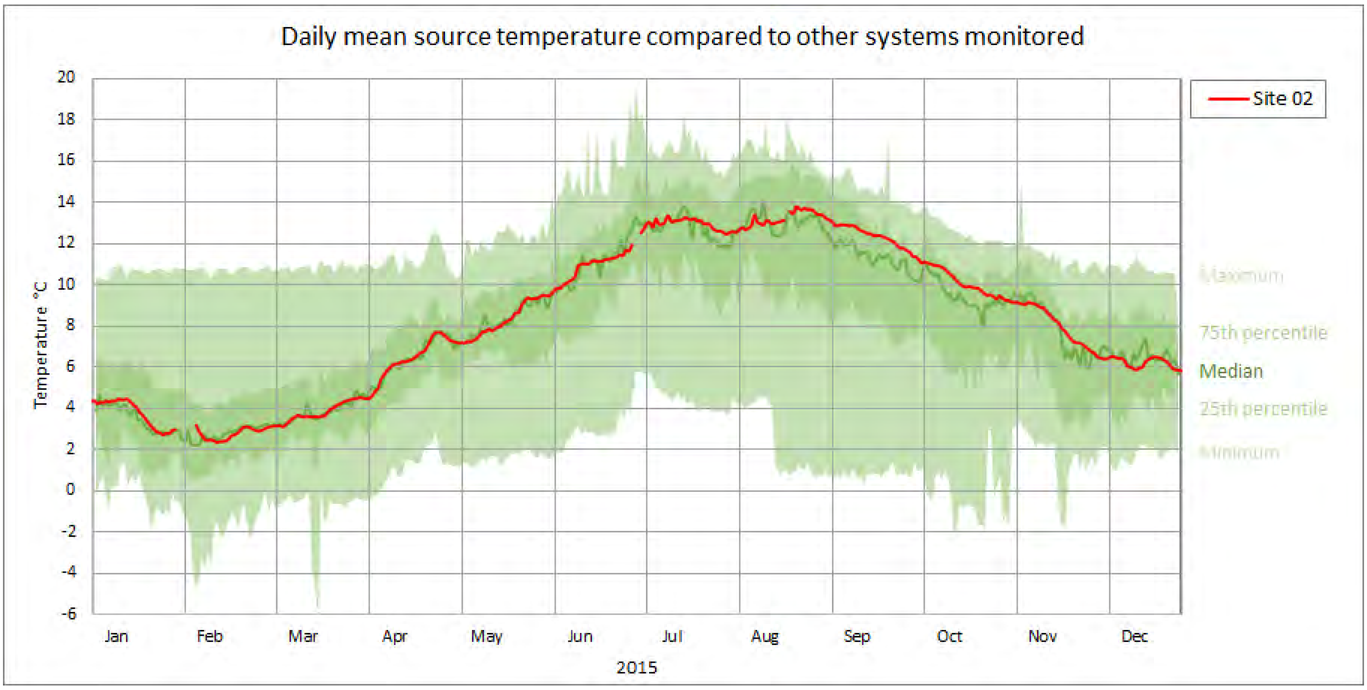

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 02 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The relatively low temperature difference on this system indicates good collector performance.

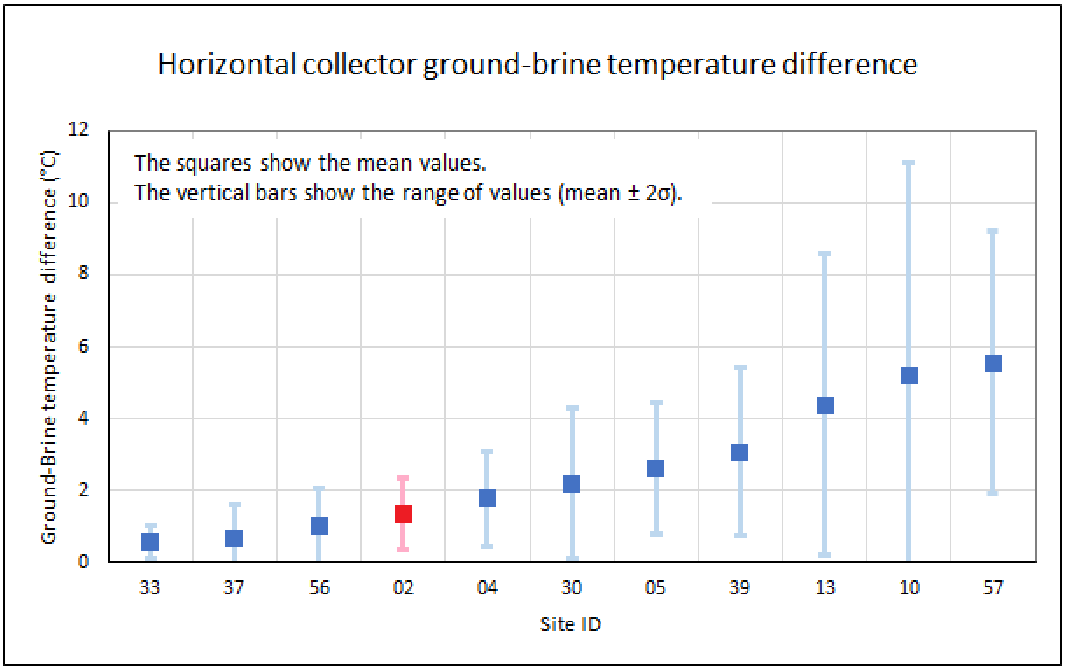

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 02 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system (plotted in red) were average compared to other installations.

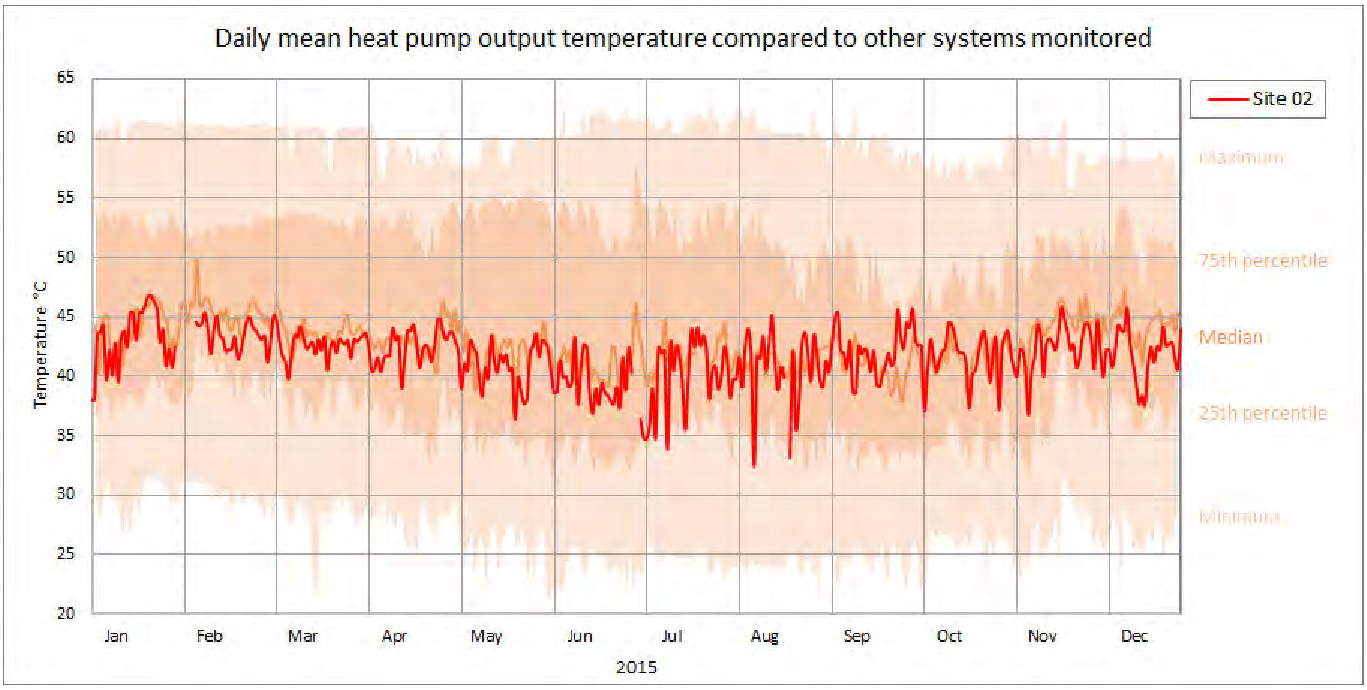

Figure 11 – Daily mean heat pump output temperature (to SH) compared to those of other systems monitored in this project (site 02 is shown in red)

Comments

The overall performance of this system (SPF_{H4} = 2.81) was above average compared to other systems providing SH only that were monitored in this project (SPF_{H4} range: 1.42 to 4.10, median value 2.23).

This performance was good, considering the difficult environment in which the system operates:

- The mean outdoor temperature during 2015 was 2 °C lower than at other sites monitored in the project.
- The grade A listed building cannot be insulated to a high standard.
- The brine and heating pipe runs are long.

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature when the outdoor temperature increased.
- No electric auxiliary heat was used.

Aspects of the system that may have negatively influenced its performance include:

- The brine pump used nearly 12% of the total electricity. (The median figure for other systems monitored in this project was 7.6%.) The 2.2 kW pump appears to be oversized, as the brine temperature drop through the evaporator was rarely more than 2 °C compared to a more usual figure of 3 °C. A smaller brine pump of say 750 W should provide a brine flow rate 70% that of the current arrangement. The evaporator temperature in the heat pump would then drop by about 1 °C which would cause a small drop in the coefficient of performance (COP). The combined effects would be an improvement in the overall SPF_{H4} of around 5%.

- The heating circulating pumps accounted for 19% of the total electricity used. (The median figure for other systems monitored in this project was 8.8%.) Variable-speed or lower power pumps might be adequate for this installation. If the energy used by these pumps could be reduced by 50%, and allowing for an increase in the condensing temperature in the heat pump of about 1 °C which would cause a small reduction in the COP, the SPF_{H4} would improve by around 7%.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps – Final Report,” BEIS, 2018.

[4] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[5] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 04

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study provides a brief description of the heat pump installation at Site 04 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 04 is a large 18th century house in a rural setting. Two ground-source heat pumps with a combined thermal capacity of 57 kW provide space heating via radiators and domestic hot water.

The heat source is 8 x 100 m horizontal ground loops at a depth of approximately 1.2 m, in a field near the house. The pipe run from the ground collector manifold to the heat pumps is approximately 100 m.

The heat emitters are radiators, which were not increased in size since previously used with an oil-fired boiler. There are 2 domestic hot water cylinders, each with 2 x 3 kW immersion heaters.

Seasonal performance factors are not presented because characteristics of the heat meters, previously installed for the Renewable Heat Incentive and used to monitor this system, have led to unacceptably high uncertainties of measurement of the heat delivered.

Aspects of this system that positively influenced its performance are:

- The brine flow temperature was generally above average compared to other systems monitored.
- Auxiliary heat was not used (except for a short period because of a fault).

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the heat pump output to space heating was generally high – in the upper quartile of the temperature range of all systems monitored.
- The brine pump used 11.4% of the total electricity used by the heat pump system – above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- Weather compensation was not used.

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[1] Incorrect heat meter installation on this system is likely to cause unacceptably large measurement errors and the performance values could therefore not reliably be determined.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
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GSHP	Ground-source heat pump
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kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	04
Survey date	06/04/2014
Monitoring installed	23/06/2014
G/WSHP	GSHP
Building type	Large house (18th century)
Location	Rural
Heat pump capacity kWTH	57
Number of heat pumps	2
Number of compressors	4 (2 in each heat pump)
Heat source	Horizontal ground loops 8 x 100m at 1.2m depth
Heat emitters	Radiators
DHW	Yes
Auxiliary heat	4 x 3kW immersion heaters in DHW cylinders
Source pump	External to heat pumps: 1 pump of 1 kW
SH circulating pump	3 pumps of 345W max; 1 pump of 50W max
DHW circulating pump	1 pump of 50W max
Buffer tank	None
DHW cylinders	2 x 300 litre
Control	Heat pump controllers + heating programmer
Weather compensation	No
Heat meter type	Ultrasonic
No. of heat meters	2
Heat meter interface	Pulse (10 kWh / pulse)
Comments	

Table 1 – System details

The site is an 18th century house, in a rural location. It is occupied by up to 20 people.

This application comprises a ground-source heat pump, retro-fitted in a building that is not well insulated by current standards (no double glazing, no wall or loft insulation) and is in a location that was colder than any of the other sites monitored – the mean outdoor temperature during the period monitored was 8.1 °C (the range for all sites was 8.1 to 12.5 °C, median 10.3 °C). The heat pump provides space heating via radiators and domestic hot water. Both of these require relatively high heat pump output temperatures. The pipe run from the ground collector to the heat pump plant room is relatively long. The seasonal performance factor of this system would not be expected to be as high as for many other installations.

Heat pump and monitoring systems

Two heat pumps (total thermal capacity 57 kW) were installed in 2011. One high-temperature heat pump provides domestic hot water or space heating as required. The other heat pump provides space heating only.

The heat source is 8 x 100 m horizontal ground loops at a depth of approximately 1.2 m, in a field near the house. The pipe run from the ground collector manifold to the heat pumps is approximately 100 m.

The heat emitters are radiators, which were not increased in size since previously used with an oil-fired boiler that dated from before 1974. No buffer tank is installed.

There are 2 domestic hot water cylinders, each with 2 x 3 kW immersion heaters.

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and to domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPF$_{H2}$ and SPF$_{H4}$ are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2]. The outdoor air and ground temperatures are also monitored.

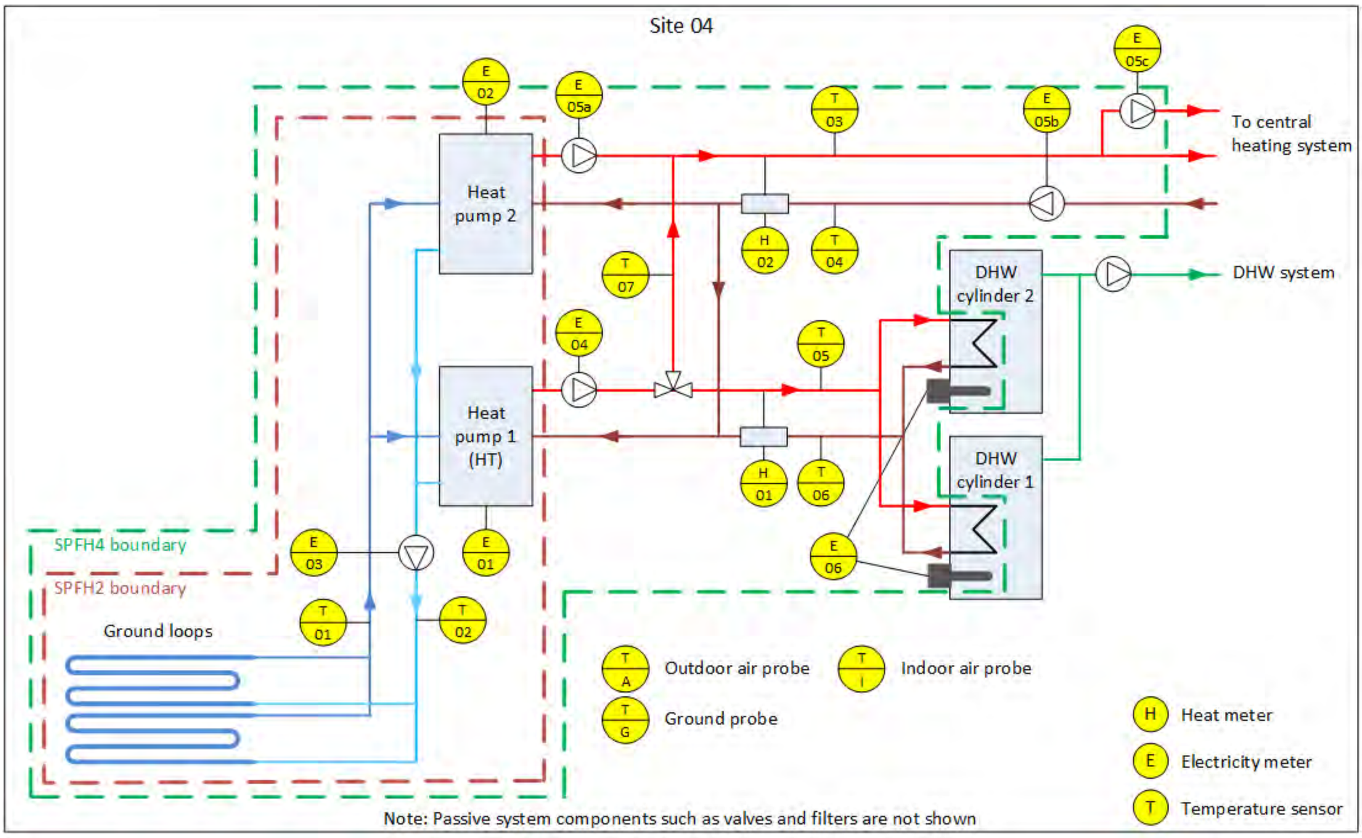

Figure 1 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meters previously installed to meet RHI metering requirements were the only available means of recording the heat output of the heat pump. Unfortunately, these meters were not correctly installed and it has not been possible to use the measurements to determine the system performance with any useful degree of accuracy. The flow meters used are of the mechanical multi-jet turbine type and the temperature sensors have been strapped to the outside of the pipes, with a minimal covering of insulation – instead of being installed in fittings in the pipes. The leads connecting the platinum-resistance temperature probes to the battery-powered calculators have been extended, contrary to the manufacturer's installation instructions. Monitoring was via the pulse interfaces.

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[2] The temperature probes were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [5] for further details. Note that these temperature measurements were not used for heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and immersion heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counters connected to the heat meters were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat measured by heat meters]} - \text{[heat added by SH circ pumps]}}{\text{Electricity used by: [heat pumps]} + \text{[brine pump]}}$$

$$SPF_{H4} = \frac{\text{[Heat measured by heat meters]} + \text{[heat added by immersion heaters]} + \text{[heat added by heating circ pumps]}}{\text{Electricity used by: [heat pumps]} + \text{[brine \& SH circ pumps]} + \text{[immersion heaters]}}$$

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pumps.

The number of 1-minute intervals selected as valid for analysis was 525 574, which represents 99.99% of the 12-month period

SPF results presented as relative values

Because of the heat metering issues noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors SPF_{H2} and SPF_{H4} are therefore presented in this case study as "relative" values, whereby each value is shown as an amount above or below a nominal performance.

Figure 2 shows the daily SPF_{H2} and SPF_{H4} behaviour of the system[5]. These values represent the combined space heating + domestic hot water performance. The lower values during the summer months were a consequence of the system providing domestic hot water only. This required higher output temperatures than for space heating, and the performance was therefore lower. However, the total heat output during the summer was quite low, so this did not significantly affect the annual SPF values.

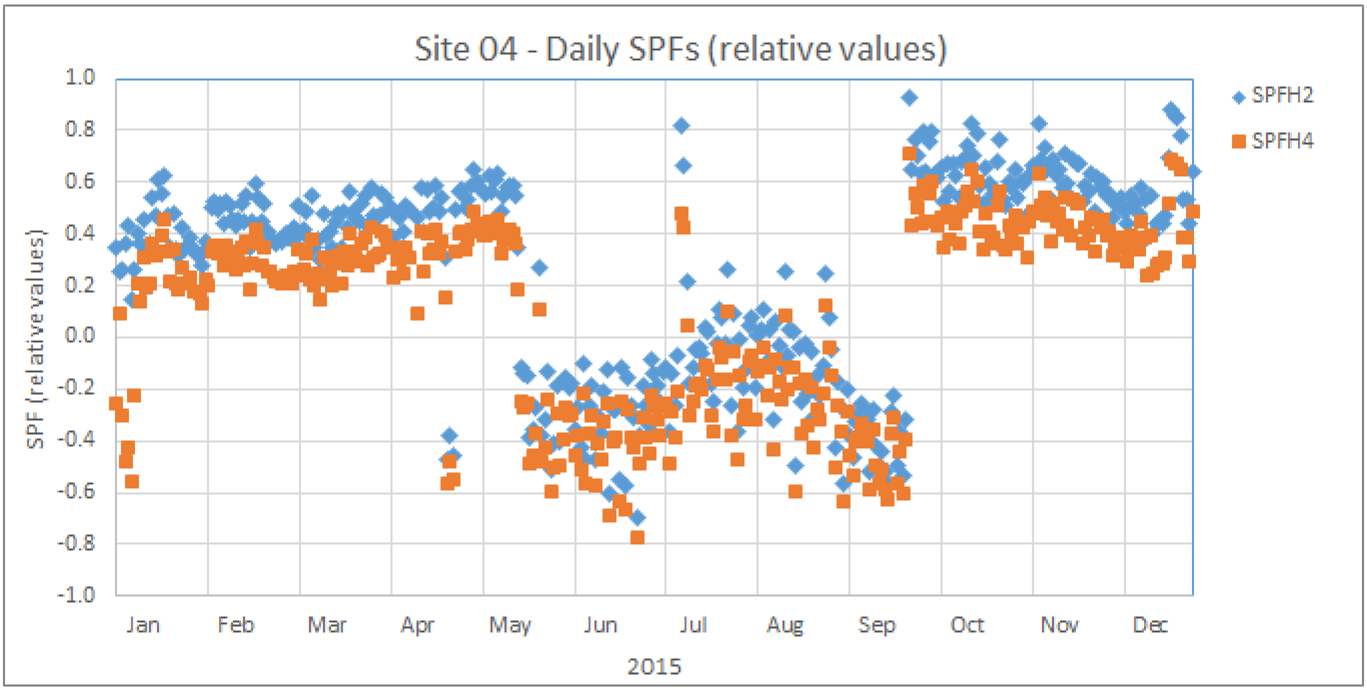

Figure 2 – Daily relative seasonal performance factors SPF_{H2} and SPF_{H4}

Figure 3 shows the daily SPF_{H4} behaviour for operation in space heating mode and in domestic hot water mode. The performance in domestic hot water mode is always lower than in space heating mode because of the higher output temperature.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[5] The actual values are not shown because of the high uncertainty of measurement of the heat metering on this system. Relative values are shown to give some indication of the scale of the behaviour.

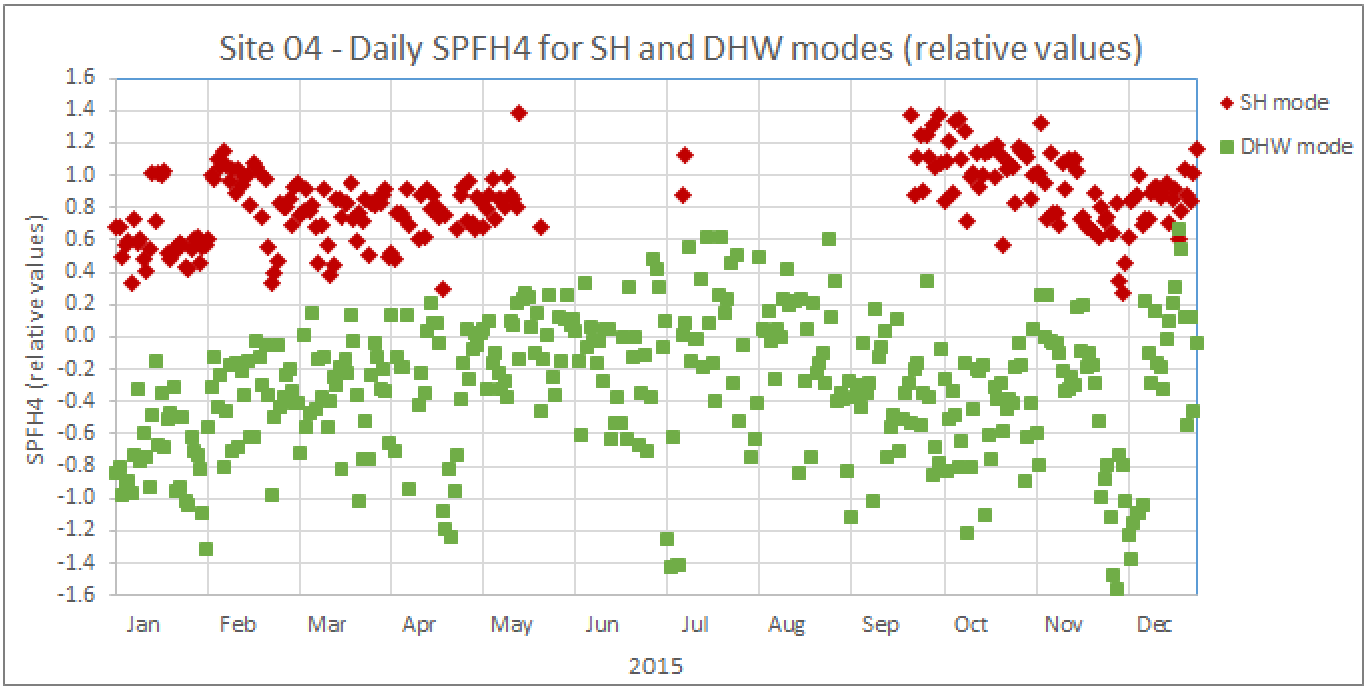

Figure 3 – Daily SPFH4 relative values for SH mode and DHW mode

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to circulate brine through the ground collector, and to circulate hot water from the heat pump to the space heating emitters and to the heating coils in the domestic hot water cylinders. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on the various factors, particularly outdoor temperature.

Figure 4 shows the daily heat output from the heat pump and from the immersion heater in the domestic hot water cylinder. The electricity used by the total heat pump system and the daily mean outdoor temperature are shown for reference. Note that the kWh values have been removed from the graph because of the high uncertainty of measurement of the heat meters.

The daily domestic hot water load was fairly constant throughout the year. The heat delivered to space heating was greatest at the times when the outdoor temperature was lowest as could be expected. The domestic hot water immersion heaters were used during the first few weeks of January as backup because of a fault in the high-temperature heat pump. Apart from this, the immersion heaters were used only once, for an hour on 11th July.

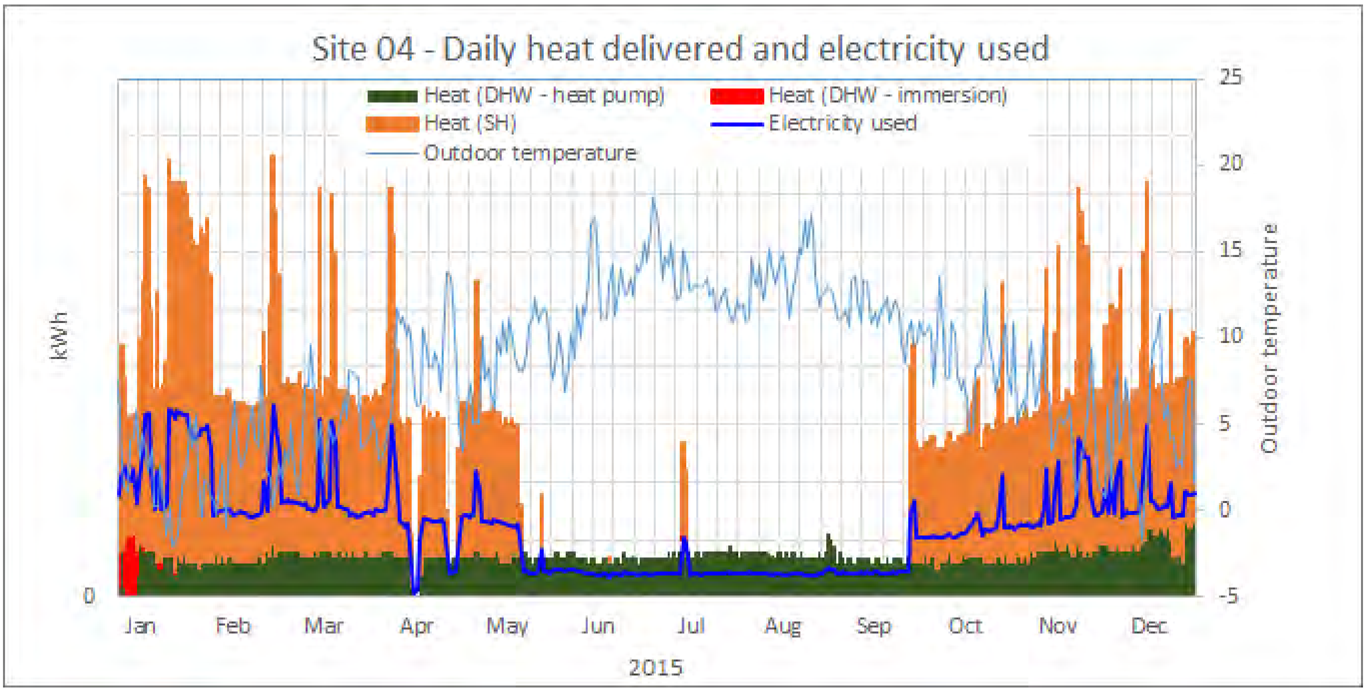

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

Table 2 shows the breakdown of the heat delivered to space heating and to domestic hot water during the period from 1st January to 31st December 2015.

	%
Heat delivered to space heating	73%
Heat to domestic hot water (from heat pump)	26.5%
Heat to domestic hot water (from immersion heaters)	0.5%

Table 2 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. It can be seen that the brine pump and the heat circulating pumps together used 17.7% of the total electricity used by the heat pump system.

The brine pump used 11.4% of the total electricity, above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

The heating and hot water circulating pumps used 6.3% of the electricity, below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).

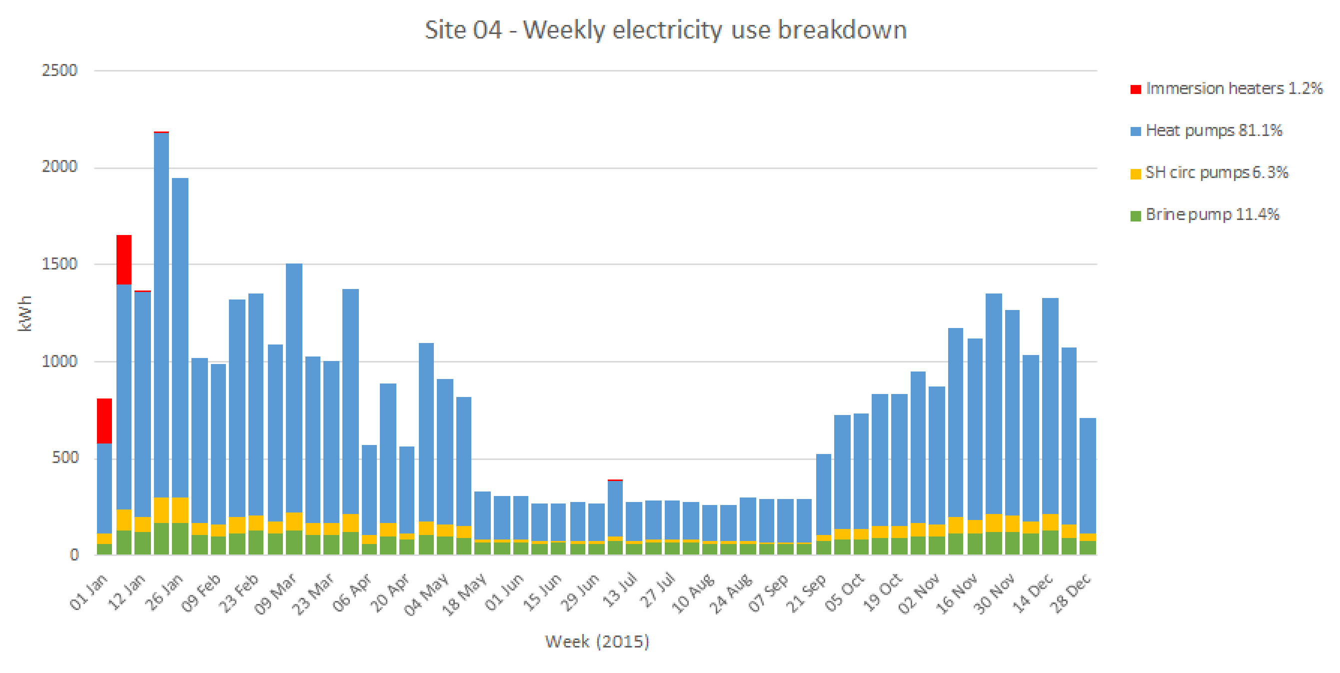

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern during a 2-day period on 17th – 18th January when the outdoor temperature was between -4 and +2 °C. The domestic hot water immersion heaters were not used. The temperature of the output to the space heating radiators was between 47 and 52 °C (at times when there was demand for space heating). The output to the domestic hot water heating coils was up to 53 °C.

The ground temperature, measured at a depth of 1 metre in the garden beside the house was 6.5 °C. The brine flow temperature, when only the smaller high-temperature heat pump was running, was between +5 and +7 °C, and when both heat pumps were running it was never lower than 4 °C.

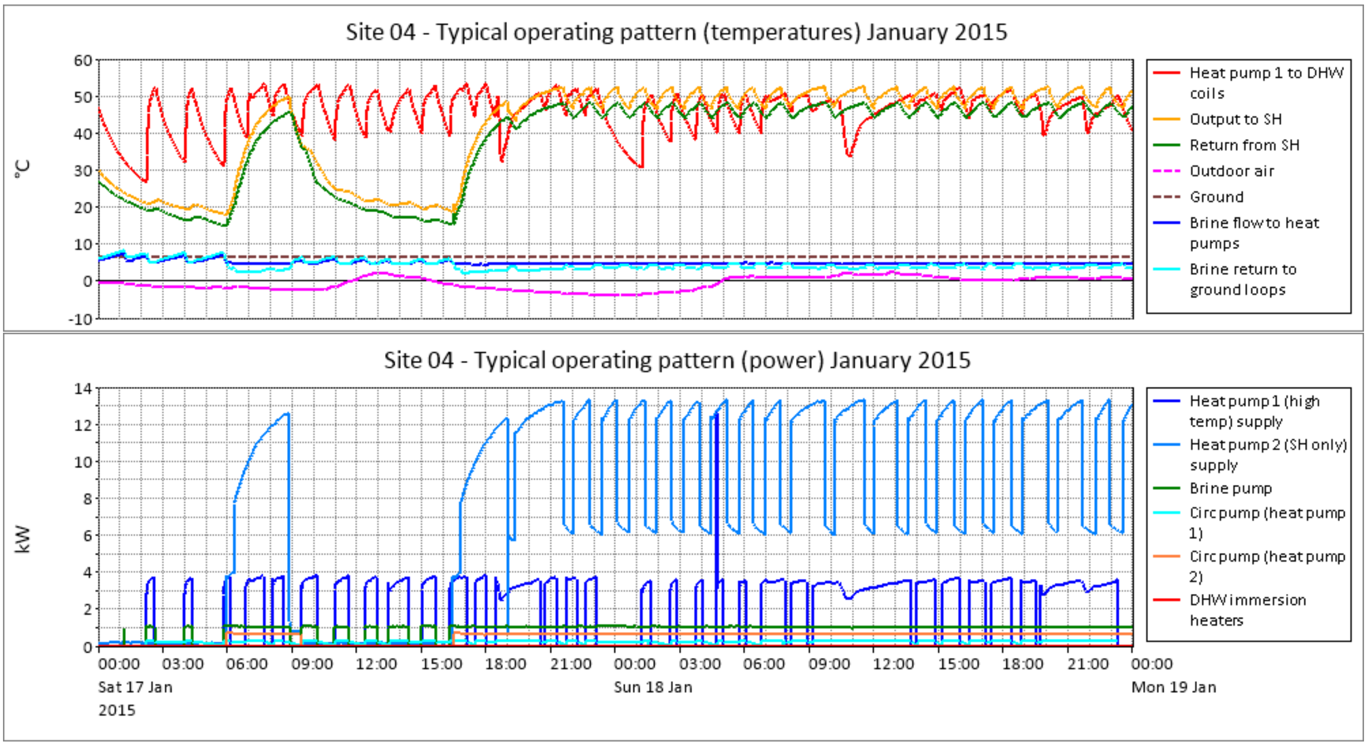

Figure 6 – Operating pattern on 17th – 18th January 2015

Figure 7 shows the typical summer operating pattern on the 14th July when the outdoor temperature was between 10 and 18 °C. Only the high-temperature heat pump was used to provide domestic hot water, with a maximum heat pump output temperature of 51 °C.

The heat pump ran 3 times an hour for approximately 7 minutes each time. This is within the cycling limits recommended by previous research [2].

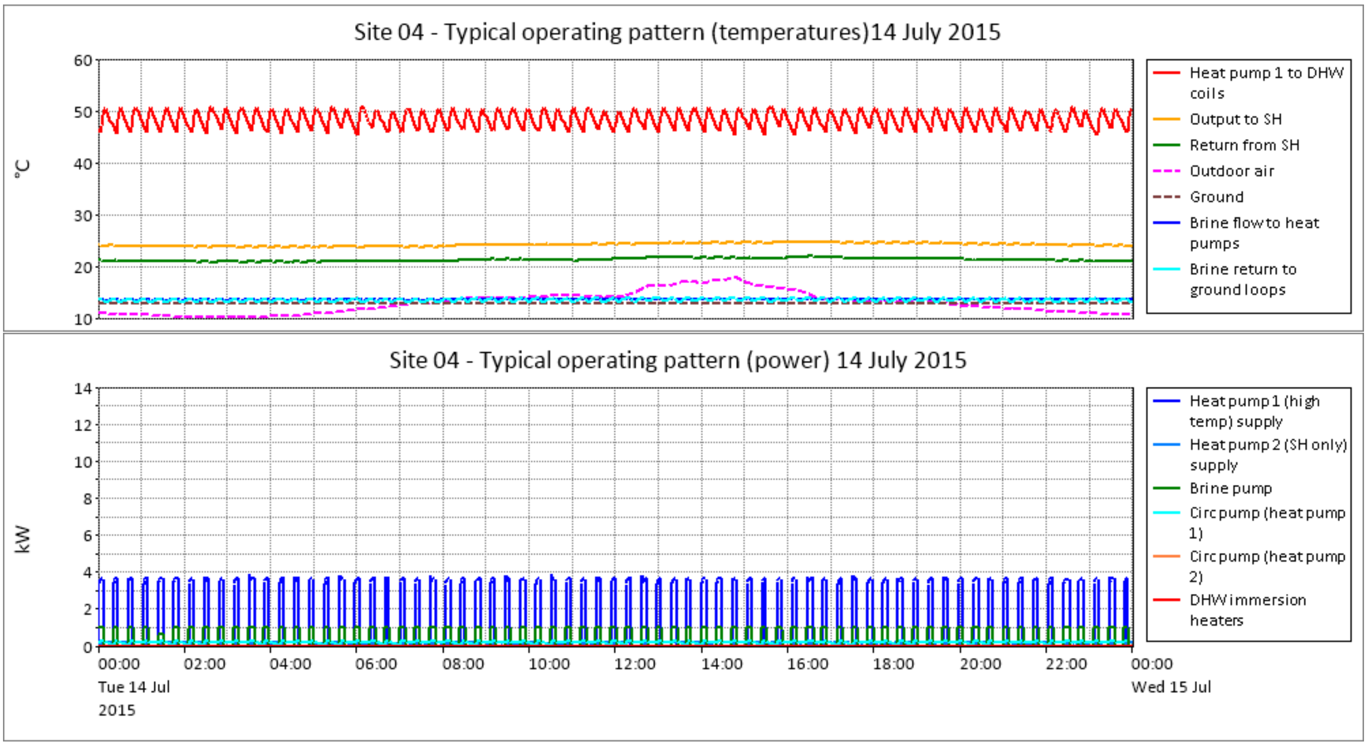

Figure 7 – Operating pattern on 14th July 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[6]. For clarity, the brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The temperature of the output to space heating was consistently up to 55 °C whenever there was a demand for heat. The temperature of the output to domestic hot water seems to have been adjusted a number of times during the year, with a maximum of 60 °C in August and September. The reason for this is not known.

The brine flow to the heat pumps was never less than 3 °C and was above the daily mean outdoor air temperature for most of the winter months.

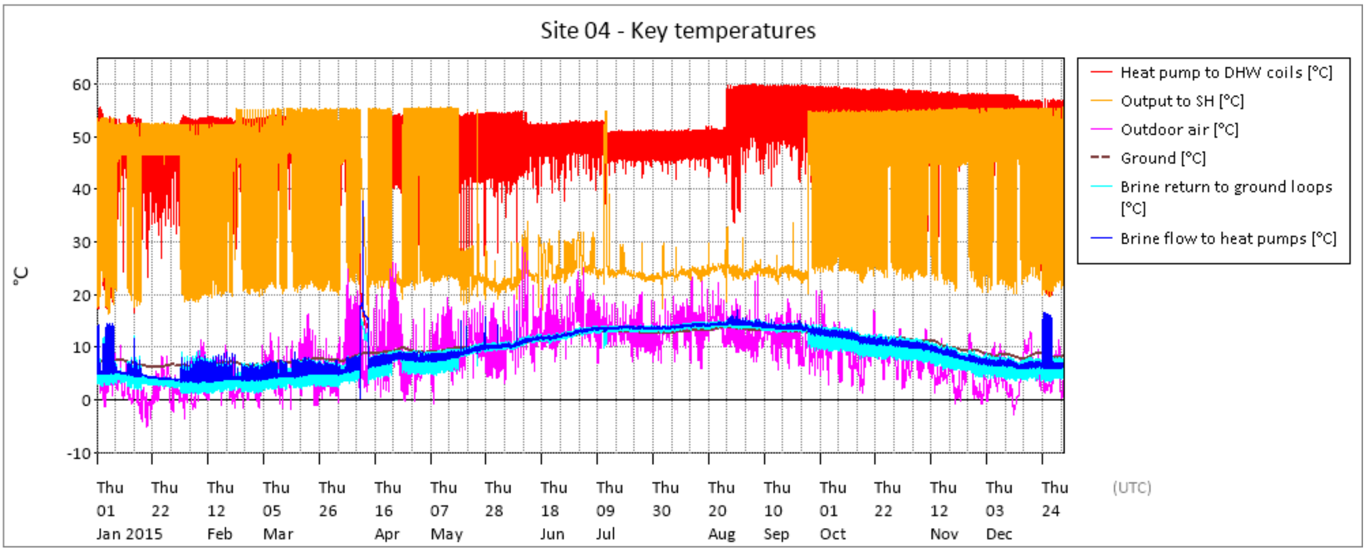

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

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[6] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were above average, which would have had a positive influence on performance. The maximum difference between the ground temperature and the brine flow temperature was 3 °C (in late January), which indicates good performance of the ground collector.

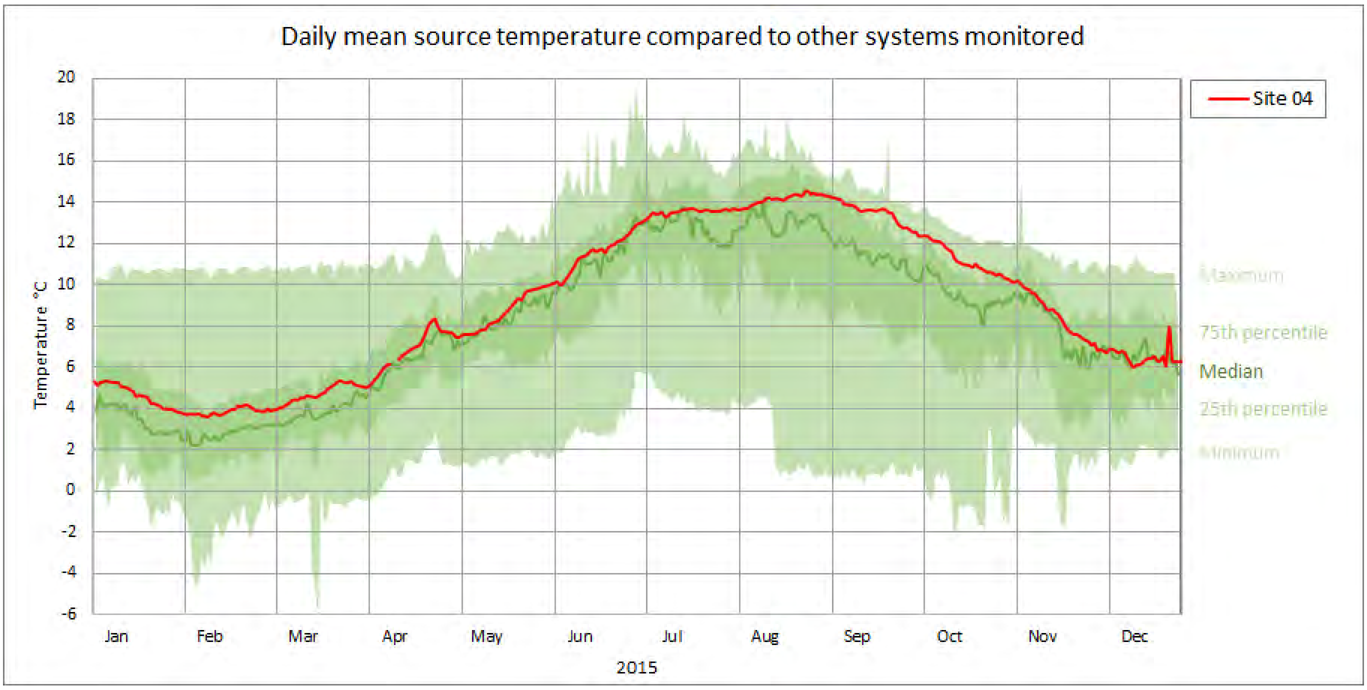

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 04 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The temperature difference on this system is below the median value, which indicates reasonably good collector performance.

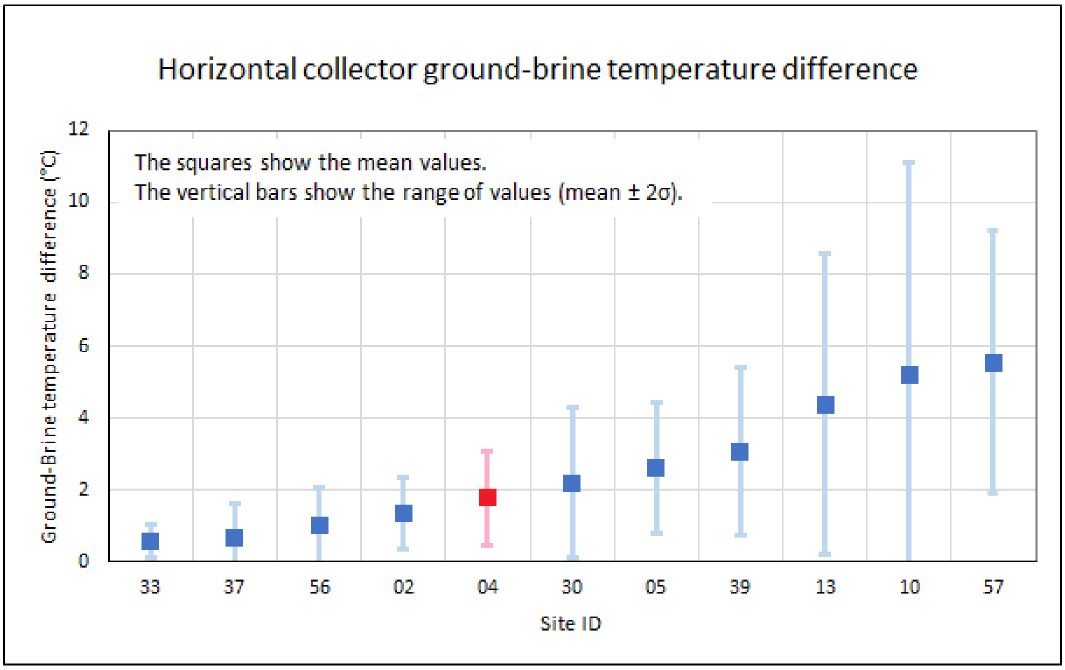

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 04 is shown in red)

Figure 11 shows the daily mean heat pump output temperature (to space heating) for this system (plotted in red) compared to other systems monitored in this project. The output temperatures on this system were well above the median, except during the summer when there was only a very small space heating load. This would have a negative influence on the system performance. The gaps in the data correspond to periods when the heat pump was not being used for space heating.

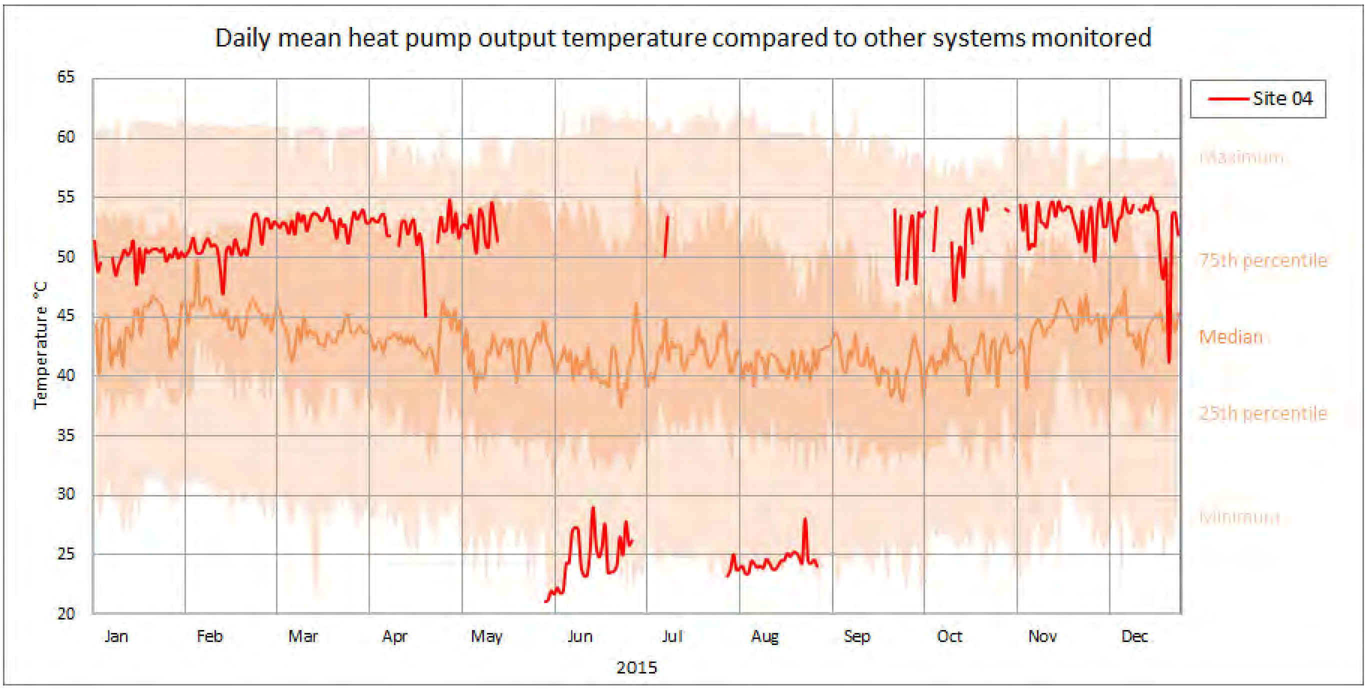

Figure 11 – Daily mean heat pump output temperature (to SH) compared to those of other systems monitored in this project (site 04 is shown in red)

Comments

This is the only system of those monitored in this project to operate without a buffer tank in the heating circuit. It is possible that a buffer tank may have positive influence on system performance. However, the design of buffer tank systems is a complex topic that is beyond the scope of this report.

Aspects of this system that positively influenced its performance are:

- The brine flow temperature was always above 3 °C, and the mean brine temperature throughout the year compared very favourably with the source temperatures of other systems.
- The domestic hot water immersion heaters were not used (except for a short period at the start of the year when there was a fault with the high temperature heat pump, and for an hour in July).

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the heat pump output to space heating was generally high compared to other systems, and was often higher than the output to the domestic hot water primary circuit – which is unusual. This is most likely due to a fault with or incorrect configuration of the controls and should be investigated.
- The brine pump used 11.4% of the total electricity used by the heat pump system. This is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). A system schematic provided by the proprietor shows an inverter (variable-speed) drive connected to the brine pump. There is no evidence of this having been installed, but it would be worth considering. The full brine flow rate should only be needed when both heat pumps are running at full capacity (4 compressors). At other times a lower brine flow rate would be adequate. If the overall electricity use of the brine pump could be reduced

by 50%, the SPF_{H4} would be increased by some 5% and the annual electricity use would be reduced by around 2500 kWh – a cost saving of £370 (assuming a unit cost of 14.7p/kWh [3]).

- Weather compensation was not in use. It was noted during survey that the outdoor temperature sensor of the heat pump appeared to be mounted inside the plant room. Repositioning this sensor outdoors should allow the weather compensation to operate and thereby reduce the space heating output temperature during warmer weather. This would have a positive influence on performance.
- The use of radiators (unmodified from their use with the previous oil-fired heating system) requires a relatively high output temperature during the cold winter months. Increasing the size of some radiators would allow the system to operate at lower temperatures, and should have a positive influence on performance.

It would also be worth investigating why the temperature of the output to domestic hot water was increased in August. It should be possible to operate with a different regime with a generally lower temperature, increased periodically for Legionella control if necessary.

Bibliography

[1] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[2] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[3] "Quarterly Energy Statistics (https://www.gov.uk/government/collections/quarterly-energy-prices)," DECC.

[4] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.," EN 14511-3.

[5] D. Hughes, "Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps - Interim Report. URN 16D/013.," DECC, 2016.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 05

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 05 and performance results from 12 consecutive months of monitoring data.

Site 05 is a public hall, which was refurbished in 2011.

A ground-source heat pump, installed as part of the refurbishment, extracts heat from horizontal ground loops and provides space heating and domestic hot water.

The seasonal heating performance factors measured over a year of operation
(1st January 2015 to 31st December 2015) were:

SPFH2	[Heat delivered by the heat pump] --- Electricity used by: [heat pump] + [brine pump]	3.32
SPFH4	Heat delivered by: [heat pump] + [SH circ pumps] + [immersion heaters] -- Electricity used by: [heat pump] + [brine pump] + [SH circ pumps] + [immersion heaters]	3.08

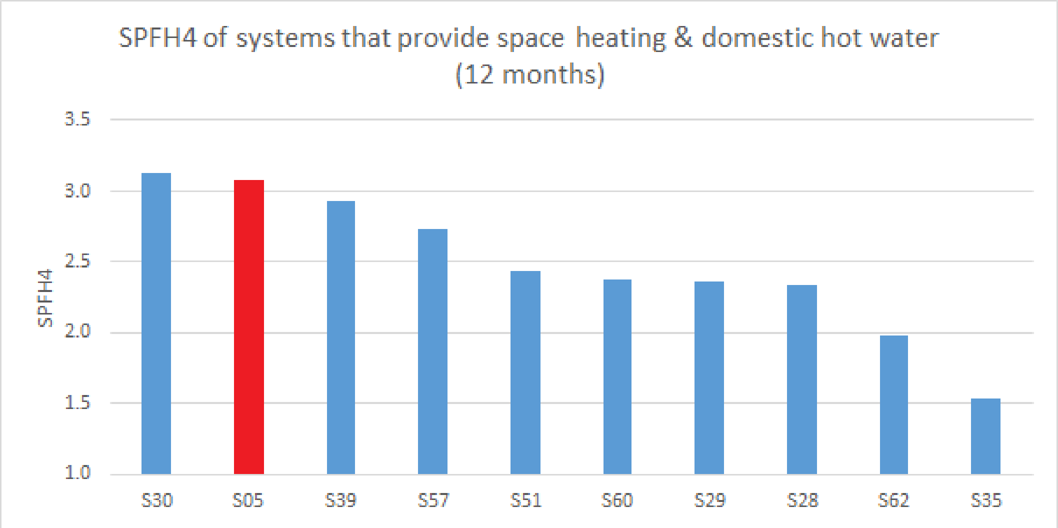


Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influenced its performance are:

- The brine flow temperature was generally above average compared to other systems monitored.
- There was no use of the auxiliary immersion heaters, with the high temperatures required for Legionella control being achieved by the heat pump.
- Weather compensation was used to good effect.

Aspects of the system that may have negatively influenced its performance include:

- The temperature required for the radiators was fairly high – up to 50 °C during cold weather. However, radiators reportedly provide better flexibility than underfloor heating, in terms of the ease of changing the temperatures of the heated spaces – something that is very desirable in a multi-use facility.

- Use of the heat pump to provide small quantities of domestic hot water may not have been justified. It may have been better to install point-of-use electric water heaters.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**05**
Survey date	18/03/2014
Monitoring installed	09/06/2014
G/WSHP	GSHP
Building type	Public hall
Location	Rural
Heat pump capacity kW$_{TH}$	21
Number of heat pumps	1
Number of compressors	2
Heat source	Horizontal ground loops: 6 x 200 m
Heat emitters	Radiators with thermostatic valves
DHW	Yes
Auxiliary heat	4 kW immersion heater in DHW cylinder 4.5 kW immersion heater in buffer tank (emergency use only)
Source pump	External to heat pump: 585 W max
SH circulating pumps	External to heat pump: 165 W max (in flow pipe) External to heat pump: 195 W max (in return pipe)
DHW primary pump	External to heat pump: 165 W max
Buffer tank	200 litre 2-pipe in flow
DHW cylinder	300 litre
Control	Heat pump controller + wireless control system + electronically-set thermostatic radiator valves
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	1
Heat meter interface	M-Bus
Comments	

Table 1 – System details

This site is a public hall, which was refurbished in 2011.

This application comprises a ground-source heat pump, retrofitted in a building during refurbishment. The building is located in an area with slightly above-average outdoor temperatures – annual mean 10.8 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3°C). The heat source is the ground adjacent to the building. The pipe runs from the heat pump to the horizontal collector and to the heat emitters are short. The seasonal performance factor of this system would be expected to be above average.

Heat pump and monitoring systems

The ground-source heat pump was installed at the time of refurbishment of the building and provides both space heating (SH) and domestic hot water (DHW). The heat pump is a high temperature model with 2 compressors.

The heat source is 6 x 200m horizontal ground loops installed in the sports field adjacent to the hall.

The heat emitters are radiators which were installed circa 2000 for use with an oil-fired central heating system. These radiators are understood to have been oversized to provide rapid warm-up. One radiator installed in a meeting room during refurbishment is known to be too small for use with the heat pump, but had not been replaced at the time of monitoring. A 200 litre 2-pipe buffer tank is installed in the flow to the heat emitters.

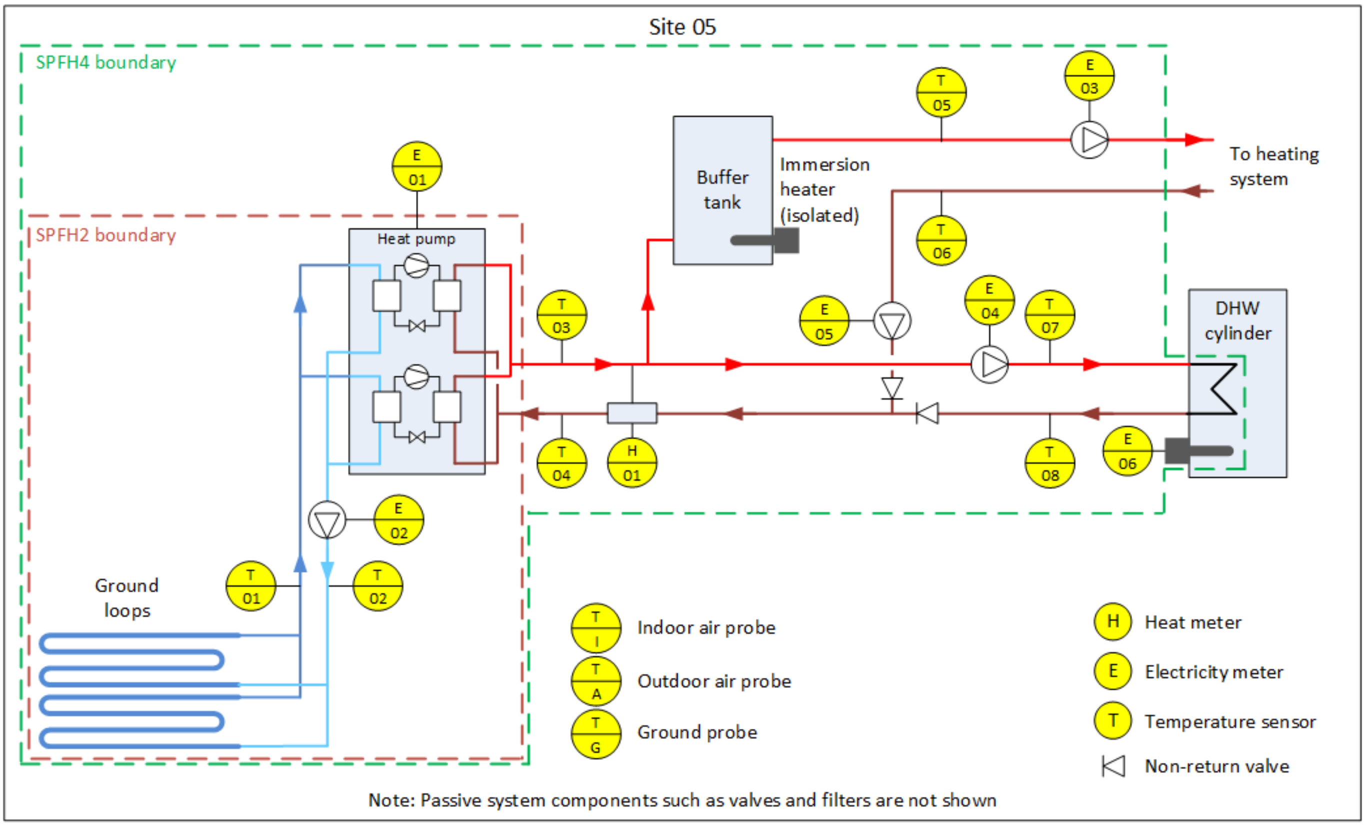
A control system with wireless-controlled thermostatic radiator valves is installed. This greatly facilitates programming the space heating for the various activities in the hall.

The immersion heater in the buffer tank is normally switched off, and is only used in emergency (e.g. heat pump failure). The immersion heater in the domestic hot water cylinder is intended for use during the winter when showers are used more frequently for sports activities.

The entire heat pump system is located within the heated envelope.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and to domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures (“T”) are monitored at key points in the system using surface-mounted probes[1]. The outdoor air and ground temperatures are also monitored.



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses an ultrasonic flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the

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[1] The temperature probes were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

probes inside the flow and return pipes. The calculator is mains-powered, and monitoring was via the M-Bus interface.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump]}}{\text{Electricity used by: [heat pump] + [brine pump]}}$$

$$SPF_{H4} = \frac{\text{Heat output of [heat pump] + [heat added by SH circ pumps] + [immersion heaters]}}{\text{Electricity used by: [heat pump] + [brine pump] + [SH circ pumps] + [immersion heaters]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.
- The buffer tank is within the heated envelope, so the heat losses from it were not deducted from the total heat output. During the summer when there was no demand for space heating, the buffer tank temperature was within 2 °C of the indoor temperature in the main hall and was probably at the same temperature as the plant room. It has therefore been assumed that any heat loss from the buffer tank outside the heating season would have been negligible.
- The electricity used by the DHW secondary circulating pump is not included in the SPF_{H4} calculation.

The number of 1-minute intervals selected as valid for analysis was 523 777, which represents 99.7% of the 12-month period.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	3.32
SPF_{H4}	3.08

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 3.08 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. These figures represent the combined space heating + domestic hot water performance. The daily performance figures are low during the summer months. This is because during warmer weather the heat pump runs mainly for heating domestic hot water, which requires higher output temperatures and is a less efficient process. However, as the total heat output under these conditions is low, the effect on the annual performance is quite small.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [3] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

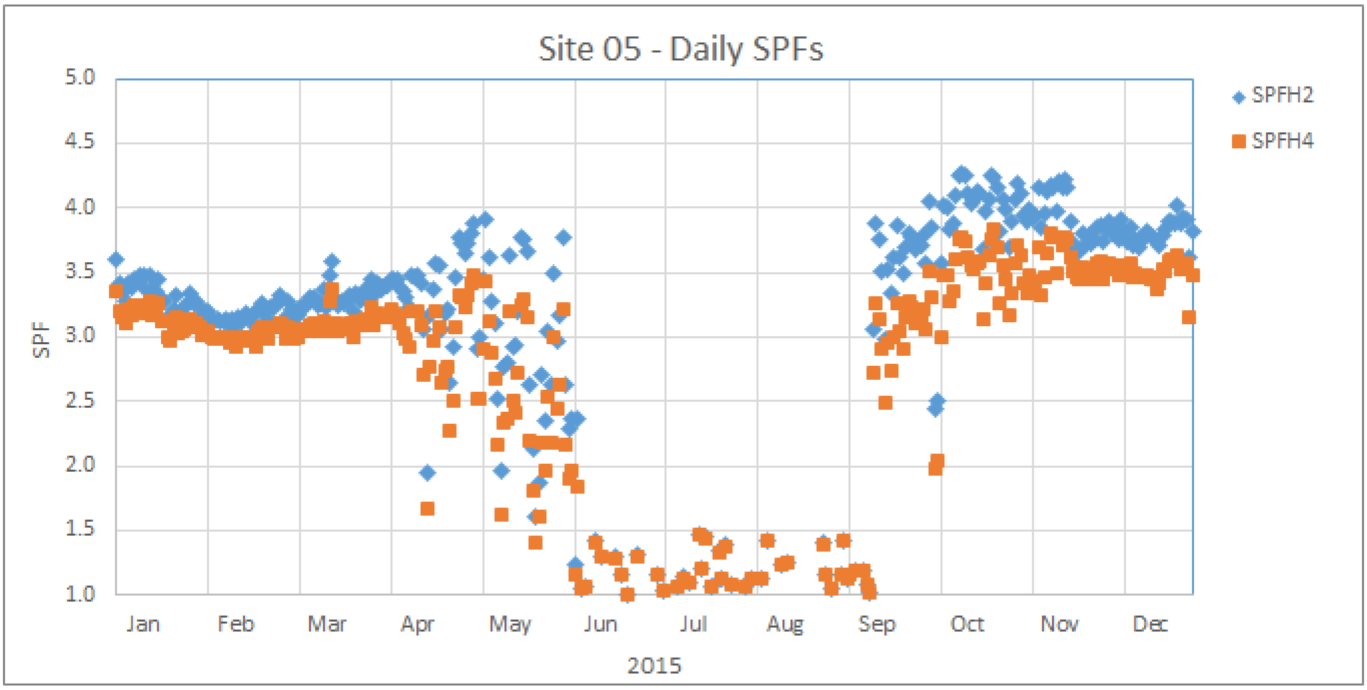

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building and through the heating coil in the domestic hot water cylinder. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output to space heating and to domestic hot water. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The total heat output was highest during the colder weather in January and February. The very low heat output (for domestic hot water only) during the summer months is clearly seen on the graph.

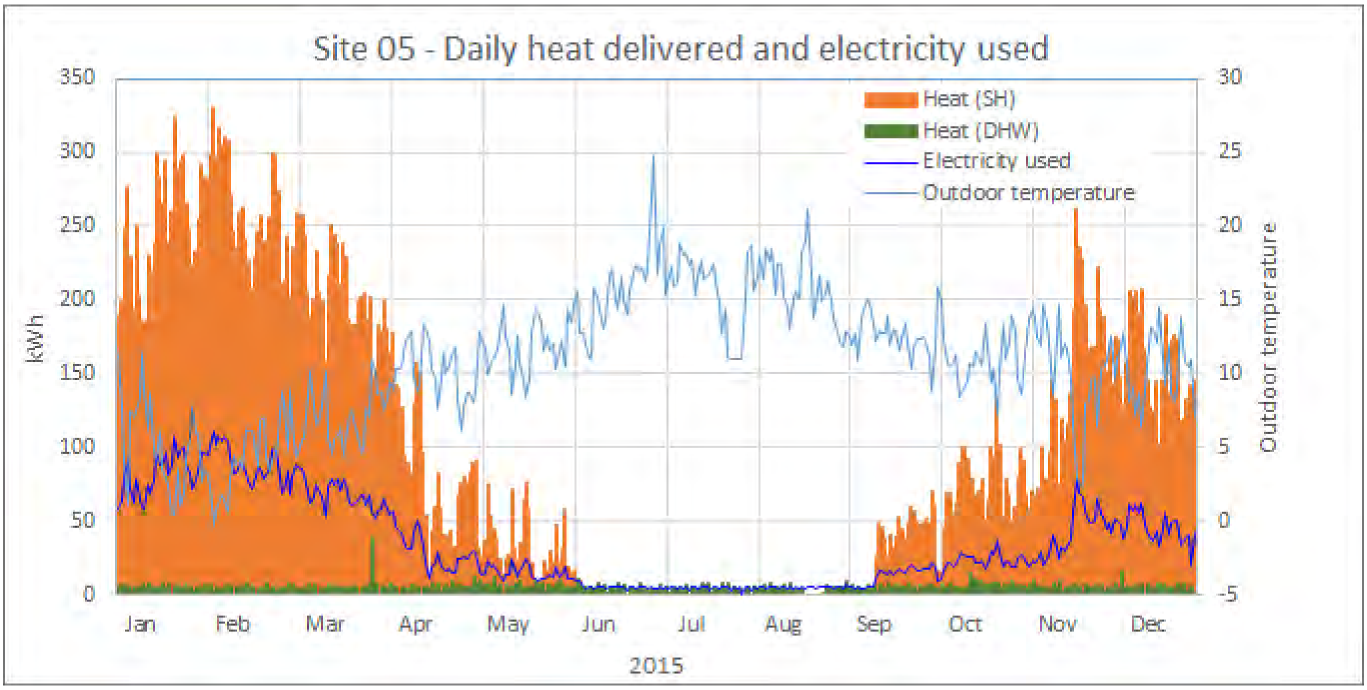

Figure 4 – Daily heat output and electricity used by the total heat pump system

Breakdown of heat delivered

Table 3 shows the breakdown of the heat delivered to space heating and to domestic hot water during the period from 1st January to 31st December 2015.

	kWh	%
Heat delivered to space heating	37 430	95%
Heat delivered to domestic hot water (from heat pump)	2083	5%
Heat delivered to domestic hot water (from immersion heaters)	0	0%

Table 3 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use.

The brine pump accounted for 12.2% of the total electricity used by the heat pump system. This is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%) and would have had a negative influence on the system performance.

The heating circulating pumps used 10% of the total electricity used by the heat pump system, slightly above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). It can be seen from the graph that the space heating circulating pump use varied more or less in proportion to the heat pump electricity use, which suggests that they were being controlled in an efficient manner.

The immersion heaters in the buffer tank and the domestic hot water cylinder were not used during the period monitored.

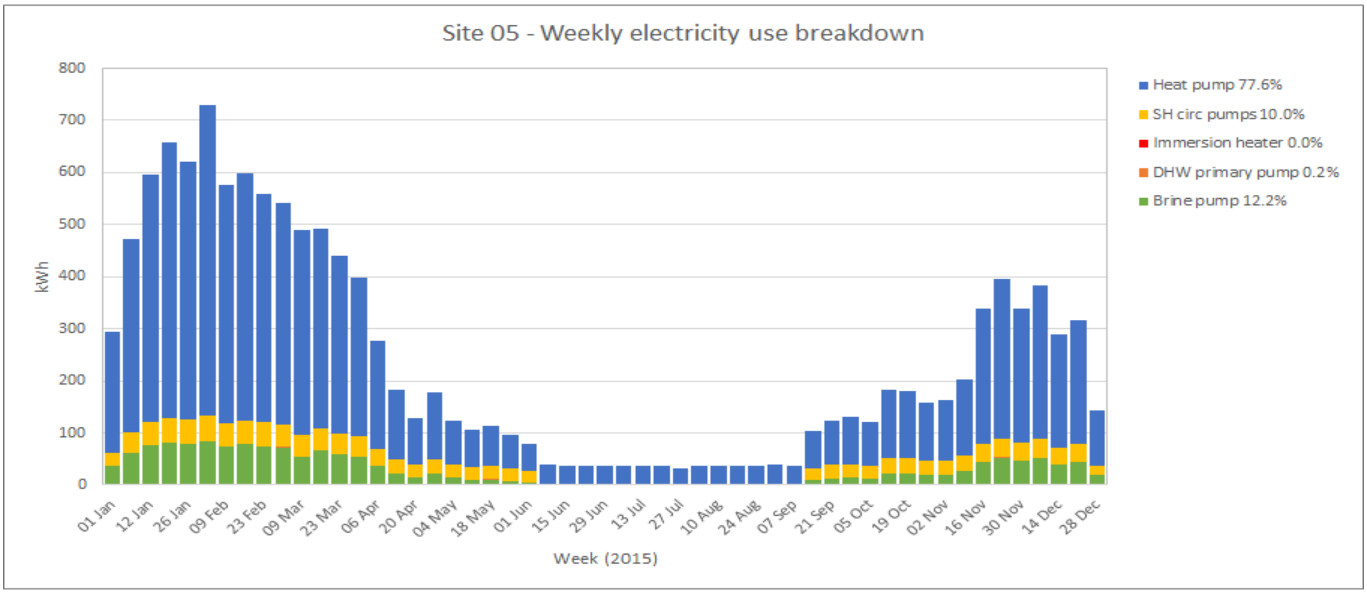

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the typical operating pattern for a 2-day period on 17th – 18th January. The outdoor temperature was low (-5 to +8 °C) and the heat pump was running for most of the time, with both compressors in use for several periods.

The output of the heat pump was periodically switched to heat the domestic hot water twice during the first day. The temperature of the flow to the domestic hot water coil can be seen rising to 62 °C during DHW operation – and once a week on Sunday morning to 67 °C, presumably for Legionella control.

The output to space heating was at a maximum temperature of 50 °C.

There was no measurable loss of temperature through the 2-pipe buffer tank.

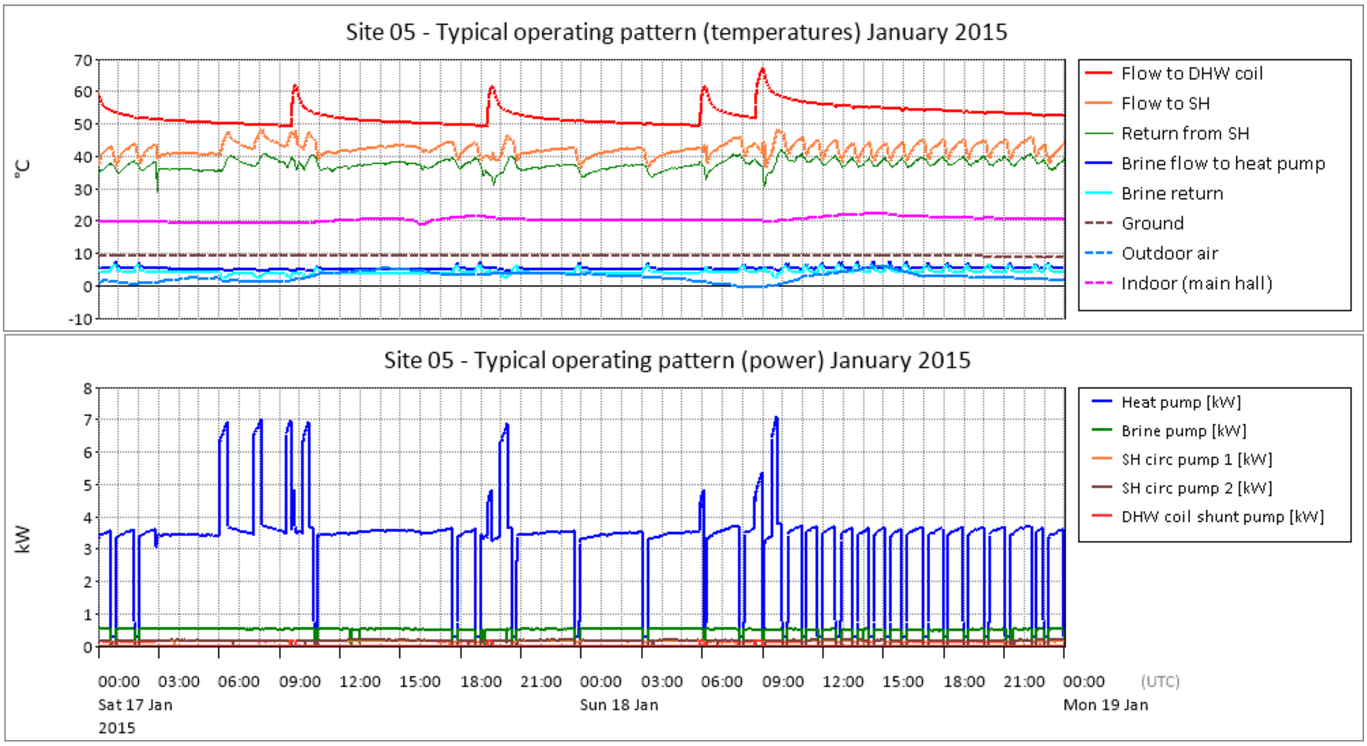

Figure 6 – Operating pattern on 17th – 18th January 2015

Figure 7 shows the typical operating pattern on 4th – 5th July when the outdoor temperature was between 11 and 24 °C. During this warm summer weather, the heat pump was running for short intervals to provide domestic hot water. The weekly temperature boost, presumably for Legionella control, can be seen on the Sunday.

The heat pump ran three times during the two days for between 12 and 15 minutes – comfortably within the limits for short cycling recommended from previous research [2].

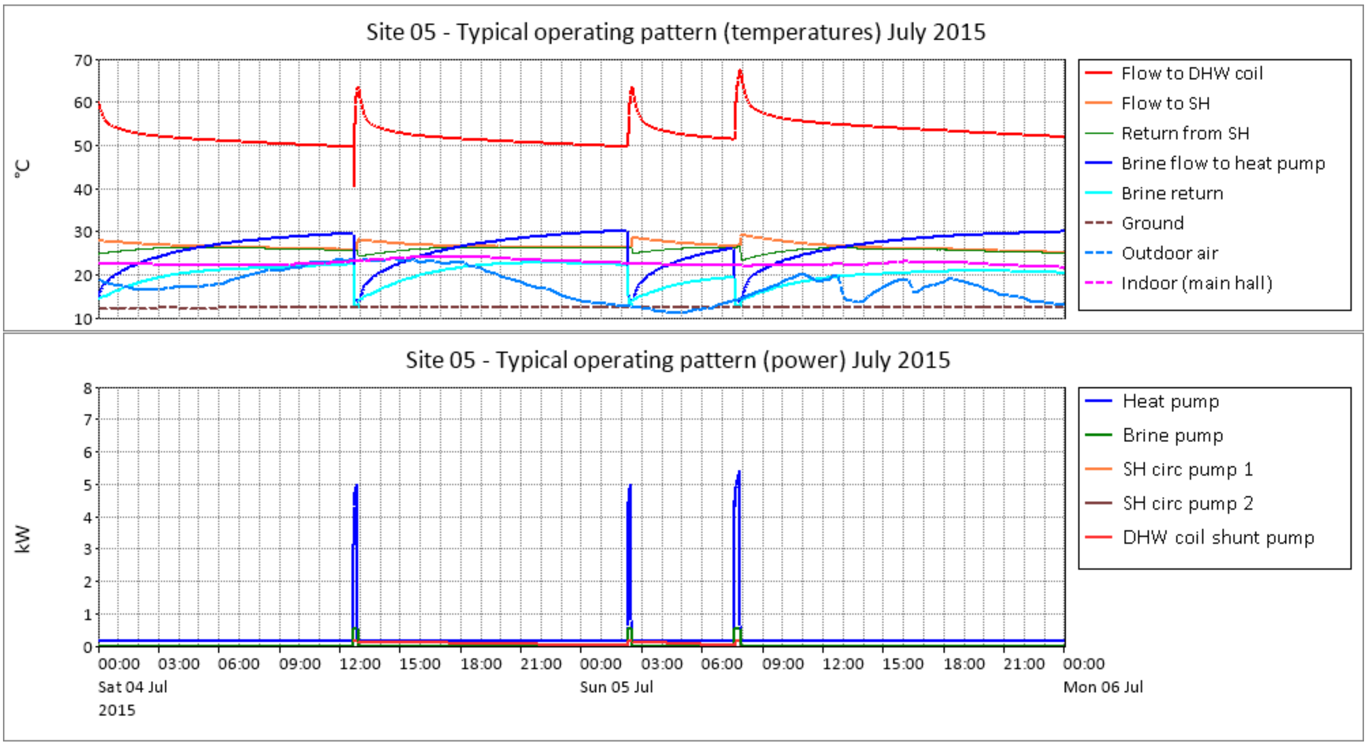

Figure 7 – Operating pattern on 4th – 5th July 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[4]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The red line shows the temperature of the output to the domestic hot water cylinder – with the weekly boost to 67 °C for Legionella control clearly visible.

The output to the space heating was at a maximum of 50 °C during the coldest day of the year on 23rd January when the outdoor air temperature was -5 °C. The lowest brine flow temperature of 2.3 °C occurred on 22nd February.

During warmer weather in May, the flow to space heating was down to around 30 °C, and the brine flow temperature was between 8 and 10 °C.

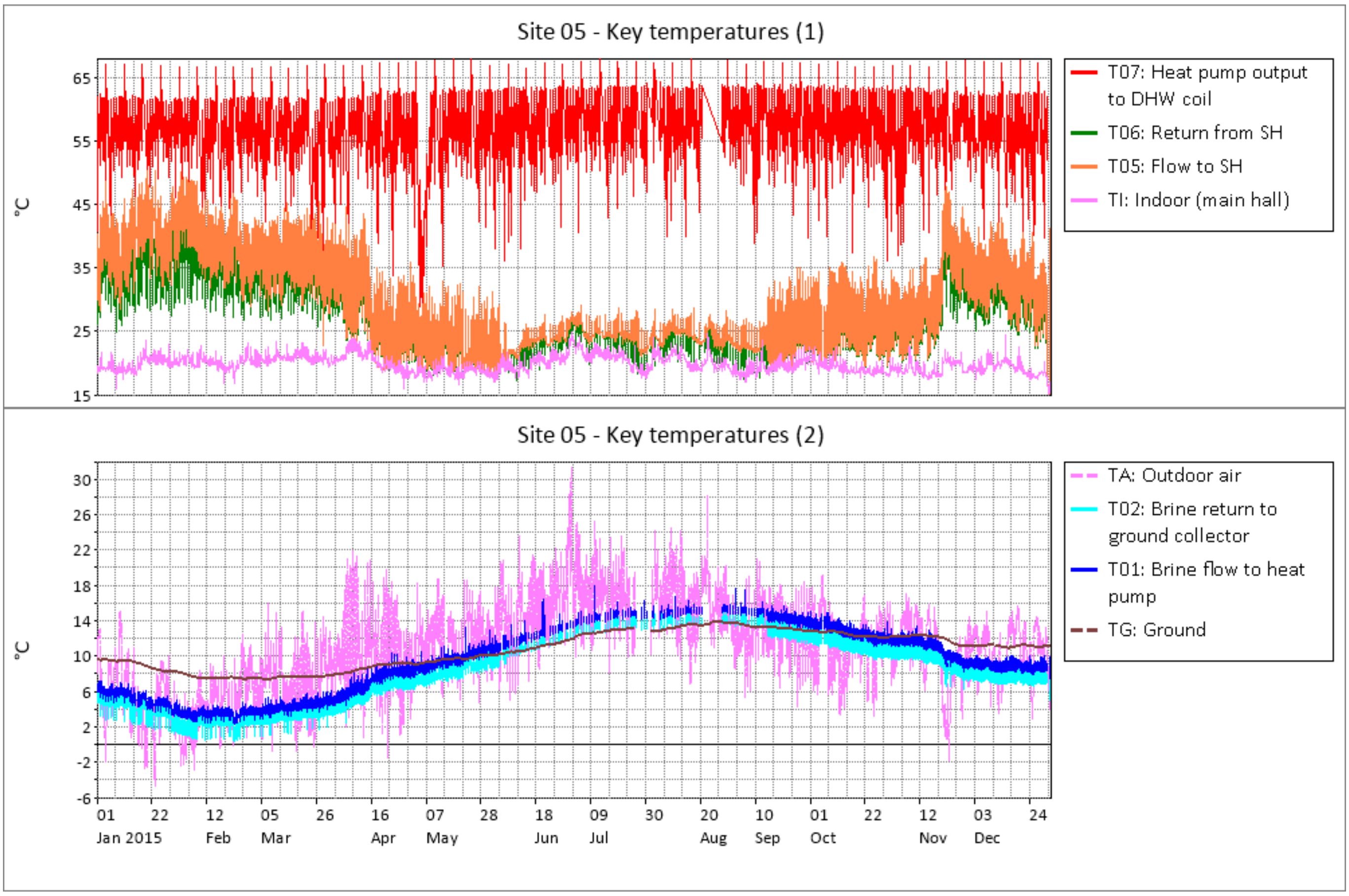

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were above average. This would have had a positive influence on system performance.

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[4] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

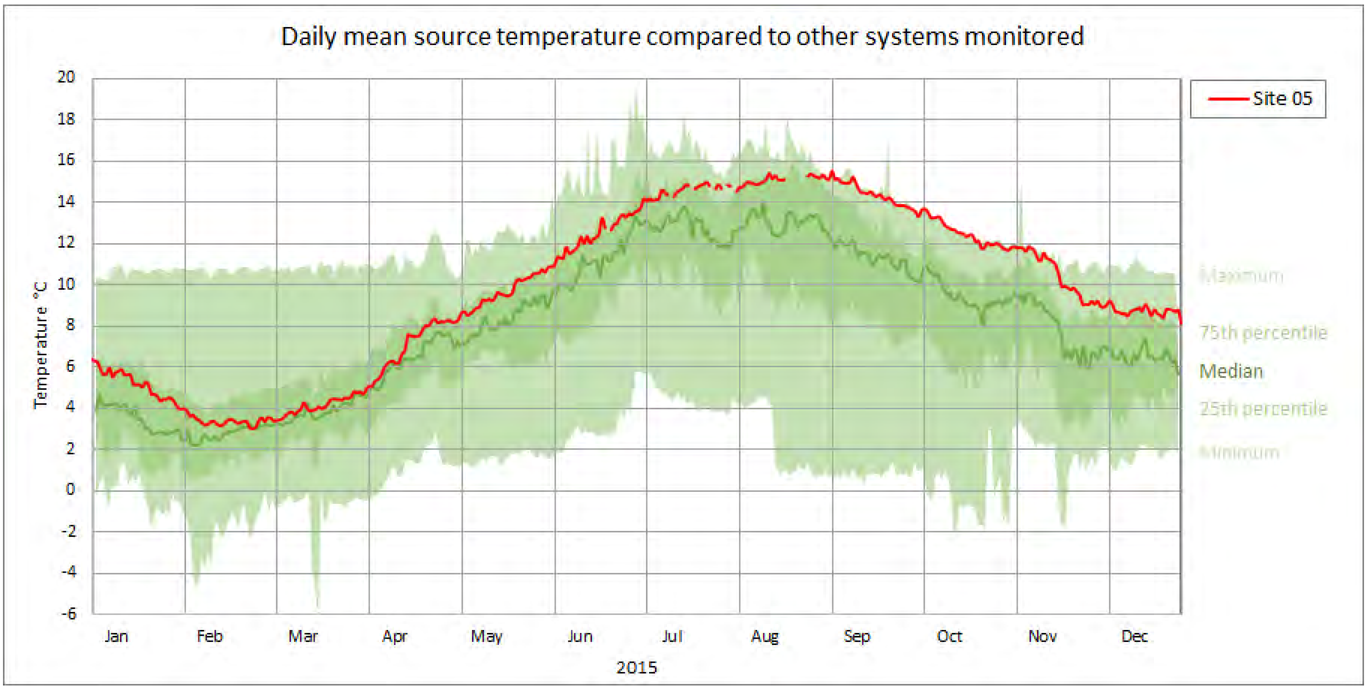

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 05 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The temperature difference on this system is above the median which indicates that the collector performance is slightly below average.

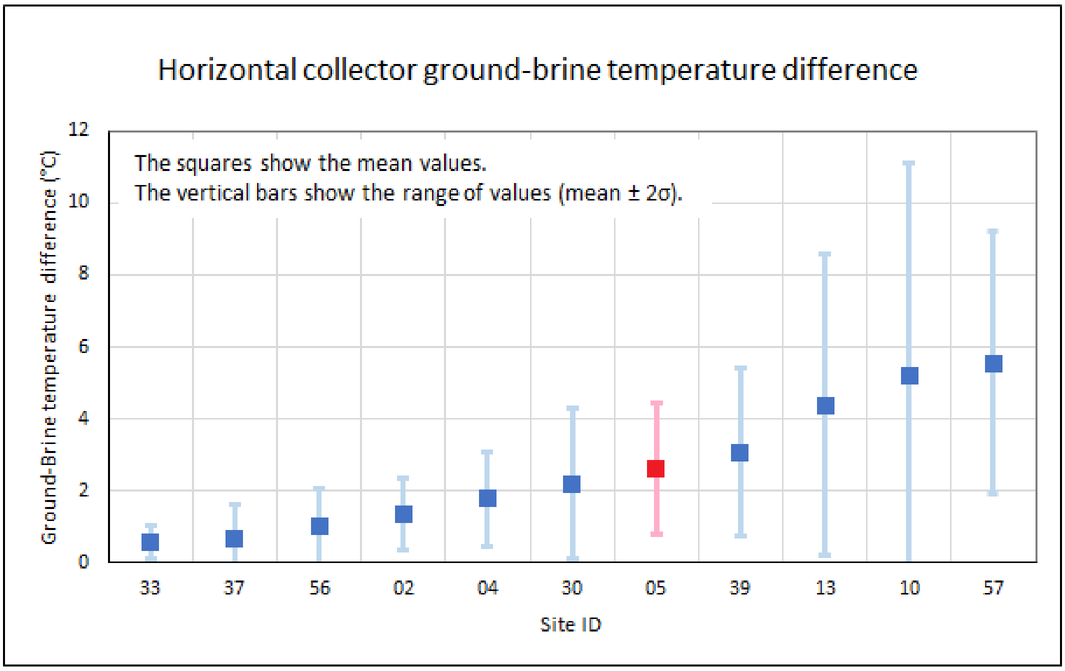

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 05 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system (plotted in red) were below average, except during the summer when the system was providing domestic hot water only and the output temperature while the heat pump was running was always high. The overall effect would have been a positive influence on the system performance.

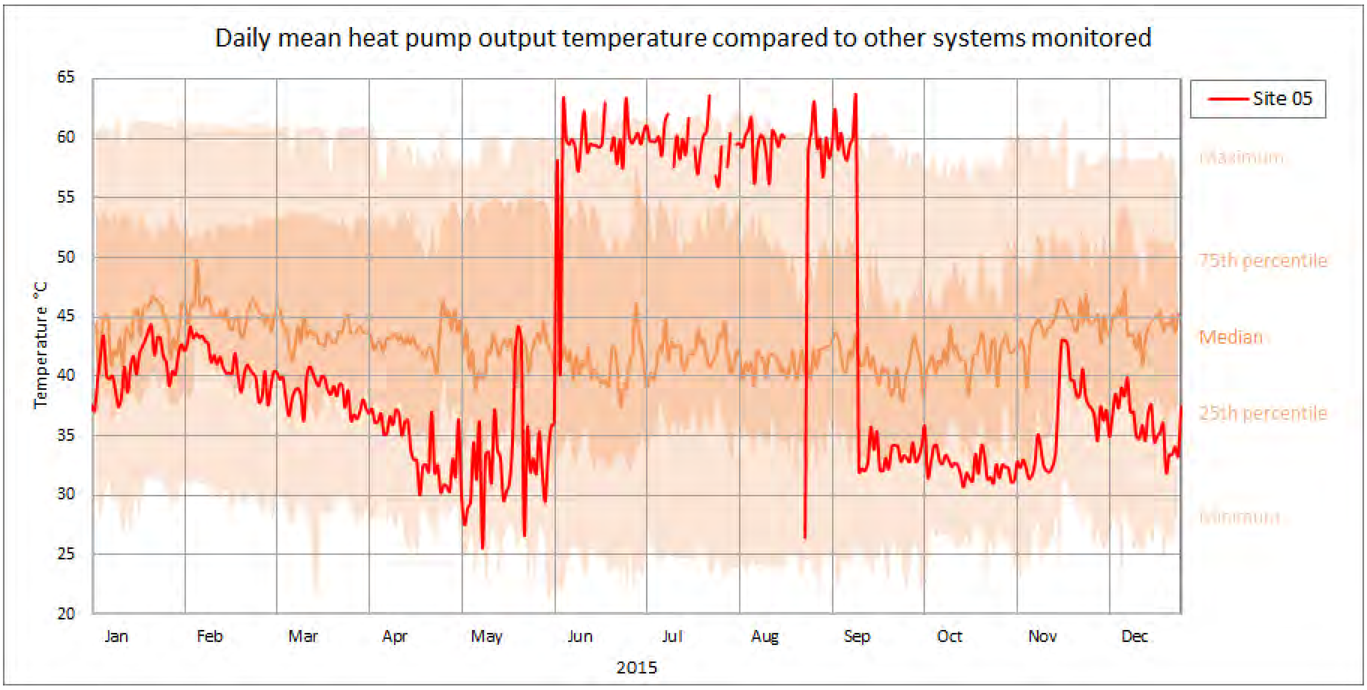

Figure 11 – Daily mean heat pump output temperature (to SH) compared to those of other systems monitored in this project (site 05 is shown in red)

Comments

This system had the third best performance (SPFH4 = 3.08) of all systems providing both space heating and domestic hot water that were monitored in this project (SPFH4 range: 1.54 to 3.13, median value 2.41).

Aspects of this system that positively influenced its performance are:

- The temperature of the brine flow to the heat pump was rarely below 3 °C. This was above average compared to other systems providing SH and DHW that were monitored in this project.
- There was no use of the auxiliary immersion heaters during the period reported.
- The high temperatures required for Legionella control were achieved without the use of immersion heaters.
- Weather compensation was used to good effect, with the temperature of the output to the heat emitters reduced when the outdoor temperature was higher.

Aspects of the system that may have negatively influenced its performance include:

- The temperature required for the radiators was up to 50 °C during cold weather. Heat emitters designed for a lower temperature (e.g. larger radiators) should improve the system performance.
  However, it is worth noting that using radiators as the heat emitters reportedly provides a good degree of flexibility in terms of the ease of changing the temperatures of the heated spaces – something that is probably very desirable in a multi-use facility. Underfloor heating may not provide the same degree of flexibility.
- Use of the system to provide domestic hot water may not have been justified. The total demand for domestic hot water appears to have been low, and it may be better to install point-of-use electric water heaters. This would increase the overall SPFH4 as there would be no requirement for the higher output temperatures used for DHW.

Bibliography

[1] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[2] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[3] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.," EN 14511-3.

[4] D. Hughes, "Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps - Interim Report. URN 16D/013.," DECC, 2016.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 07

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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Dr David Hughes asserts his moral right under the Copyright, Designs and Patents Act 1988 to be identified as the author of this work.

This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 07 and performance results from 12 consecutive months of monitoring data.

Site 07 is a recently-built refectory and office building. A single heat pump (thermal capacity 96 kW) supplies space heating only to an underfloor heating system.

The heat source is water from a mountain tarn, supplied via a nearby lagoon from where it is pumped directly to the heat pump evaporator in an open-loop arrangement.

Domestic hot water is provided separately by LPG-fired boilers, with solar thermal collectors used for pre-heating the boiler feed water. The boilers can also provide auxiliary heat for space heating when necessary.

The system is controlled by a building management system.

The seasonal heating performance factors measured over a year of operation
(1st April 2015 to 31st March 2016) were:

SPFH2	[Heat delivered by the heat pump] -- Electricity used by: [the heat pump] + {source pump]	2.72
SPFH4	[Heat delivered by the heat pump] + [heat added by the buffer and heating circ pumps] - [heat loss from the buffer tank] -- Electricity used by: [the heat pump] + [source pump] + [buffer and heating circ pumps]	1.50

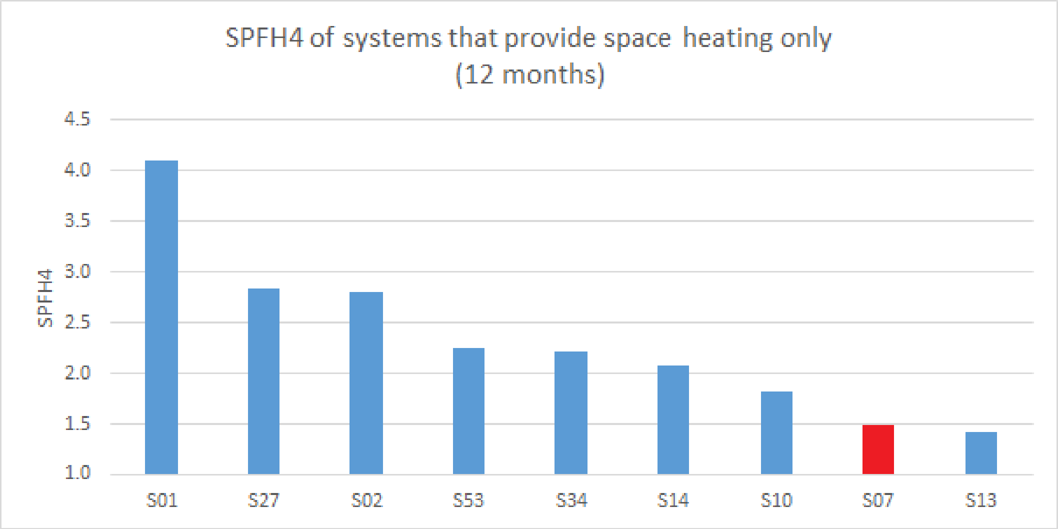


Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

Aspects of this system that positively influenced its performance are:

- The source temperature was high compared to most other systems monitored.
- The source water is pumped directly to the evaporator, without an intermediate heat exchanger which would introduce temperature loss.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump was not used to the extent that it could have been: the LPG-fired boilers provided heat to the space heating system at times when the heat pump could have been used. This appears to have been due to inappropriate control strategy or settings.
- The buffer and heating circulating pumps together accounted for 48.6% of the total electricity used by the heat pump system. This is exceptionally high compared to other systems monitored (range for other systems monitored 2.9% - 20.5%, median 8.8%).

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	07
Survey date	30/01/2014
Monitoring installed	26/03/2015
G/WSHP	WSHP
Building type	Refectory and offices
Location	Rural (on a site with other buildings)
Heat pump capacity kWTH	96
Number of heat pumps	1
Number of compressors	2
Heat source	Water from tarn
Heat emitters	Underfloor heating pipes
DHW	No
Auxiliary heat	LPG boiler
Source pump	External to heat pump: 1 pump of 3 kW max (fixed-speed)
Buffer pump	External to heat pump: 1 pump of 1.3 kW max (fixed-speed)
SH circulating pump	External to heat pump: 1 pump of 670 W max (fixed-speed)
Buffer tank	1000 litre 4-pipe
Control	BMS
Weather compensation	Yes
Heat meter type	Multi-jet turbine
No. of heat meters	1
Heat meter interface	Pulse (100 kWh / pulse)
Comments	Auxiliary heat is provided as hot water from the LPG boilers, fed to the underfloor heating header via a thermostatic valve & pump.

Table 1 – System details

Site 07 is a recently-built (2012) refectory and office building in a rural location, on a site of several hectares along with by a variety of other buildings.

The application entails extracting heat from surface water to provide space heating via underfloor heating pipes in a modern well-insulated building in a location with outdoor temperatures slightly below the median for all sites monitored. (The mean outdoor temperature for site 07 was 9.7 °C. The range for all sites was 8.1 – 12.6 °C, median 10.5 °C.). The system design performance would be expected to be above average.

Heat pump and monitoring systems

A single heat pump (thermal capacity 96 kW) supplies space heating only to an underfloor heating system.

The heat source is water from a mountain tarn, supplied via a lagoon within the site. The water is pumped from the lagoon directly to the heat pump evaporator, and thence to local drainage.

A set of three gas-fired (LPG) boilers provides domestic hot water and auxiliary heat for space heating. Solar thermal collectors are used to pre-heat the cold feed to the boilers.

Auxiliary heat is supplied to the underfloor heating system when needed by feeding hot water from the boilers via a thermostatically-controlled valve to the underfloor heating header. This auxiliary heat is not metered.

A 1000-litre 4-pipe buffer tank is installed between the heat pump output and the underfloor heating header.

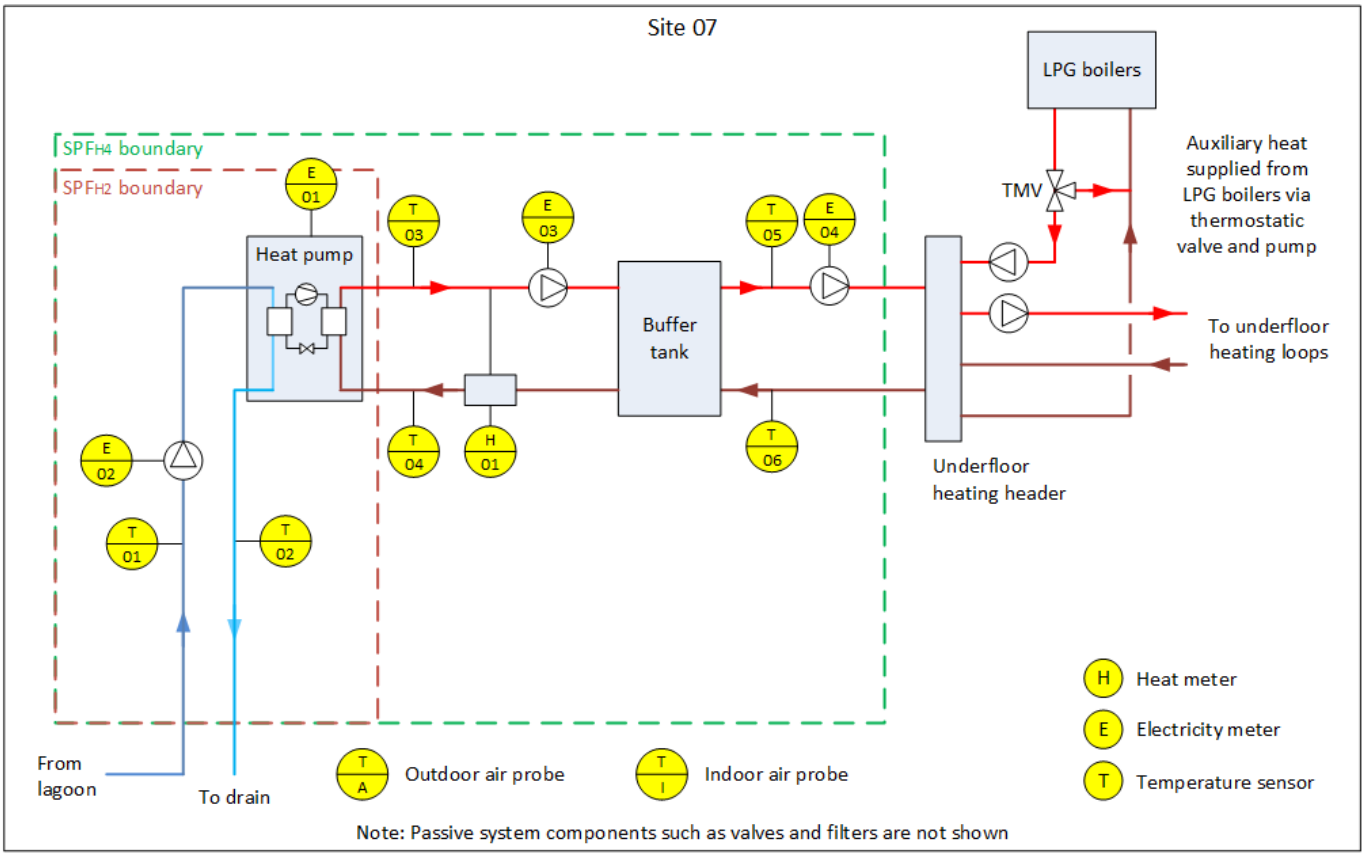
The system is controlled by a building management system (BMS) that also controls other plant (boilers, air handling units, etc.).

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

On this installation, it was impractical to measure the heat supplied to space heating by the LPG boilers or the electricity used by the underfloor heating pumps. The SPFH4 boundary used for analysis therefore excludes these elements.

It is also noted that it may be possible for heat from the LPG boilers to back-feed the heat pump system and thereby affect its performance.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1]. The outdoor air temperature is also monitored.



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses a mechanical multi-jet turbine flow meter installed in the return pipe, with matched temperature sensors installed

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

in fittings with the probes inside the flow and return pipes. The calculator is battery-powered. Monitoring was via the pulse interface.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including the auxiliary pumps used to deliver heat to the underfloor heating header.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.
- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump]}}{\text{Electricity used by: [heat pump] + [source pump]}}$$

$$SPF_{H4} = \frac{\text{[Heat output of heat pump] – [heat loss from buffer tank] + [heat added by buffer \& SH circ pumps]}}{\text{Electricity used by: [heat pump] + [source pump] + [buffer \& SH circulating pumps]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer and heating circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.
- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 525 336, which represents 99.9% of the 12-month period.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st April 2015 and 31st March 2016, are shown in Table 2.

SPF_{H2}	2.72
SPF_{H4}	1.50

Table 2 – SPF values measured for the period 1st April 2015 to 31st March 2016

This means that for each unit of electricity used, this system delivers on average 1.50 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. The wide variation in the SPF values is explained by the low use of the heat pump (not at all on some days – when the SPF_{H2} is shown as zero), but with the buffer pump continuing to run periodically (at least 10 minutes every hour) to allow the heat pump controller to monitor the return temperature. The heating circulating pump also ran most days, often for much longer than the heat pump, so the electricity used was relatively high for the heat delivered. The SPF_{H4} values were higher than the SPF_{H2} values on some of these days, because the buffer and heating circulating pumps were running and provided some heat through the process of water pumping.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [3] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

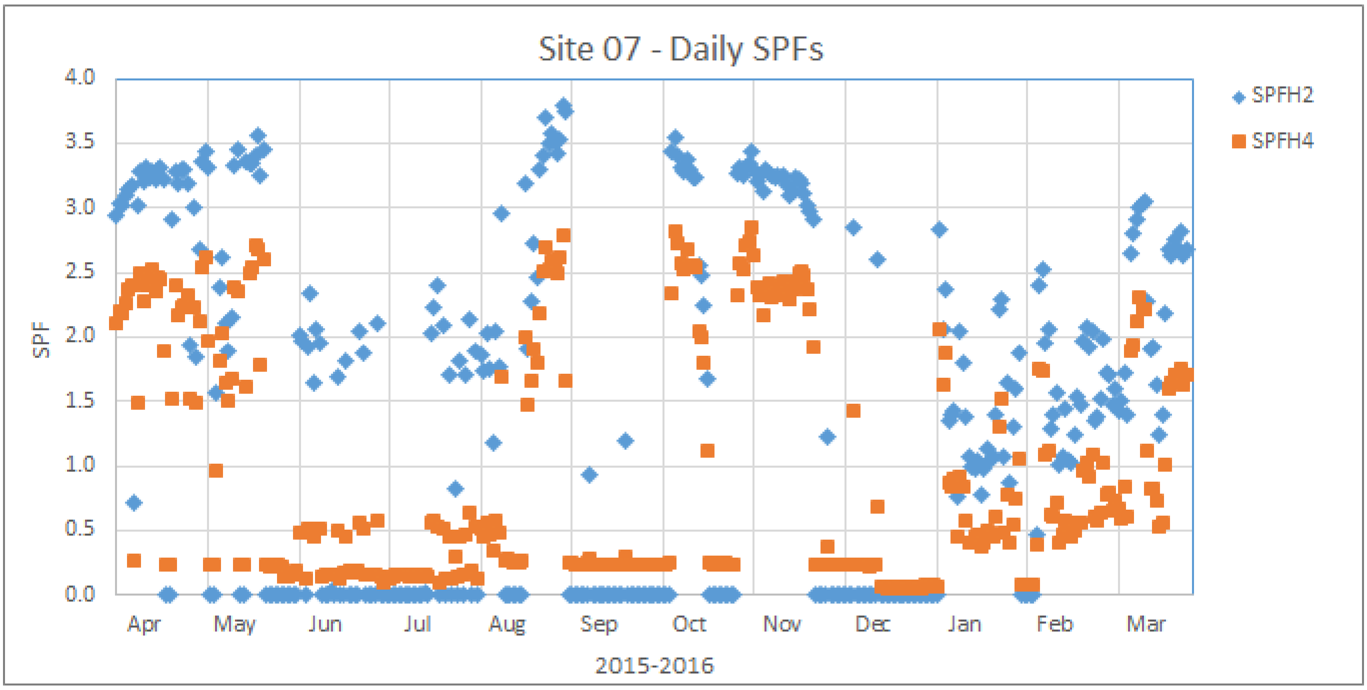

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the tarn water and the sink is the space being heated. Heat extraction from the source to the heat pump is via an open-loop circuit from the lagoon, directly to the evaporator of heat pump.

Heat delivery from the heat pump to the heated space is via a hot water circuit. This water will always be warmer than the space because of the need for a temperature difference to transfer the heat. An objective of good system design and operation should be to maximise the temperature of the source at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the water from the source to the heat pump, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters or gas-fired boilers to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions. It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required for the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference.

It can be seen that the heat pump was not always used during cold weather. This is believed to be due to the LPG-fired boilers providing heat instead of the heat pump. There is no obvious reason why the heat pump could not have been used at all times when there was a demand for space heating. Doing so would have provided a greater proportion of the total heat as renewable energy.

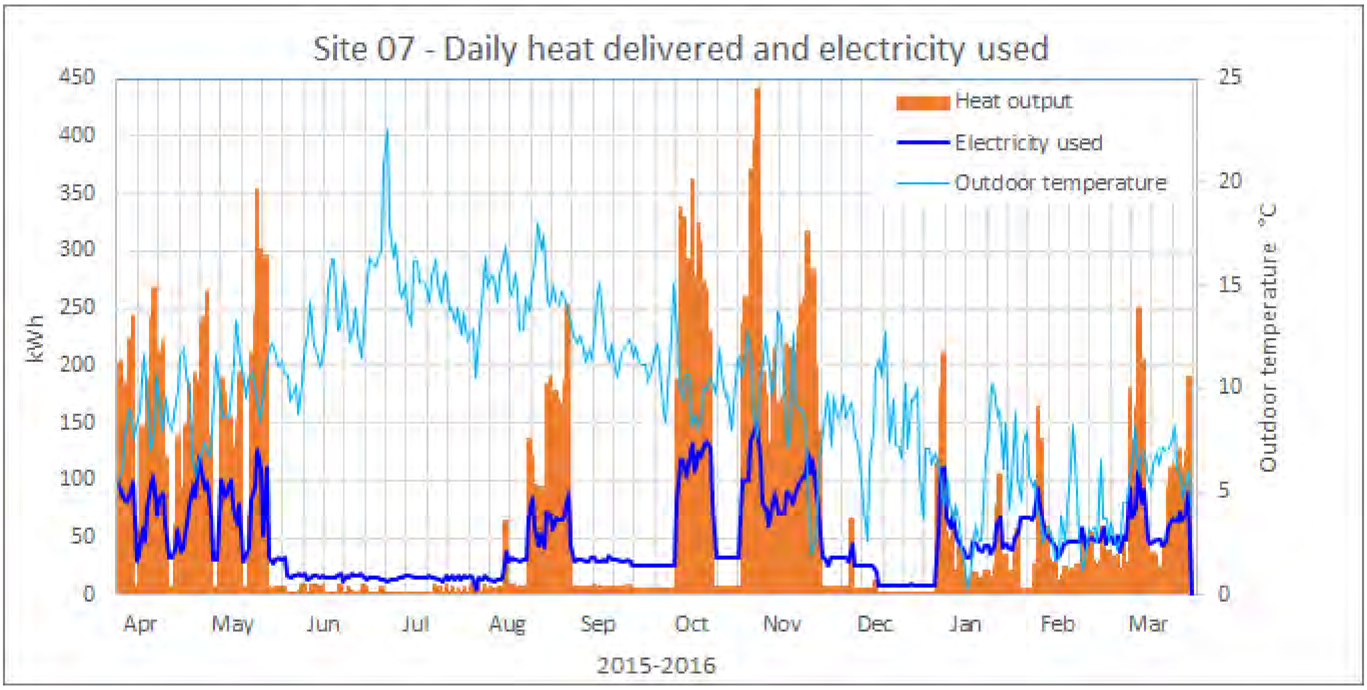

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use.

The source pump accounted for 6.3% of electricity use by the total heat pump system. This was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%) and would have had a positive influence on the system performance.

The buffer and heating circulating pumps together accounted for 48.6% of the total electricity used by the heat pump system. This is exceptionally high compared to other systems monitored (range for other systems monitored 2.9% - 20.5%, median 8.8%) and would have had a strong negative influence on the system performance.

It is notable that the buffer pump was run for all but two of the weeks when the heat pump was used very little or not at all. It is understood that the buffer pump is run every hour or so to allow the heat pump controller to measure the return temperature[4]. The control strategy could probably be altered to avoid this excessive electricity use.

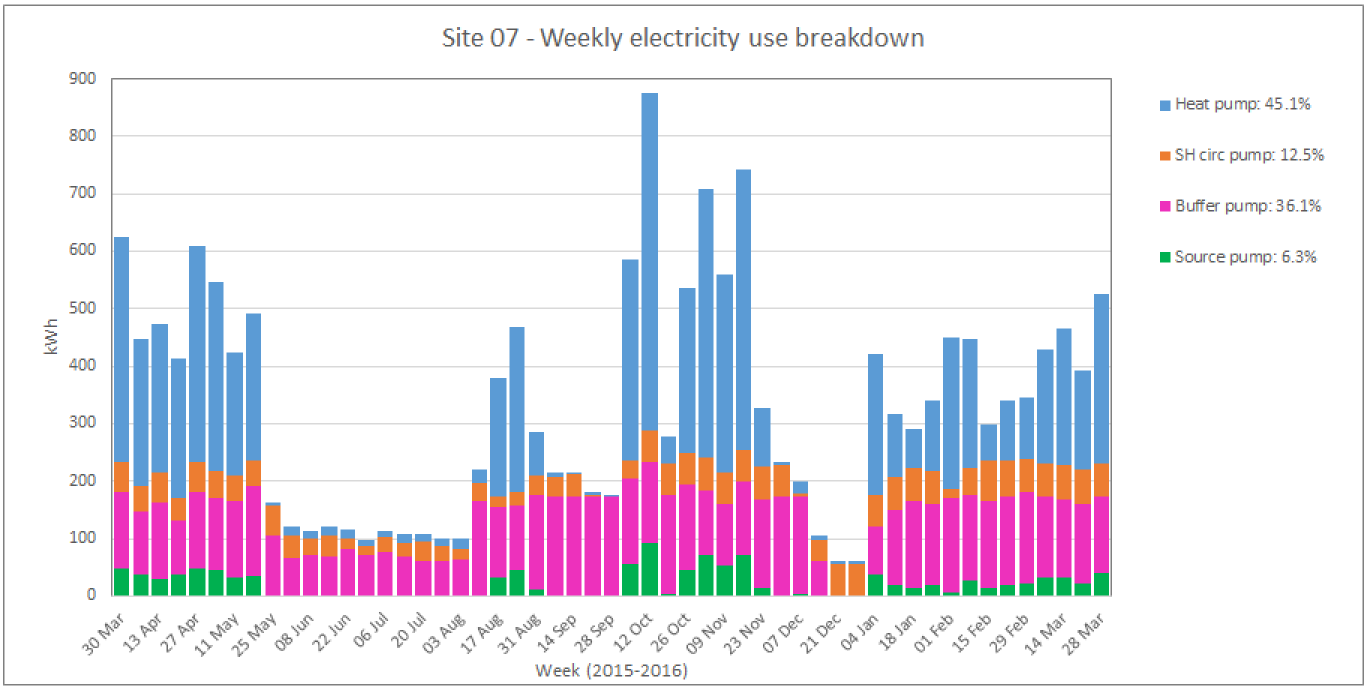

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical operation.

The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump and circulating pumps. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 2nd November 2015 when the outdoor temperature was between 7 and 11 °C. The indoor temperature was between 17 and 19 °C.

The heating circulating pump ran from 02:00 to 03:00 and then from 05:00 to 22:00, presumably under control of the BMS. In response to this call for heat, the heat pump ran for 50 minutes from 02:25, using both compressors for part of the run, and then during the day for a number of runs of 20 to 50 minutes with only one compressor.

The heat pump delivered 392 kWh of heat during this 24-hour period.

At times when the heat pump was not running, the buffer pump ran approximately once an hour for 10 minutes.

The temperature of the source water flow to the heat pump when it was running was between 11 and 12 °C.

The heat pump output temperature was between 33 and 52 °C. The temperature loss through the buffer tank was not more than 2 °C while the heat pump was running.

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[4] This behaviour was confirmed by the system installer.

Figure 6 – Operating pattern on 2nd November 2015

Figure 7 shows the operating pattern on 27th January 2016 the when the outdoor temperature was between 5 and 11 °C, and the indoor temperature was between 20 and 22 °C.

It is interesting to compare the operation on this day to that on 2nd November 2015 (presented above). The space heating load on 27th January would have been similar to 2nd November, or slightly higher because of the higher indoor temperatures.

The heat pump delivered only 100 kWh of heat (compared to 392 kWh on 2nd November 2015). The run times were much shorter, between 7 and 30 minutes, and only one compressor was used except for a short time at 08:30.

This significantly reduced use of the heat pump appears to indicate that the boilers were also providing heat to the space heating system.

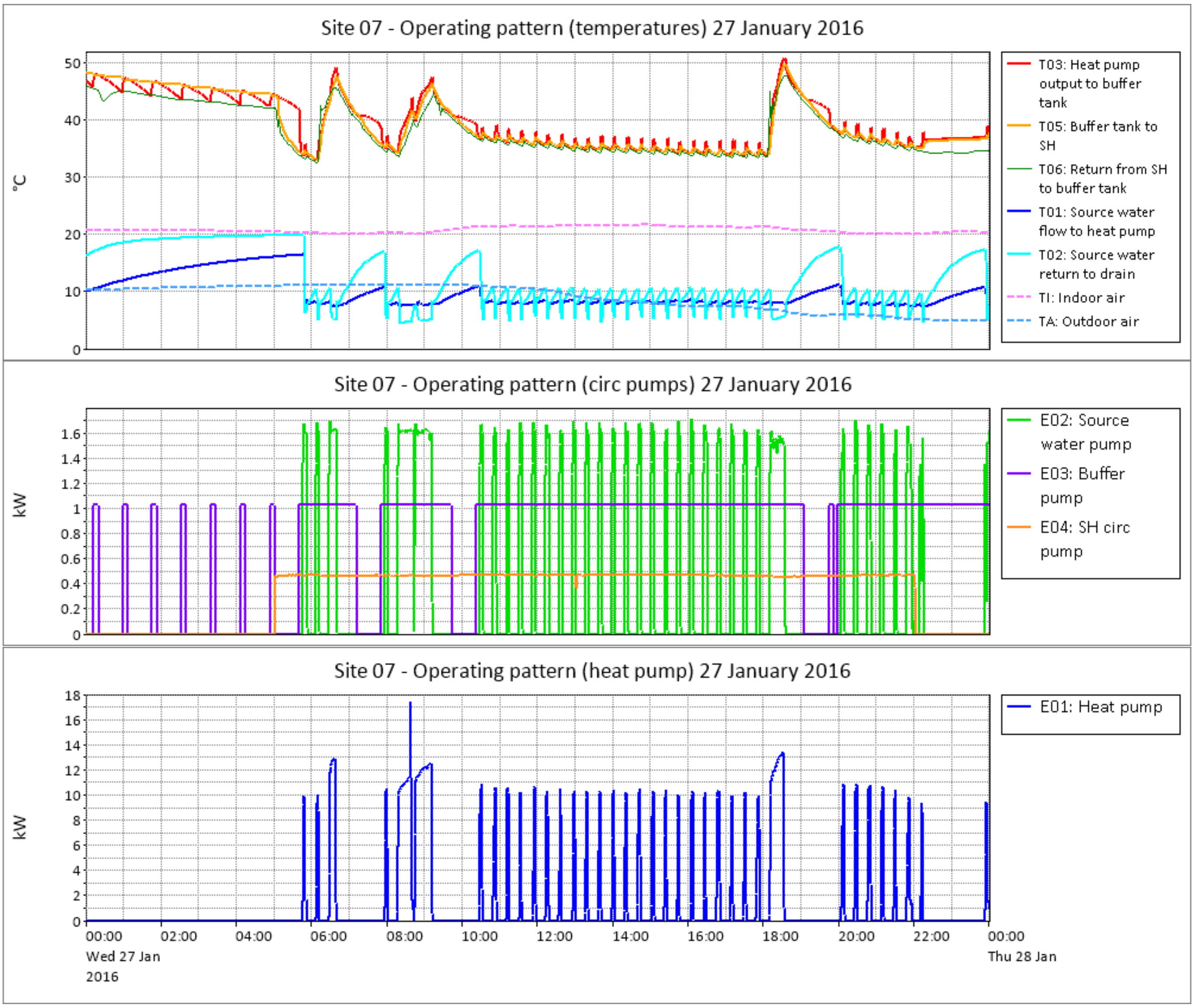

Figure 7 – Operating pattern on 27th January 2016

Between 18th and 24th February, the heat pump output temperature dropped to a very low level (20 – 23 °C). Figure 8 shows the behaviour on 19th February, when the outdoor air temperature was between 2 and 7 °C. The indoor temperature increased from 15 °C to 23 °C during the day, so it appears that heat was being provided to the underfloor heating pipes – but clearly not by the heat pump.

The heat pump ran approximately twice every two hours for very short runs of between 4 and 7 minutes, but with very little effect on the output temperature. The buffer pump and the heating circulating pumps were running continuously.

The reason for this behaviour is unknown, but it appears to have been due to a malfunction of the control system.

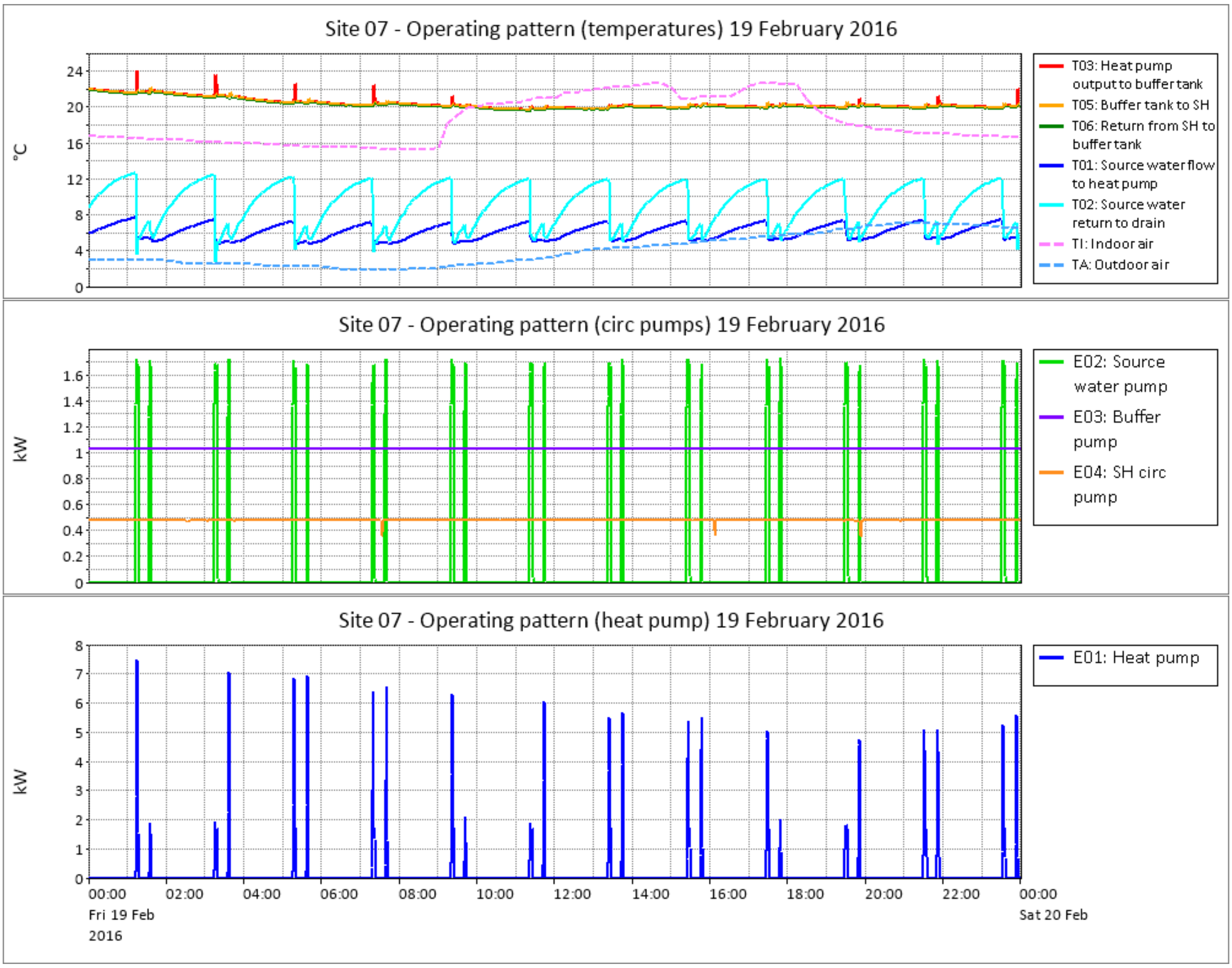

Figure 8 – Operating pattern on 19th February 2016

Source and sink temperatures

Figure 9 shows the principal temperatures of the outdoor air, source water and the outputs from the heat pump, plotted over the year[5]. The source water and heat pump output temperatures have been plotted only for times when the heat pump was running.

The source water temperature varied during the year between 4 and 13 °C (ignoring short spikes to around 20 °C when the pump was started after a lengthy idle period).

The heat pump output temperature varied between 34 and 54 °C. The temperature from the buffer tank to the heating circuits varied between 30 and 52 °C.

The temperature loss through the buffer tank was generally not more than 2 °C.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

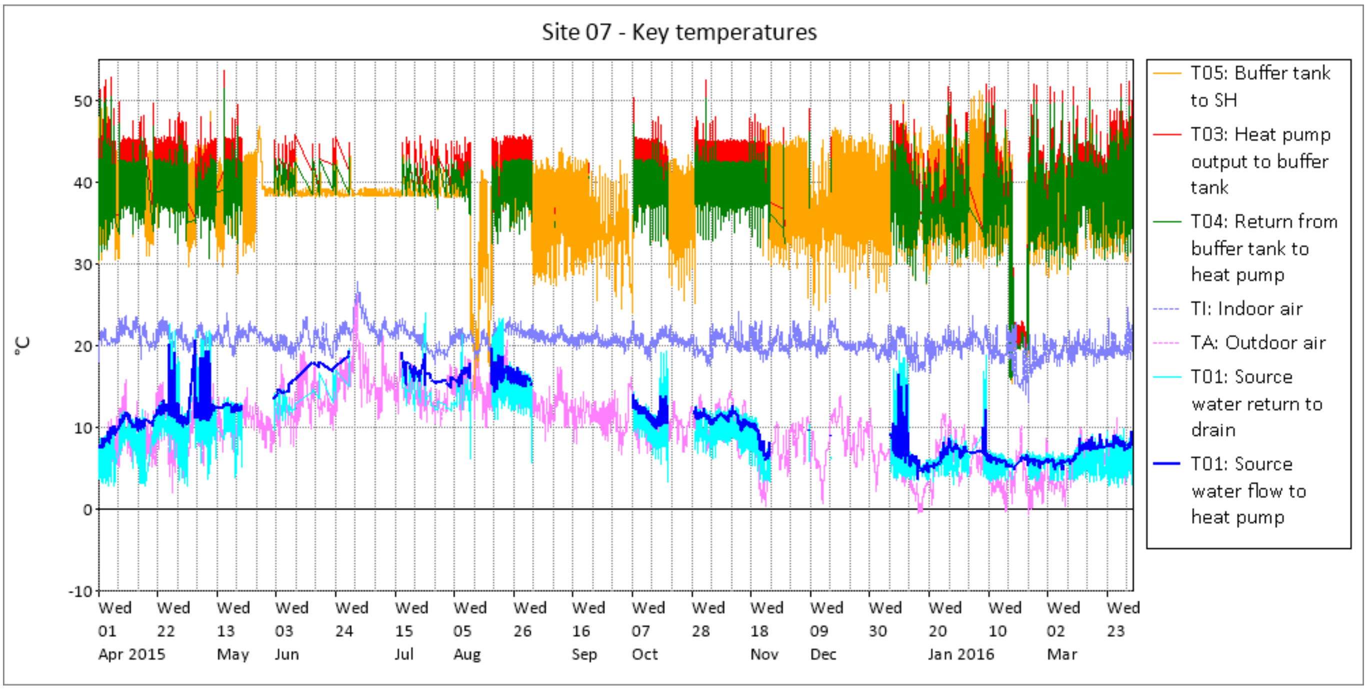

Figure 9 – Key temperatures measured during the period 1st April 2015 – 31st March 2016

Figure 10 shows the daily mean source flow temperature compared to the source temperatures (at the heat pump) of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were above average compared to other systems monitored. This would have had a positive influence on system performance.

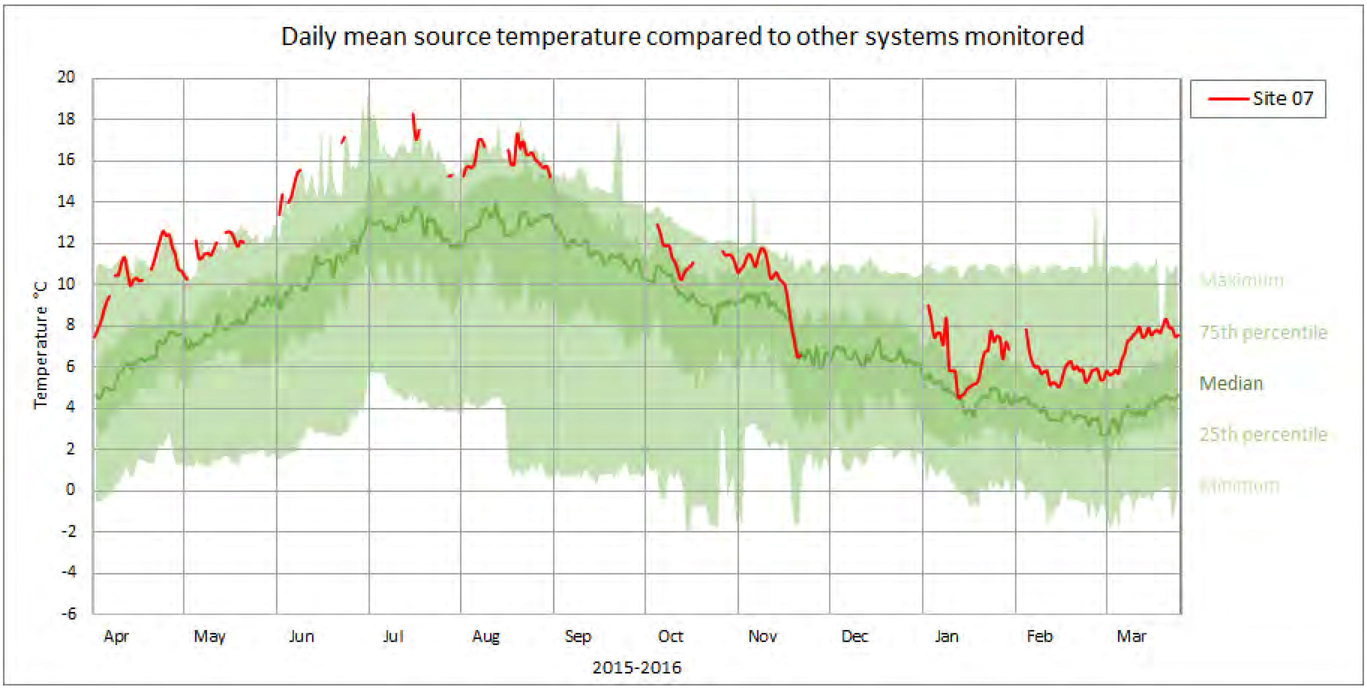

Figure 10 – Daily mean source flow temperature compared to the source temperatures of other systems monitored in this project (site 07 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems using underfloor heating monitored in this project. The output temperatures on this system were average compared to other systems.

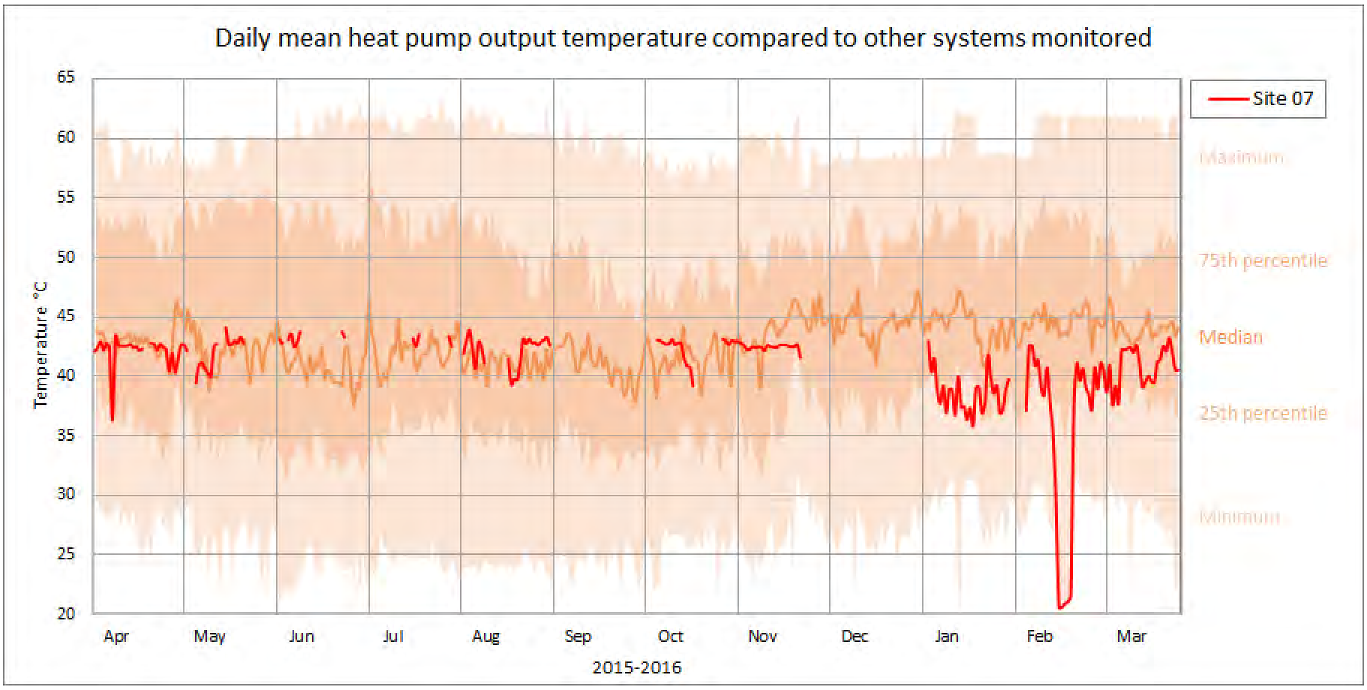

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems using underfloor heating monitored in this project (site 07 is shown in red)

Comments

The overall performance of this system (SPF_{H4} = 1.50) was very low compared to other systems providing space heating only that were monitored in this project (SPF_{H4} range: 1.42 to 4.10, median value 2.23).

Aspects of this system that positively influenced its performance are:

- The source temperature was high compared to most other systems monitored (see Figure 10).
- The source water is pumped directly to the evaporator, without an intermediate heat exchanger which would introduce temperature loss.
- The electricity used by the source pump was below average compared to other systems monitored: 6.3% of electricity use by the total heat pump system (the range for other systems was 2.3% - 29.8%, median 7.6%).

Aspects of the system that may have negatively influenced its performance include:

- The heat pump was not used to the extent that it could have been: the LPG-fired boilers provided heat to the space heating system at times when the heat pump could have been used. This appears to have been due to inappropriate control strategy or settings. This should be investigated and the control system adjusted so that better use is made of the heat pump.
- The electricity used by the buffer pump was very high – 36% of the electricity used by the total heat pump system. It was run periodically when the heat pump was not running to allow the control system to determine the return temperature. A change of control strategy could reduce the electricity used by the buffer pump.
- The electricity used by the space heating circulating pump was high at 12.5% of the electricity used by the total heat pump system.

The high proportion of electricity used by the buffer and heating pumps was at least partly due to the heat pump not being used as much as it apparently could have been. As a consequence, the heat pump used only a relatively small proportion of the total system electricity.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

[4] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps - Interim Report. URN 16D/013.,” DECC, 2016.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 10

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 10 and performance results from 12 consecutive months of monitoring data.

Site 10 is a converted barn, used as offices. It is situated in an exposed location.

A ground-source heat pump (thermal capacity 22 kW) extracts heat from horizontal ground loops and provides space heating via radiators.

The seasonal heating performance factors measured over a year of operation (1st January to 31st December 2015) were:

SPFH2	[Total heat delivered by the heat pump] -- [Electricity used by the heat pump + the brine pump]	2.33
SPFH4	[Total heat delivered by the heat pump system] -- [Electricity used by heat pump + brine pump + circulation pumps]	1.82

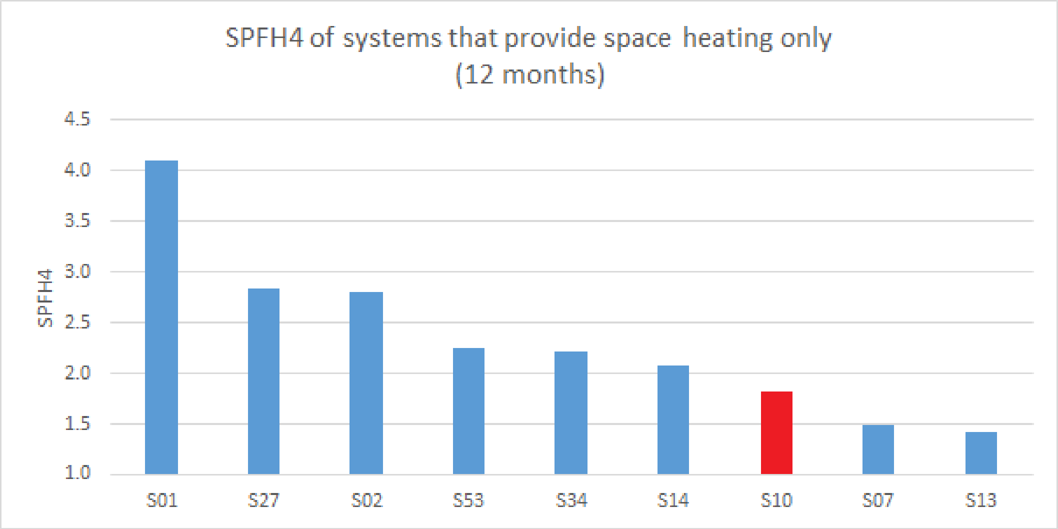


Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

An aspect of this system that positively influenced its performance is:

- No auxiliary heat was used in the heat pump system.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump ran at times when it was evidently not needed. This wasted energy and caused undesirable short-cycling behaviour.
- There was a significant loss of temperature between the heat pump output and the flow to the heating system – apparently due to the arrangement of the buffer tank and automatic bypass valve.
- The buffer pump appeared to run almost continuously.

- The temperature of the output to the radiators was high compared to other systems monitored.
- Weather compensation was not used.
- The temperature difference between the brine flow to the heat pump and the ground was unusually large: mean 6.9 °C and up to 11.5 °C during the coldest days. The median value for other horizontal ground collector systems monitored in this project was 2.4 °C.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**10**
Survey date	17/02/2014
Monitoring installed	09/06/2014
G/WSHP	GSHP
Building type	Offices
Location	Rural
Heat pump capacity kWTH	22
Number of heat pumps	1
Number of compressors	1
Heat source	Horizontal ground loops: 8 x 100m
Heat emitters	Radiators with thermostatic valves
DHW	No
Auxiliary heat	None
Source pump	External to heat pump: 300W
Buffer pump	External to heat pump: 70W max
SH circulating pumps	External to heat pump: 70W max
Buffer tank	200 litre 2-pipe in flow
DHW cylinder	N/A
Control	Programmable thermostat + radiator thermostatic valves + heat pump controller
Weather compensation	No
Heat meter type	Vortex
No. of heat meters	1
Heat meter interface	M-Bus
Comments	The heat meter is installed inside the building

Table 1 – System details

The site is a converted barn that is used as offices. The building is in an exposed location.

This application comprises a ground source heat pump that provides space heating only to an office building in a location with average outdoor temperatures – annual mean 10.4 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). It is occupied during weekday office hours. The performance of the system would be expected to be good.

Heat and monitoring systems

A 22 kWTH heat pump is installed in small wooden shed at one end of the barn.

The heat source is an array of 8 x 100 metre horizontal ground loops at a depth of approximately 1.2 metres in a field adjacent to the building.

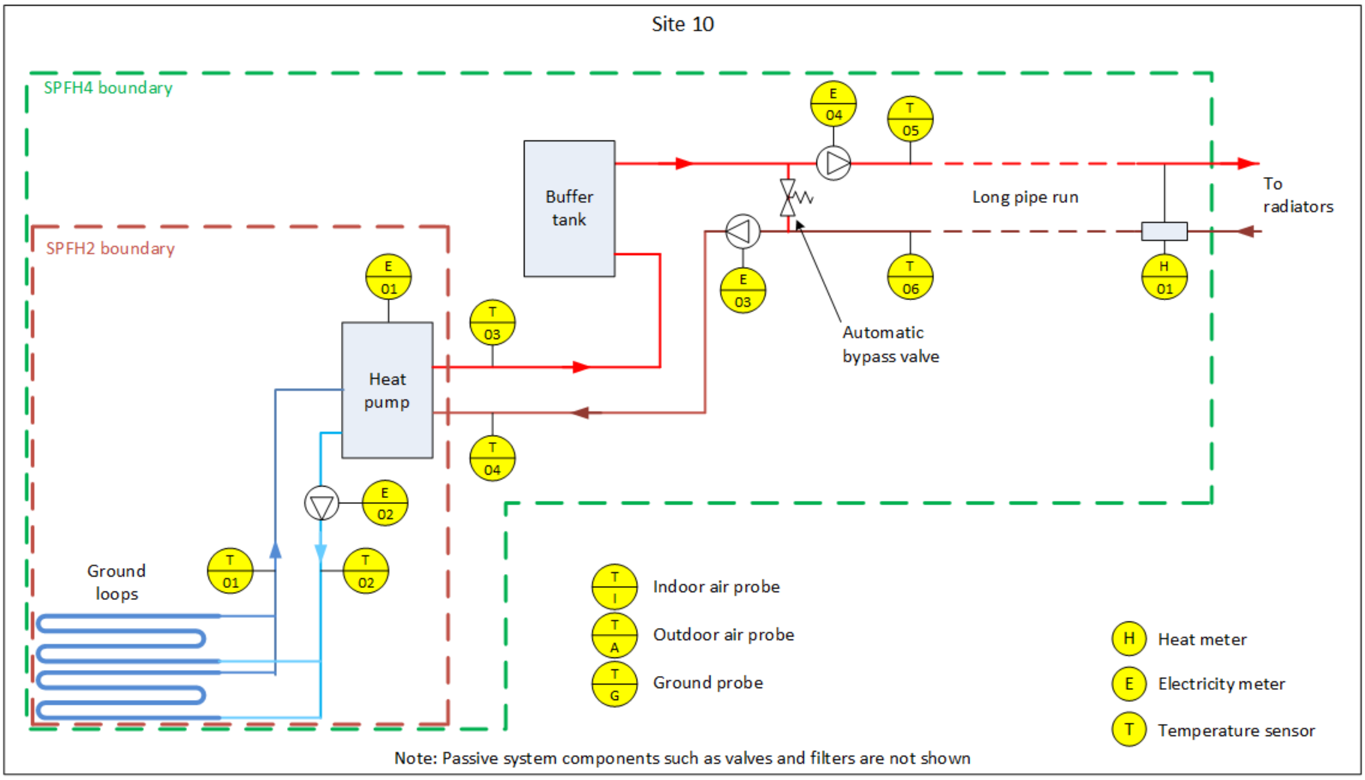
The heat emitters are radiators, installed at the time of the barn conversion and sized for use with a heat pump. All radiators are fitted with thermostatic valves.

A 200-litre 2-pipe buffer tank is installed in the flow from the heat pump to the heating circuit. An automatic bypass valve and bypass pump are installed, presumably to ensure that a minimum flow rate is maintained through the heat pump condenser.

The heating circulating pump is controlled by a programmable thermostat inside the building.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1]. The outdoor air and ground temperatures are also monitored.



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the system. The meter on this system is installed inside the building, remote from the heat pump. This arrangement is to ensure that only the heat delivered to the heating system is measured. The flow meter is of the vortex type. The matched temperature sensors are installed in fittings with the probes inside the flow and return pipes. The calculator is mains-powered, and the monitoring was via the M-Bus interface.

The pipes connecting the heat pump with the heating system are approximately 25 metres long (from the heat pump to the heat meter). Part of the pipe run (about 3 metres) is clipped to the outside of the building. The pipes are insulated with weatherproof black flexible closed-cell foam approximately 20mm thick.

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[1] The temperature probes were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [2] for further details. Note that these temperature measurements were not used for heat metering.

The location of the heat meter unfortunately does not permit accurate calculation of the heat pump performance, for which the heat meter should be located close to the output of the heat pump.

The heat delivered by from the heat pump plant room was estimated using the flow readings from the heat meter (obtained via the M-Bus interface) and the temperature measurements on the flow and return pipes inside the plant room. The heat lost between the plant room and the heat meter was approximately 6% of the heat delivered from the heat pump plant room, although part of this heat was "lost" into the heated envelope.

The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

Heat meter correction

A further complication is that the heat meter was found to have been configured for use with antifreeze in the working fluid, although none was present in the heating circuit at the time monitoring started.

On 2nd August 2015, antifreeze (ethylene glycol) was added to the heating circuit at a concentration[2] of 35% by volume. The heat meter configuration was not changed.

A correction factor was applied to heat meter readings taken before 2nd August 2015. This factor was determined using the flow rate and temperature readings from the heat meter to calculate the correct thermal power at the meter, using the specific heat capacity of water, and dividing that value by the thermal power reported by the heat meter. The heat meter is apparently configured for a 35% concentration of ethylene glycol.

Readings from the heat meter after 2nd August 2015 have been taken to be correct.

Heat loss from pipes

In order to determine the heat delivered from the heat pump plant room it was necessary to estimate the heat losses from the pipes between the plant room and the heat meter inside the building. Two methods were used, with the calculations performed for each 1-minute interval.

- Calculation of heat losses based on temperatures and insulation thermal performance data. The estimated heat loss using this method was 15% of the heat recorded by the heat meter. However, the calculation ignored the effects of wind and rain, so the heat losses from the outdoor section may have been significantly underestimated.
- Comparison of the temperature difference measured at the plant room (T05 - T06) with that measured by the heat meter, using the flow rate measured by the heat meter to calculate the heat at the two locations in the same circuit. The estimated heat loss using this method was 26% of the heat recorded by the heat meter.

The second method was the one adopted for determining the heat delivered by the heat pump and the SPF_{H2} value.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries

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[2] The concentration was confirmed by the system installer.

(denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive.

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

- The heat delivered from the plant room (H_{PR}) was calculated using the flow rate measurements from the heat meter and the temperature measurements (T_{05} & T_{06}) of the flow and return at the plant room:

$$H_{PR} = [\text{Flow rate}] * (T_{05} - T_{06}) * [\text{Specific heat capacity of water or glycol/water}]$$

- The heat loss (H_{LossBT}) from the buffer tank was estimated from published heat loss data for buffer tanks and using the measured buffer tank temperature (T_{03}) and an assumed plant room temperature of 15 °C.

$$H_{LossBT} = [\text{Tank heat loss rate}] * (T_{03} – 15)$$

Heat loss rate of 200 litre tank: 1.5 W/K

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the SH circulating pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pumps (E_{03} & E_{04}).

- The heat output of the heat pump (H_{HP}) was determined by adding the buffer tank heat loss and subtracting the heat added by the circulating pumps to the heat delivered from the plant room (H_{PR})

$$SPF_{H2} = \frac{\text{[Heat output of heat pump } (H_{HP})\text{]}}{\text{Electricity used by: [heat pump } (E_{01})\text{] + [brine pump } (E_{02})\text{]}}$$

$$SPF_{H4} = \frac{\text{[Heat measured by the heat meter } (H_{01})\text{]}}{\text{Electricity used by: [heat pump } (E_{01})\text{] + [brine pump } (E_{02})\text{] + [SH circ pumps } (E_{03}+E_{04})\text{]}}$$

The number of 1-minute intervals selected as valid for analysis was 378 094, which represents 91.8% of the time that the heat pump was operating. Most of the invalid intervals were during February when there was an unexplained problem with the wireless link from the M-Bus device connected to the heat meter.

The mean SPF_{H2} and SPF_{H4} values for this system, between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	2.33
SPF_{H4}	1.82

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 1.82 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. The gap in the data during February is due to missing heat meter readings (as noted above). The gaps during the summer months were when the heat pump system was switched off.

The highest daily SPF_{H4} values were during the coldest weather in January, February and March, with the daily SPF_{H4} tending to reduce as the outdoor temperature increased. The explanation appears to be that the heat pump continued to cycle on and off at all times even when the weather was warmer and when there was little or no heat demand. Consequently, much of the heat output was simply wasted through losses from the buffer tank and pipework in the plant room and outside the building. This is discussed further in the following paragraphs.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [3] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

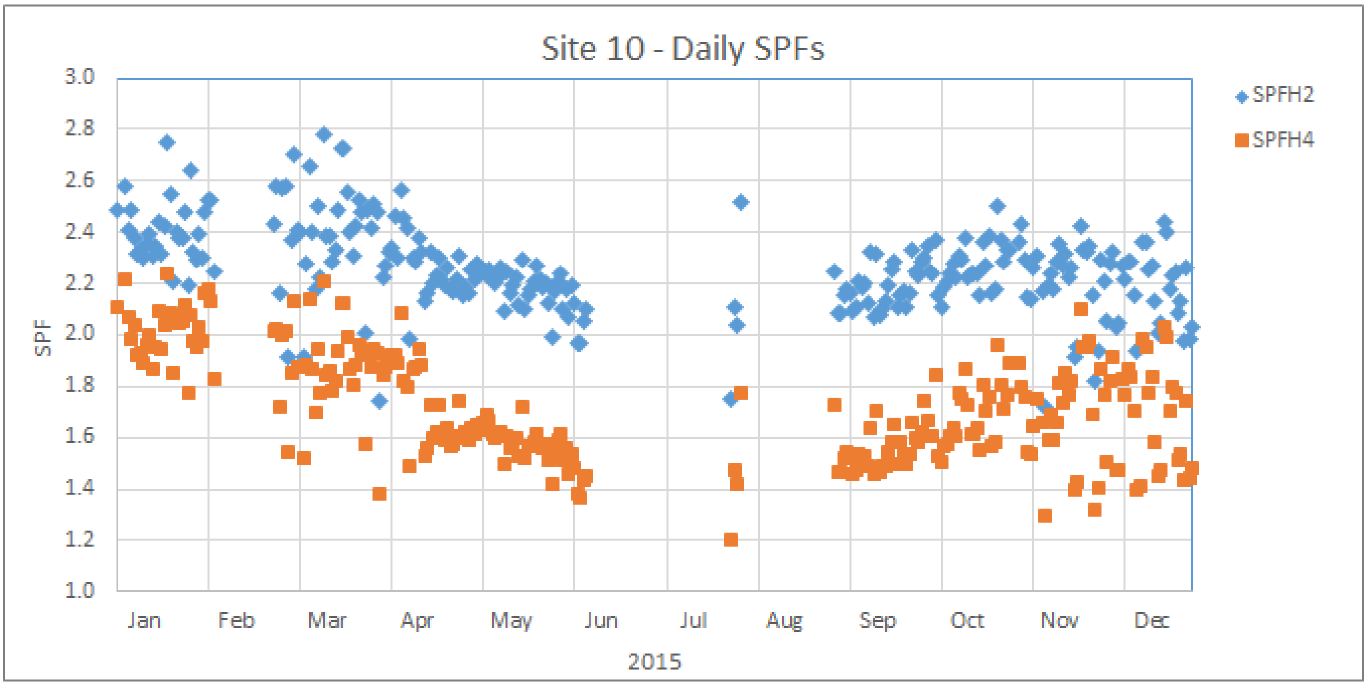

Figure 3 – Seasonal performance factors SPF$_{H2}$ and SPF$_{H4}$ calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to circulate brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [1] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The heat output increased as the outdoor temperature reduced, as would be expected. The heat pump system was switched off for most of the summer months.

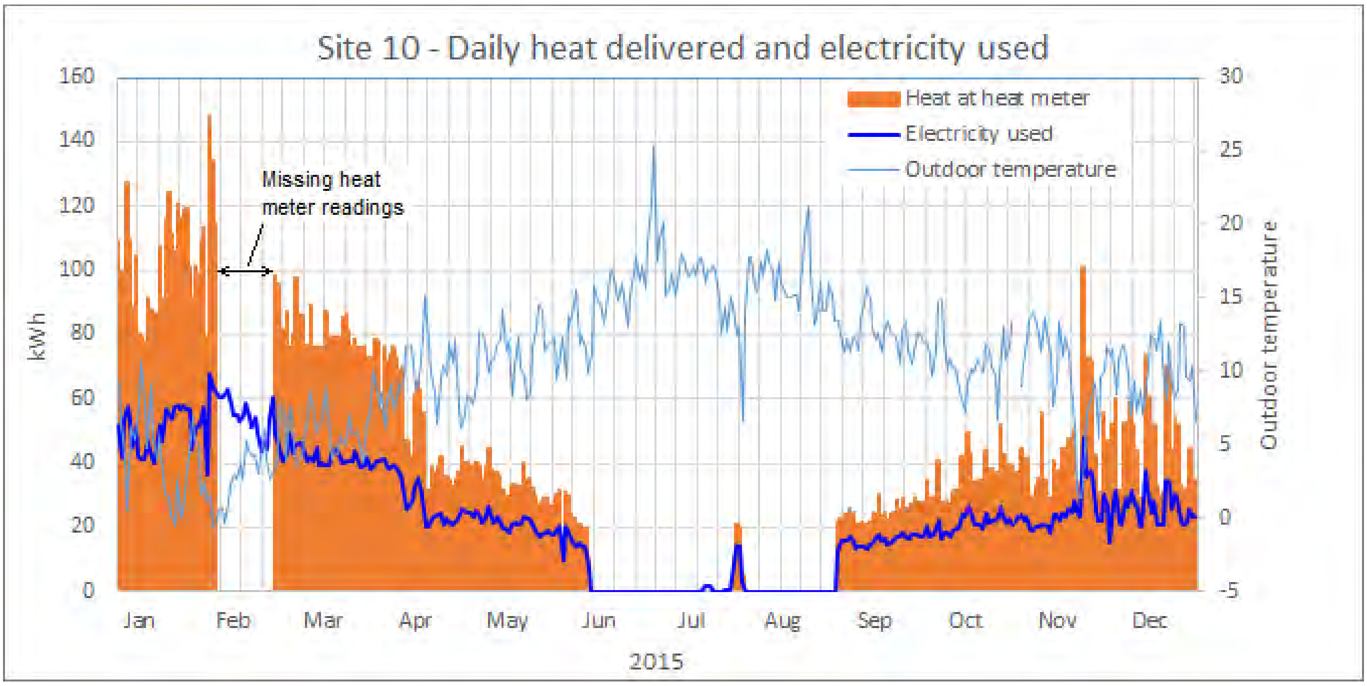

Figure 4 – Daily heat delivered and electricity used

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use.

The brine pump accounted for 5% of the total electricity used by the heat pump system. This is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%) and would have had a positive influence on the system performance.

The buffer pump and the heating circulating pump together accounted for 4.4% of the total. This is below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). However, it can be seen that both of these pumps were running at times during the summer period when there was no demand for space heating. Although the effect on the overall performance was negligible (less than 0.1% reduction of the SFPH4), wasteful operation like this should be avoided.

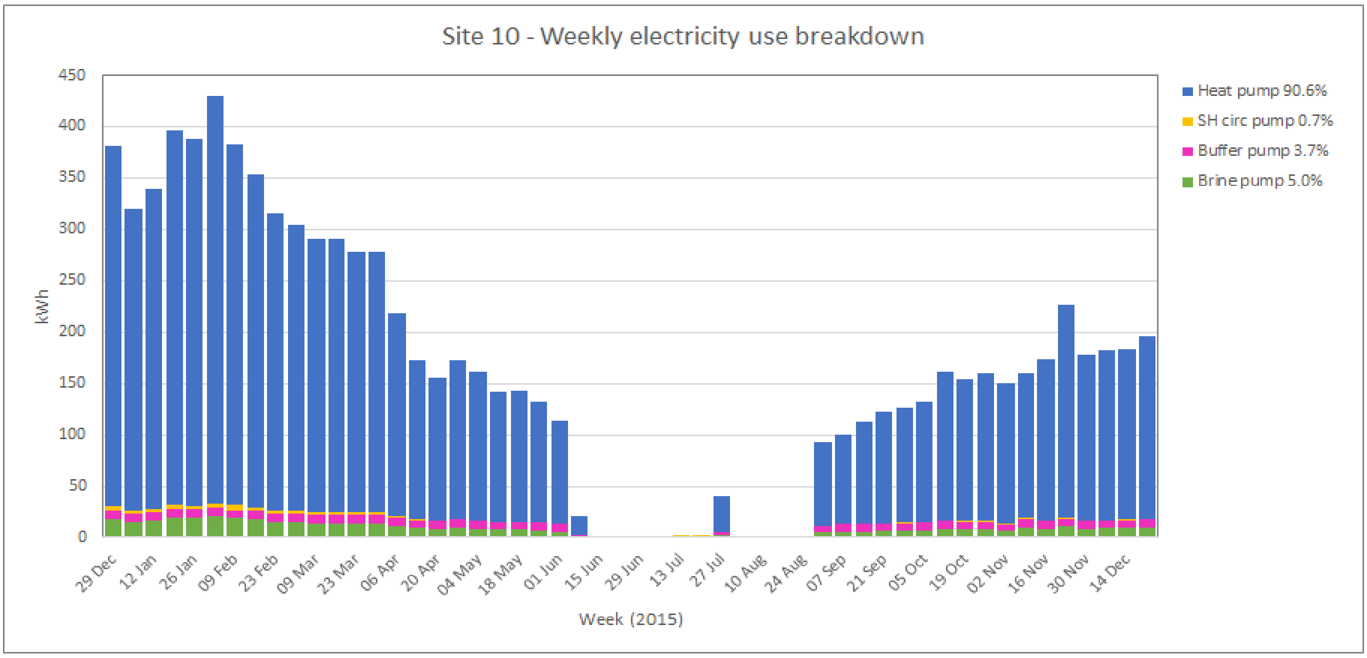

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern during a cold day on 23rd January 2015 when the outdoor temperature was between -6 and +7 °C.

The heat pump system was cycling on and off all 24 hours, with the space heating circulating pump on from 05:30 to 17:00. The buffer pump was running continuously all day. The increase in thermal power measured by the heat meter while the space heating pump was on can be clearly seen. The indoor temperature rose during this period – from 17 °C at 05:30 to 20 °C at 09:00, but then continued to rise to 24 °C at 17:00. This appears to have been due to an inadequate control strategy.

The heat pump output temperature was at a maximum of 57 °C during the day, although the temperature of the flow to the heating system was never above 52 °C. Also, the temperature of the return to the heat pump was always higher than the return from the heating system. These observations indicate that there was flow through the automatic bypass valve, causing a loss of temperature between the heat pump and the heat emitters. This would have had a negative effect on the performance.

There was some heat recorded by the heat meter during the night (23 kWh). This was presumably a consequence of flow through the heating circuit being induced by the buffer pump. This heat was not needed, so the heat pump could have been switched off during the night. The saving of electricity would have been approximately half of that used during the night (the heat pump would have needed to run for longer at the start of the heating period to raise the indoor temperature): a saving of 8 kWh with a value of around £1.20 per day[5].

The temperature of the ground[6] was an almost constant 6.6 °C. The brine flow to the heat pump was 2 °C during the low load operation at night time, but fell to -4 °C between 06:00 and 08:00 when there was the biggest heat load. The brine return to the ground loops dropped to -6.8 °C during this period. These brine temperatures are lower than on most other systems monitored: see Figure 12.

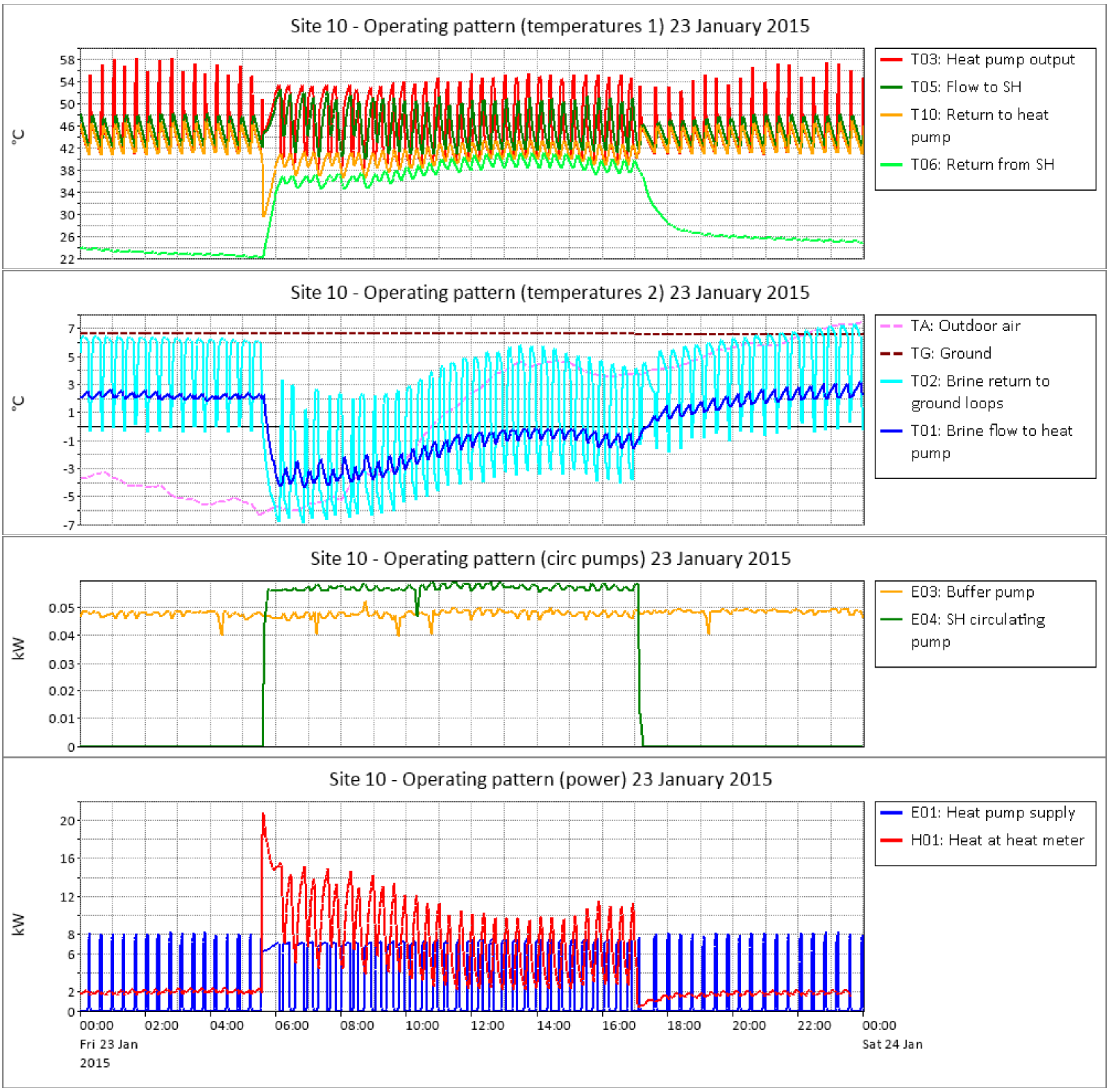

Figure 6 – Operating pattern on 23rd January 2015

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[5] Assuming a unit cost for electricity of 14.7 p/kWh [4].

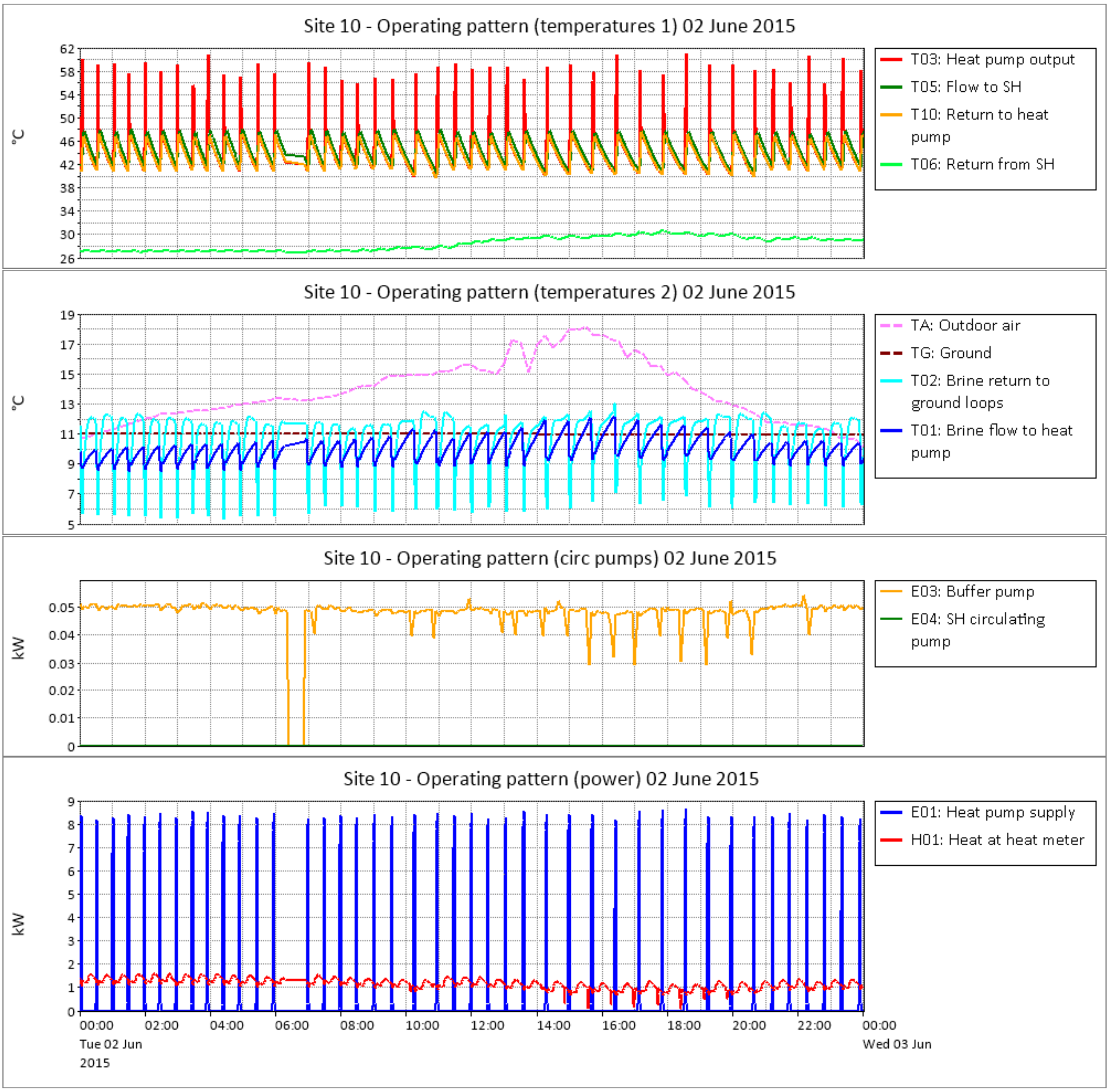
[6] The ground temperature was measured 1 metre below the surface at a point remote from the ground collector.

Figure 7 shows the operating pattern on 2nd June 2015 when the outdoor temperature was between 10 and 18 °C. The temperature at the heat pump output was up to 61 °C (slightly higher than it was in January) but the output to the heating system was never above 48 °C – again indicating a high flow through the automatic bypass.

It is unclear why the heat pump system was cycling on and off all day. The space heating circulating pump, which is controlled by the heating programmer/thermostat, was not on at any time during the day, so there was presumably no demand for heat. The buffer pump was running for most of the day. There was some heat delivered (28 kWh) as shown by the heat meter power curve, but this seems to have been due to the buffer pump inducing some flow through the heating system.

The SPF_{H4} measured for this day was 1.54.

The heat pump was not producing any useful heat so it could have been switched off on this day. This would have saved 19 kWh of electricity – a cost saving of around £2.80 per day.


Site 10 - Operating pattern (temperatures 1) 02 June 2015

Site 10 - Operating pattern (temperatures 2) 02 June 2015

Site 10 - Operating pattern (circ pumps) 02 June 2015

Site 10 - Operating pattern (power) 02 June 2015

Figure 7 – Operating pattern on 2nd June 2015

Cycling behaviour

The heat pump on this system ran for very short times throughout the year.

Figure 8 shows the tapestry of operation for the 12-month monitoring period. Each red marker indicates the heat pump running. Although the building is normally occupied only during office hours, the heat pump operated at all times of the day and night, except during most of July and August when the system was switched off. The increased use between 06:00 and 17:00 during the winter is clearly seen.

Most of the short runs during periods of low load (at night and from May to October) were for less than 4 minutes. The longest run during the year was for 32 minutes, but most runs were much shorter. Figure 9 shows a summary of the daily average run times and number of starts per hour.

These short run times are less than the minimum 6 minutes recommended by the heat pump manufacturer and are known from previous research [1] to be a cause of poor performance, as well as causing excessive wear and tear on the equipment.

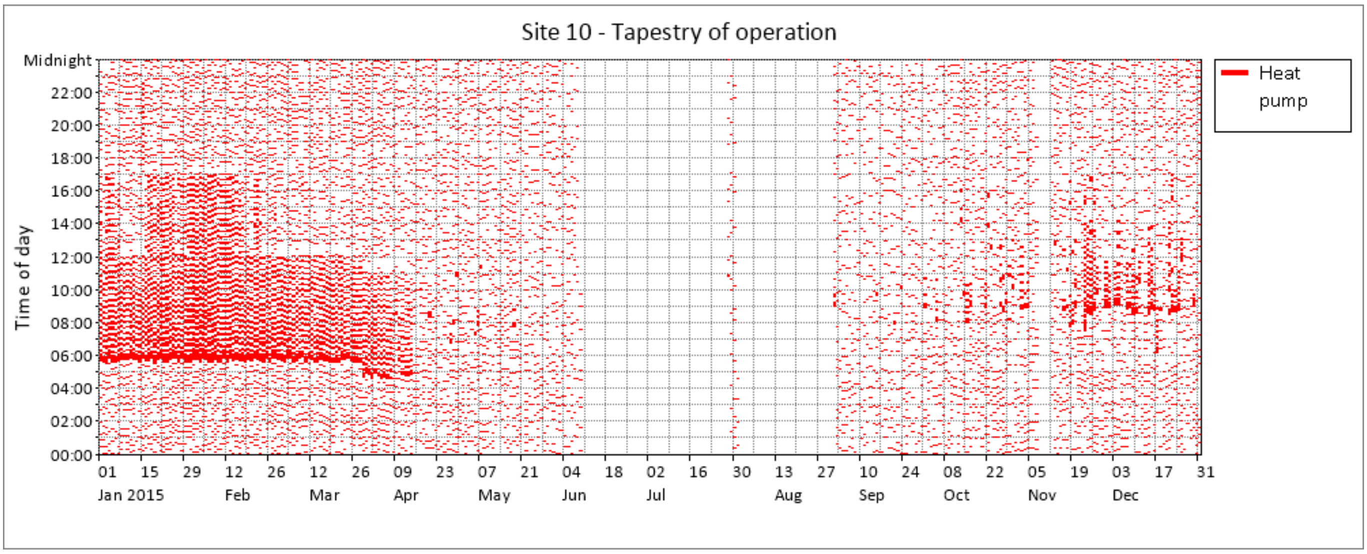


Figure 8 – Tapestry of operation for 1st January to 31st December 2015

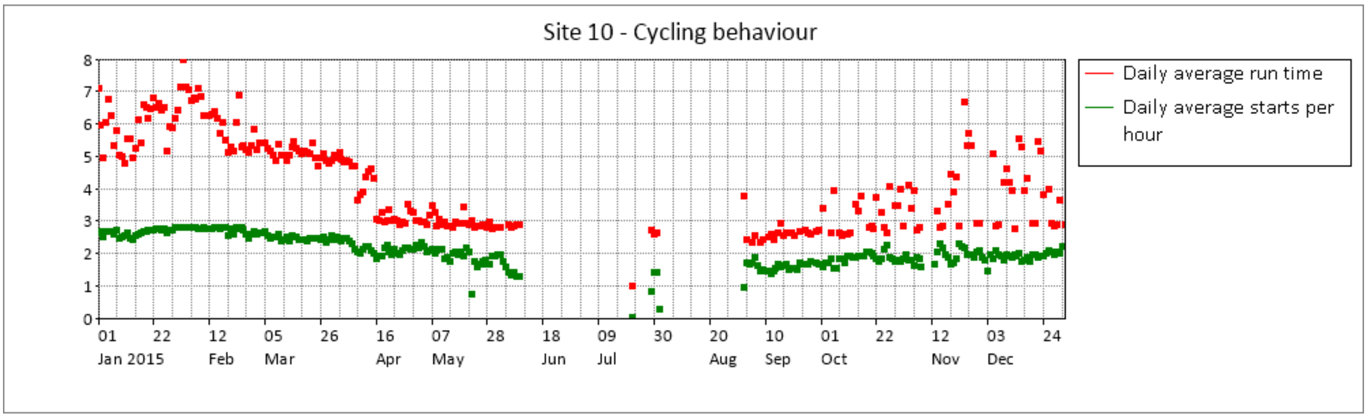


Figure 9 – Summary of cycling behaviour

Source and sink temperatures

Figure 10 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[7]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

It can be seen that the maximum heat pump output temperature was higher during warm weather than during the winter. This effect is the opposite of what would be expected if weather compensation were used. The temperature of the output to the heating system is seen to be up to 58 °C during colder weather, but not above 48 °C during most of April, May, September and October. This lower temperature corresponds with the times that the space heating circulating pump was not running, and the times during which the heat pump could be switched off as noted above.

The heat pump was not run during most of June, July and August.

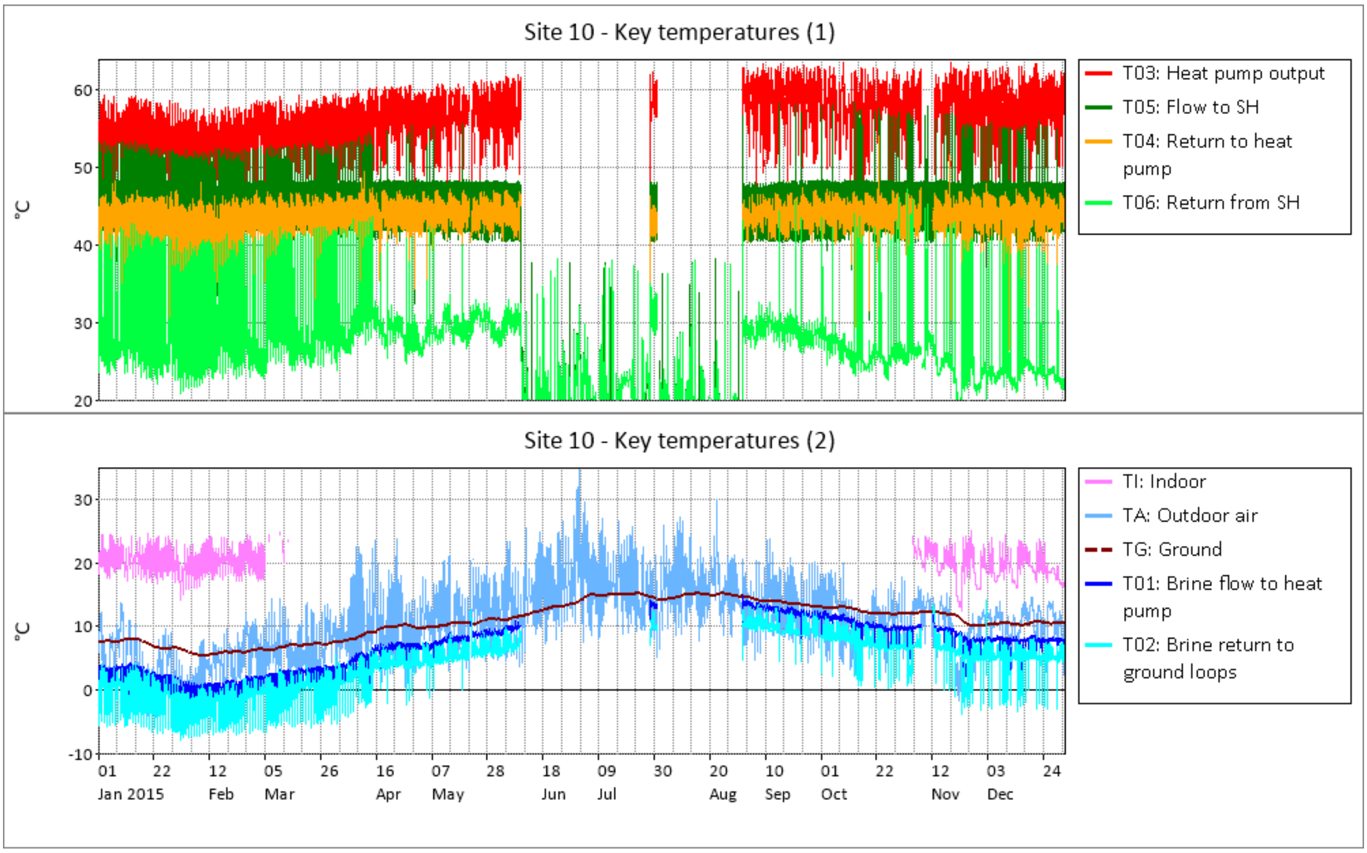


Figure 10 – Key temperatures measured during the period 1st January – 31st December 2015

The temperature of the brine flow to the heat pump was frequently below 0 °C from January to mid-April, reaching a minimum of -5 °C on 1st February. At times of maximum heat demand, the temperature of the brine flow was between 8 and 11.5 °C below the ground temperature. This temperature difference between the ground and the brine is larger than on most other horizontal-loop ground-source systems monitored in this project (as shown in Figure 11), which suggests that the ground collector may be undersized, although the design calculations would need to be reviewed to confirm this.

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[7] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

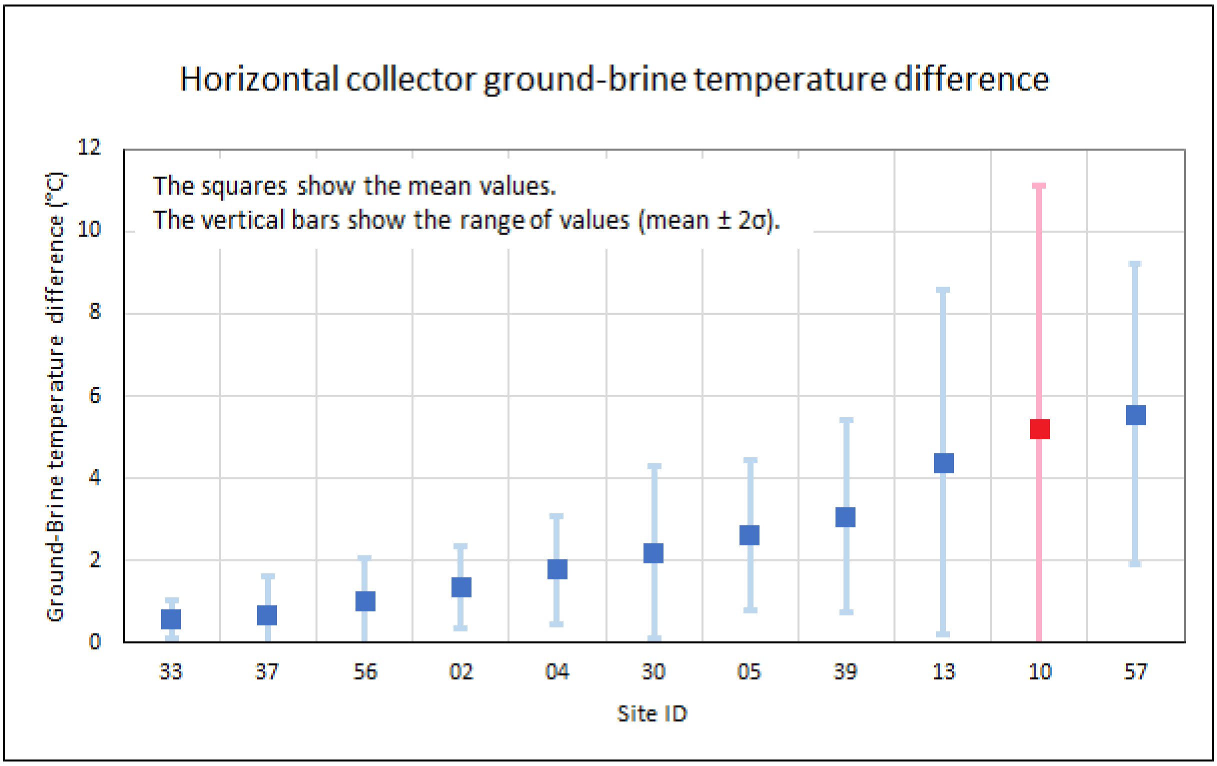

Figure 11 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 10 is shown in red)

Figure 12 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were very low during the first three months of the year. This would have had a negative effect on the system performance. However, the brine temperatures were average compared to other systems from April onward, when the heat load was lower compared to the start of the year.

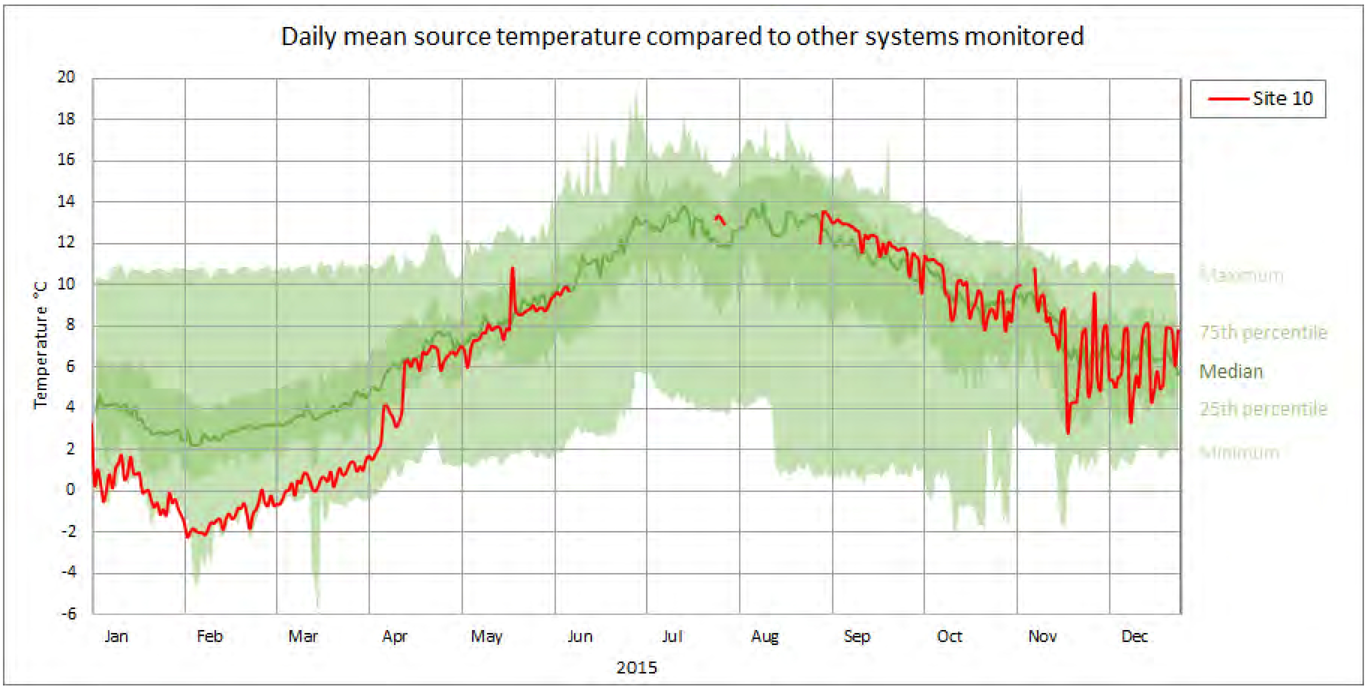

Figure 12 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 10 is shown in red)

Figure 13 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperature range on this system is at the upper end of the values observed on other systems. This would have had a negative effect on the system performance.

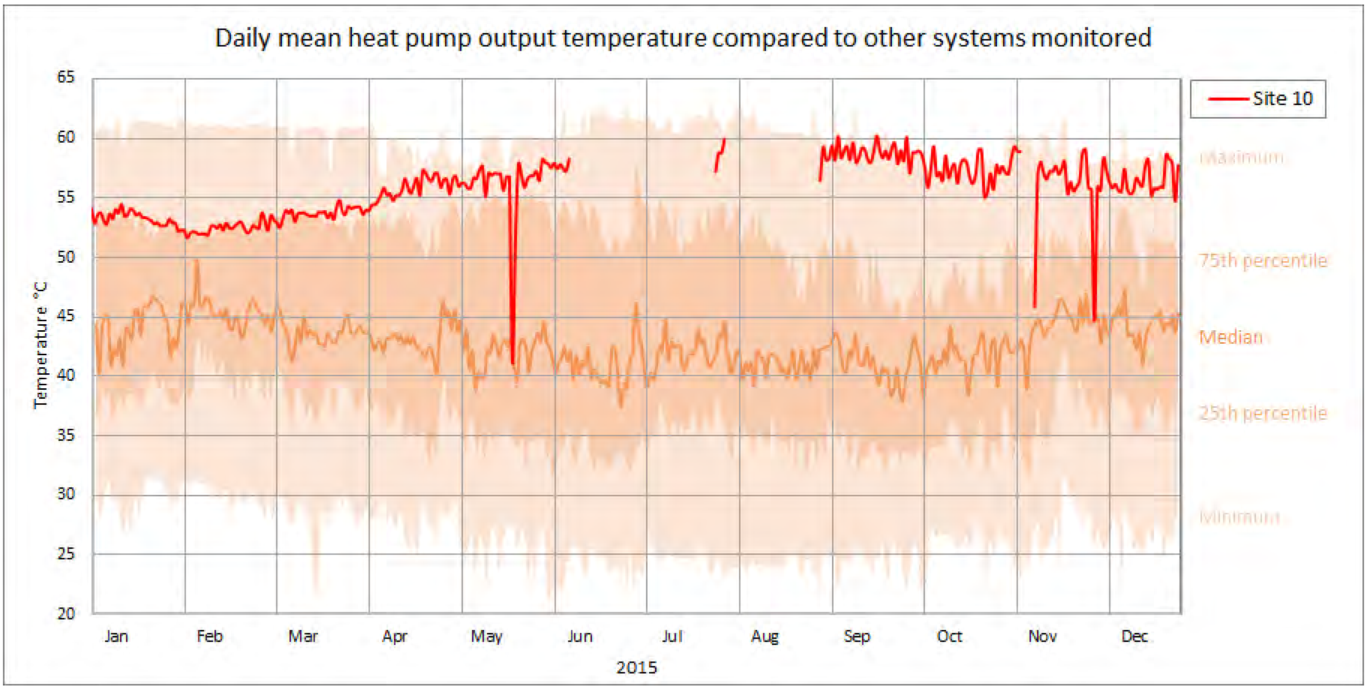

Figure 13 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 10 is shown in red)

Comments

The overall performance of this system (SPF_{H4} = 1.82) is low compared to other systems providing space heating only that were monitored in this project (SPF_{H4} range: 1.42 to 4.10, median value 2.23).

Aspects of this system that positively influenced its performance are:

- No auxiliary heat was used in the heat pump system.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump ran at times when it was evidently not needed – i.e. all night and at weekends, even when the weather was mild. A reduction in out-of-hours and other unnecessary operation should improve the overall system performance. The number of compressor starts would also be reduced, which would help improve the lifetime of the equipment.
- The short-cycling behaviour is undesirable as it reduces performance and causes excessive wear and tear on the equipment. Avoiding the out-of-hours operation should help to improve this, but it would also be worth checking that the heat pump controller is configured in the most appropriate way. It is possible that a change of configuration could reduce short-cycling and improve overall performance.
- There was a significant loss of temperature between the heat pump output and the flow to the heating system – e.g. 5 °C during high load conditions (as shown in Figure 6) up to 10 °C during low load conditions when the space heating circulating pump was not running (as shown in Figure 7). Other similar systems monitored in this project that have 2-pipe buffer tanks typically operate with temperature loss of less than 2 °C. The automatic bypass valve should be checked to ensure that it is operating correctly.

Note: there was no evidence that the thermostatic radiator valves played any part in reducing the flow through the heating circuit – the flow rate measured by the heat meter was always constant while the heating circulating pump was running.

- The buffer pump appeared to run almost continuously. This should be unnecessary and may have been a contributory cause of the heat pump short cycling. The heat pump controller settings should be checked to ensure that this pump is being run only when needed.
- The temperature of the output to the radiators was high compared to other systems monitored. If this can be reduced the performance will be improved.
- Weather compensation was evidently not being used, although the sensor for this has been installed and is visible on the outside of the heat pump building. It is understood that the heat pump controller has weather compensation functionality, so it would be worth investigating if this can be brought into use. The reduction in output temperature during warmer weather should give additional performance improvement.
- The temperature difference between the brine flow to the heat pump and the ground (remote from the ground loops) was unusually large: mean 6.9 °C and up to 11.5 °C during the coldest days. The median value for other horizontal ground collector systems monitored in this project was 2.4 °C. The ground collector on this system may be undersized, although the design calculations would need to be reviewed to confirm this.

Bibliography

[1] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[2] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[3] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

[4] “Quarterly Energy Statistics (https://www.gov.uk/government/collections/quarterly-energy-prices),” BEIS.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 13

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 13 and performance results from 12 consecutive months of monitoring data.

Site 13 is a greenhouse that is used for growing flowers. Three heat pumps (total thermal capacity 144 kW) extract heat from horizontal ground loops and provide space heating to the greenhouse. An oil-fired boiler has been retained to provide additional heat during cold periods.

The system has been analysed as a bivalent system.

The seasonal heating performance factors (including heat from the oil-fired boiler) measured over a year of operation (1st January to 31st December 2015) were:

SPFH2	Heat delivered by [heat pumps] – [heat added by buffer pumps] --- Electricity used by [heat pumps] + [brine pumps] – [buffer pumps]	2.29
SPFH4	Heat delivered by [heat pumps] + [oil-fired boiler] + [heating circ pump] – [buffer tank heat loss] --- Electricity used by [heat pumps + [brine & heating circ pumps] + [fuel used by boiler]	1.42

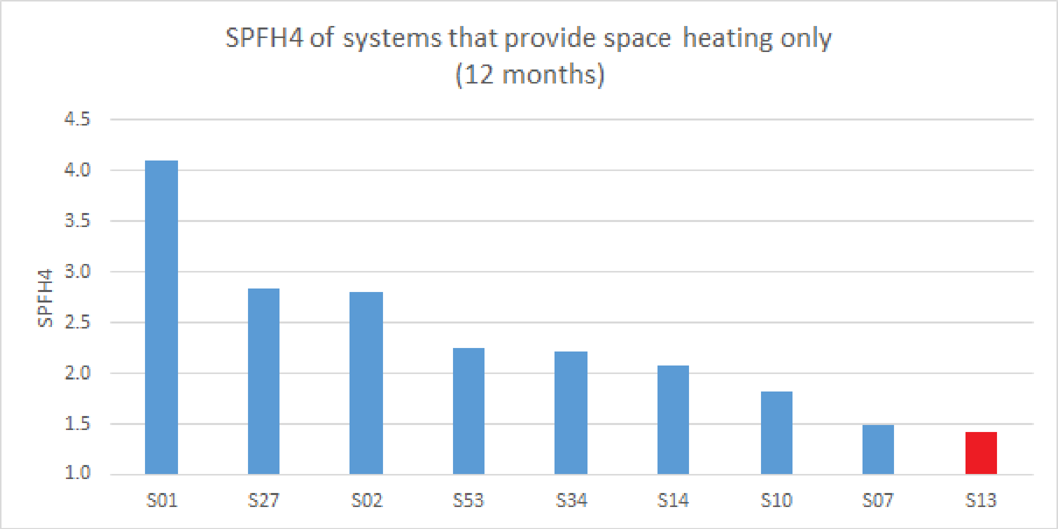

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

This system is quite different in character to the others monitored in this study. The building is poorly insulated, has low thermal inertia and is strongly affected by direct sunlight. The required indoor temperature is lower than typically required for occupied buildings, but the temperature needed by the heat emitters is considerably higher than required by other systems.

Aspects of the system that may have negatively influenced its performance include:

- Bivalent operation (heat-pump plus oil-fired boiler).
- The mean temperature difference between the ground and the brine flow to the heat pumps was above average compared to other horizontal collector systems monitored.
- The type of heat emitter used requires high temperatures (having been designed for an oil-fired system).

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	13
Survey date	10/03/2014
Monitoring installed	27/05/2014
G/WSHP	GSHP
Building type	Greenhouse
Location	Rural
Heat pump capacity kW$_{TH}$	144 (total)
Number of heat pumps	3
Number of compressors	6
Heat source	Horizontal ground loops: 4000m at 1m depth
Heat emitters	Pipes at high and low level
DHW	No
Auxiliary heat	Oil-fired boiler
Source pumps	2 external 1 kW; 1 internal 120 W
Buffer pumps	Internal to heat pump: 4 x 75 W; 2 x 70 W
SH circulating pumps	2 x 200 W variable-speed
Buffer tank	3000 litre 4-pipe
DHW cylinder	N/A
Control	Greenhouse climate controller with dedicated weather station + heat pump controller (master + 2 slaves)
Weather compensation	No
Heat meter types	Vortex / Ultrasonic
No. of heat meters	2
Heat meter interface	M-Bus / pulse
Comments	The heat pumps and the oil-fired boiler operate as a bivalent heating system

Table 1 – System details

This site is a greenhouse that is used for growing flowers. The application entails extracting heat from the ground to provide space heating to the greenhouse which is by its nature poorly insulated and has a low thermal inertia. It is also strongly affected by thermal radiation – heating during daylight and cooling during darkness. The temperature needed in the greenhouse is between 14 and 16 °C. The site is located in an area with slightly above-average outdoor temperatures – annual mean 10.8 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3°C).

Heat pump and monitoring systems

Three heat pumps (total thermal capacity 144 kW) were installed in 2012 to provide space heating. Each heat pump comprises two vapour-compression systems.

The heat source is 4000 metres of horizontal ground loops at a depth of approximately 1 metre, in a field adjacent to the greenhouse.

The 3000-litre, 4-pipe buffer tank is intended as a thermal store. The heat pump charges the buffer tank during the warm part of the day when heating is not required in the greenhouse. The stored heat can then be used when needed.

The heat emitters are iron pipes at high and low level. These were installed for use with the oil-fired boiler and were designed to operate with hot water at 70 °C. This temperature is still required during very cold spells. As the heat pumps cannot provide hot water at this temperature, the oil-fired boiler is used when needed – often at short notice, given the low thermal inertia of the greenhouse.

Bivalent operation

The system operates mainly in “bivalent alternative” mode (heat provided either by the heat pump or by the oil-fired boiler) but sometimes in “bivalent parallel” mode (heat provided by the heat pump and the boiler at the same time).

The system is controlled by a specialised greenhouse climate controller which has a dedicated weather station. The heat pumps are controlled in a master/slave arrangement by the controller in the master heat pump.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures (“T”) are monitored at key points in the system using surface-mounted probes[1]. The outdoor air and ground temperatures are also monitored.

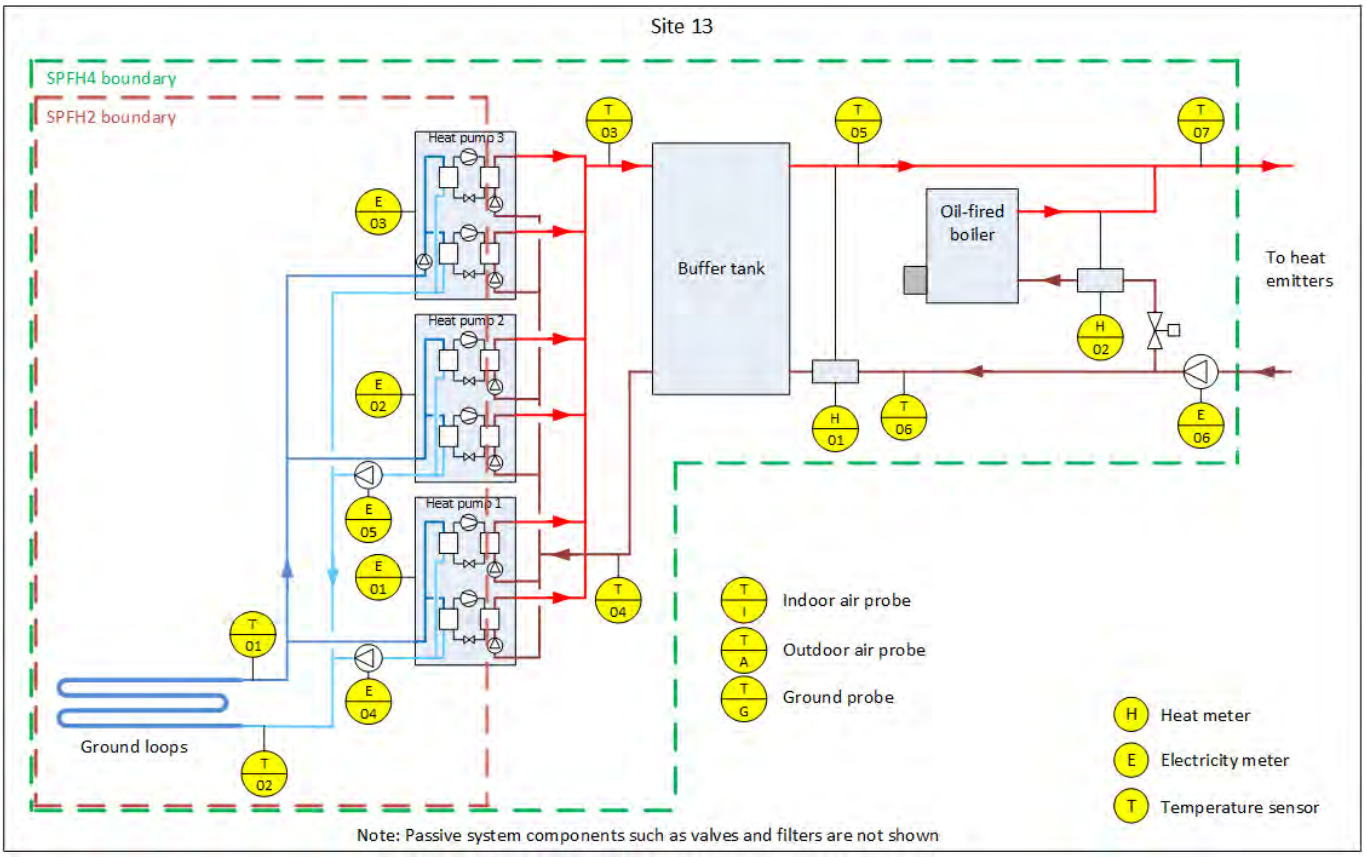

Figure 2 – System schematic showing the monitoring instrumentation installed

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[1] The temperature probes were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Heat metering

The heat meter H_{01} previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. This heat meter is installed between the buffer tank and the heat emitters. It uses a vortex flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is mains-powered and is monitored via its M-Bus interface.

A second heat meter H_{02} (not used for RHI) is installed on the output from the oil-fired boiler. This meter uses an ultrasonic flow meter, temperature probes installed in fittings in the pipes, and a battery-powered calculator. Monitoring was via the pulse output from the calculator.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pumps together with the source pumps.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and the oil-fired boiler.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the boiler heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pumps and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

---

[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat measured by heat meter H01]} - \text{[heat added by buffer pumps]} - \text{[heat loss from buffer tank]}}{\text{Electricity used by: [heat pumps]} - \text{[buffer pumps]} + \text{[brine pumps]}}$$

- This calculation required the electrical energy used by the buffer pumps inside the heat pumps to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pumps, calculated for intervals that the heat pump was running.

- The heat added by the buffer pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.

$$SPF_{H4} = \frac{\text{[Heat measured by heat meter H01]} + \text{[heat added by heating circ pump]} + \text{[heat output from oil-fired boiler]}}{\text{Electricity used by: [heat pumps]} + \text{[brine pumps]} + \text{[heating circulating pump]} + \text{[energy value of fuel used by the oil-fired boiler]}}$$

- The heat added by the heating circulating pump was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pump.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 10 °C [4].

- The energy of the fuel supplied to the oil-fired boiler E_{OFB} was calculated using an assumed boiler efficiency of 85%.

$$E_{OFB} = \frac{\text{[Boiler heat output]}}{\text{[Boiler efficiency]}}$$

The number of 1-minute intervals selected as valid for analysis was 523 204, which represents 99.5% of the 12-month period.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	2.29
SPF_{H4}	1.42

Table 2 – SPF values measured for the period 1st January to 31st December 2015

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[4] The assumed plant room temperature on this site is lower than for other sites monitored because of the poor thermal insulation of a greenhouse.

This means that for each unit of electricity used, this system delivers on average 1.42 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPFH2 and SPFH4 values for the system. The system has been considered as a bivalent heating system, with the heat output from the oil-fired boiler and the energy supplied by the oil included in the SPFH4 calculation.

The very low SPFH4 values during the winter months (January – March and November) are due to the oil-fired boiler being used. From April to June, the boiler was not used and the SPFH4 values are close to the SPFH2 values.

The higher SPF values during November and December can be explained by the heat pump output temperature being lower during that period (see Figure 8).

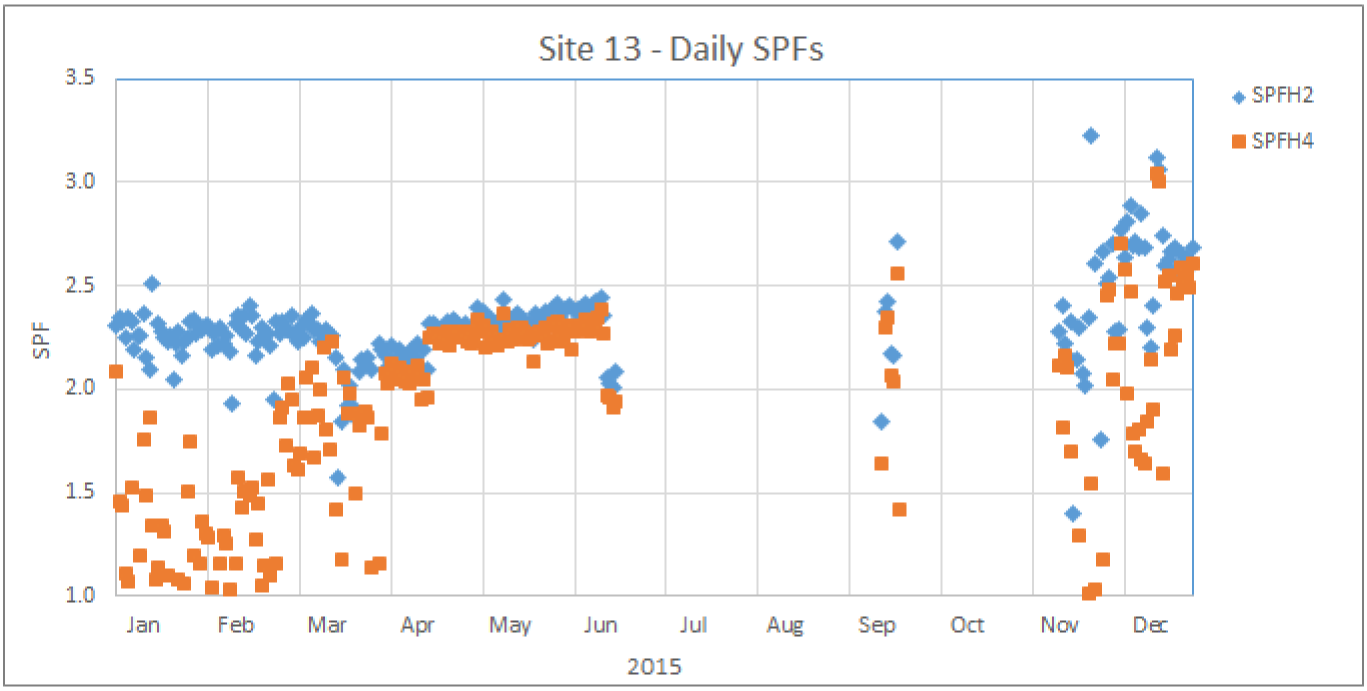

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature and the intensity of solar radiation.

Figure 4 shows the daily heat output from the heat pump and from the oil-fired boiler. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The heat load was highest during January and February, when the outdoor temperature fell below 0 °C at times. The oil-fired boiler was used extensively during this period, and again in November. The boiler provided 35% of the total heat during the year.

From 20th June to 16th November there was apparently very little demand for heat – apart from a few days from 18th to 22nd September. This is assumed to have been due to seasonal change in use of the greenhouse.

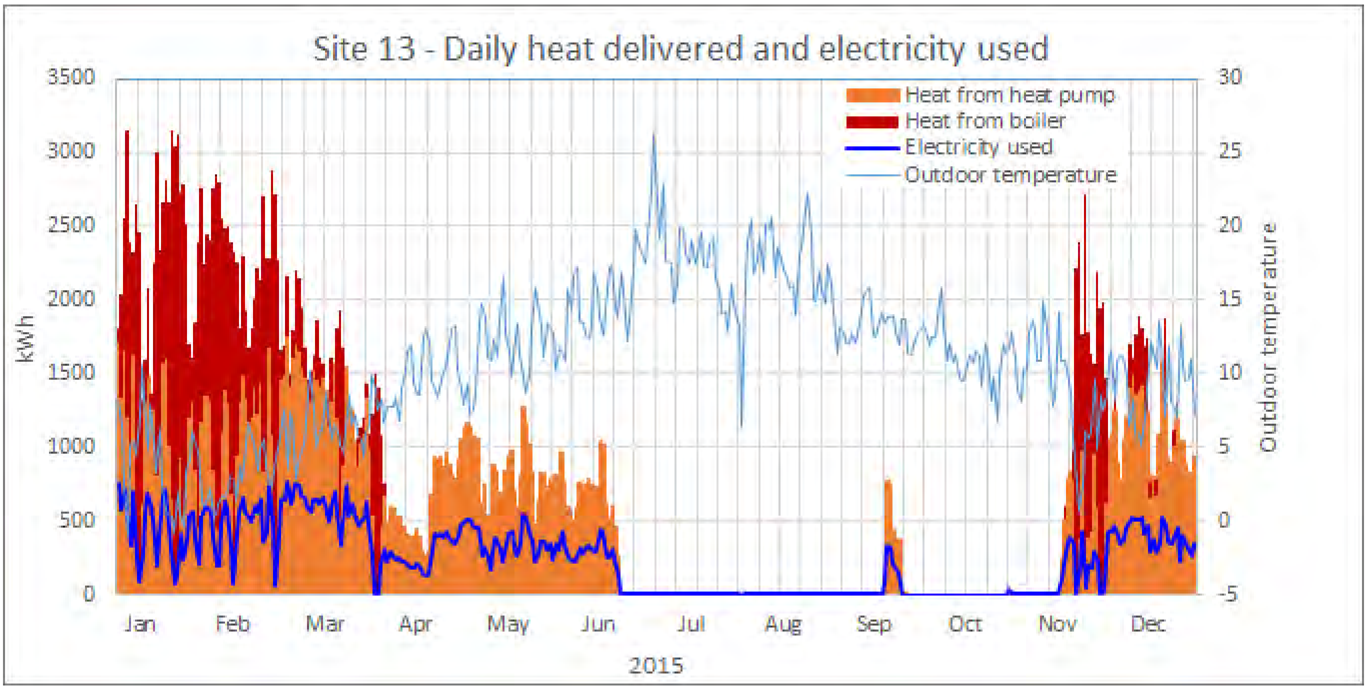

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The electricity used by each heat pump is shown. It should be noted that heat pump number 3 is smaller than the other two.

The brine pumps accounted for 6.4% of electricity used by the total heat pump system, which is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the performance.

The buffer pumps and the space heating circulation pump together accounted for just 2.9% of the total electricity – the lowest of all systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance.

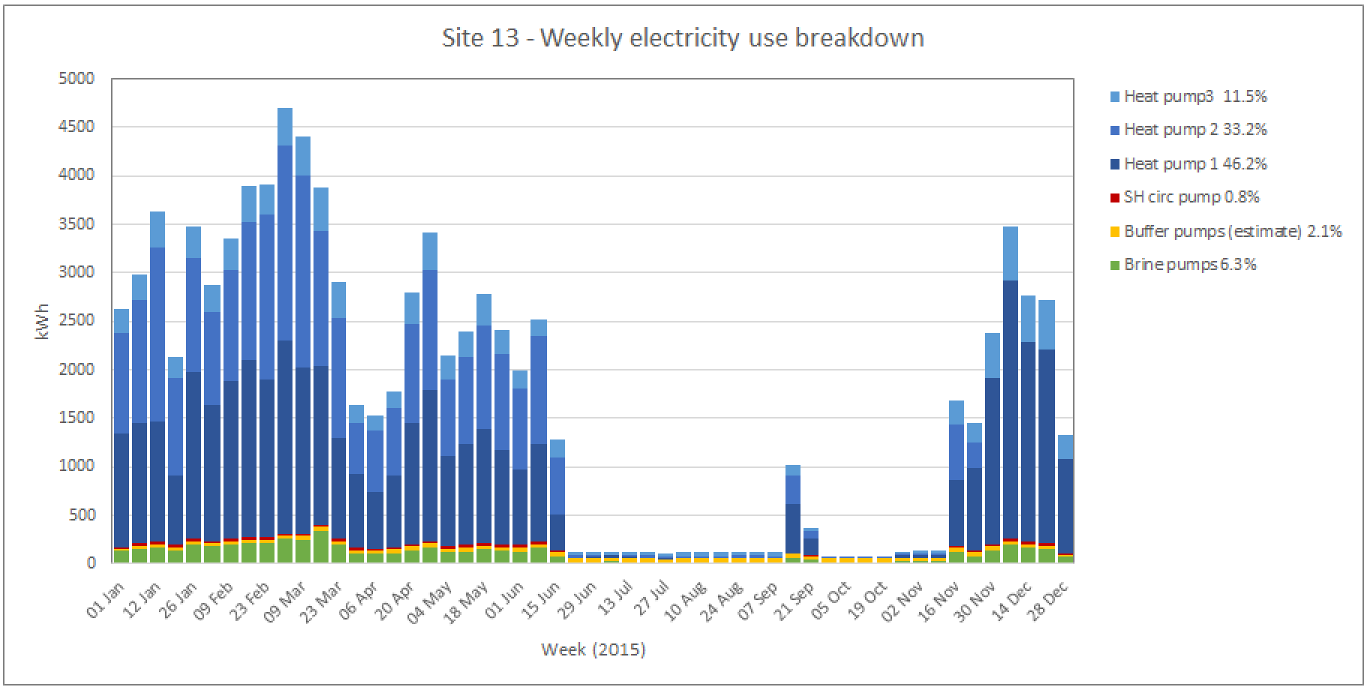

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 24th January 2015 when the outdoor temperature was between 0 and 7 °C. The oil-fired boiler was running until 09:00 while the outdoor temperature dropped from 6 °C to 1 °C. The output to the heat emitters was up to 70 °C during this time. Thereafter, as the outdoor temperature started to rise and the direct solar heating increased, the heat pumps took over and the output to the heat emitters was between 42 and 61 °C.

The temperature of the output from the heat pump was between 40 and 61 °C. The loss of temperature through the buffer tank while the heat pumps were running varied from 3 to 12 °C, but was generally around 6 - 7 °C.

Figure 6 – Operating pattern on 24th January 2015

Figure 7 shows the operating pattern during on 8th June 2015 when some heating was still needed. The outdoor temperature was between 6 and 19 °C. The oil-fired boiler was not required on this day. However, all three heat pumps were in use at times. The temperature of the output from the heat pumps was between 43 and 62 °C, although the maximum temperature of the flow to the heat emitters was 52 °C. The loss of temperature through the buffer tank varied between 3 and 12 °C.

The temperature of the brine flow to the heat pumps was between 5 and 9 °C (while at least one heat pump was running). The brine temperature was higher in the middle of the day when the outdoor air temperature was higher. This effect was probably due to the reduced heat load (as indicated by the reduced heat pump run times and power) and consequently reduced rate of heat extraction from the ground. There may also have been some influence of solar radiation on the horizontal ground collector.

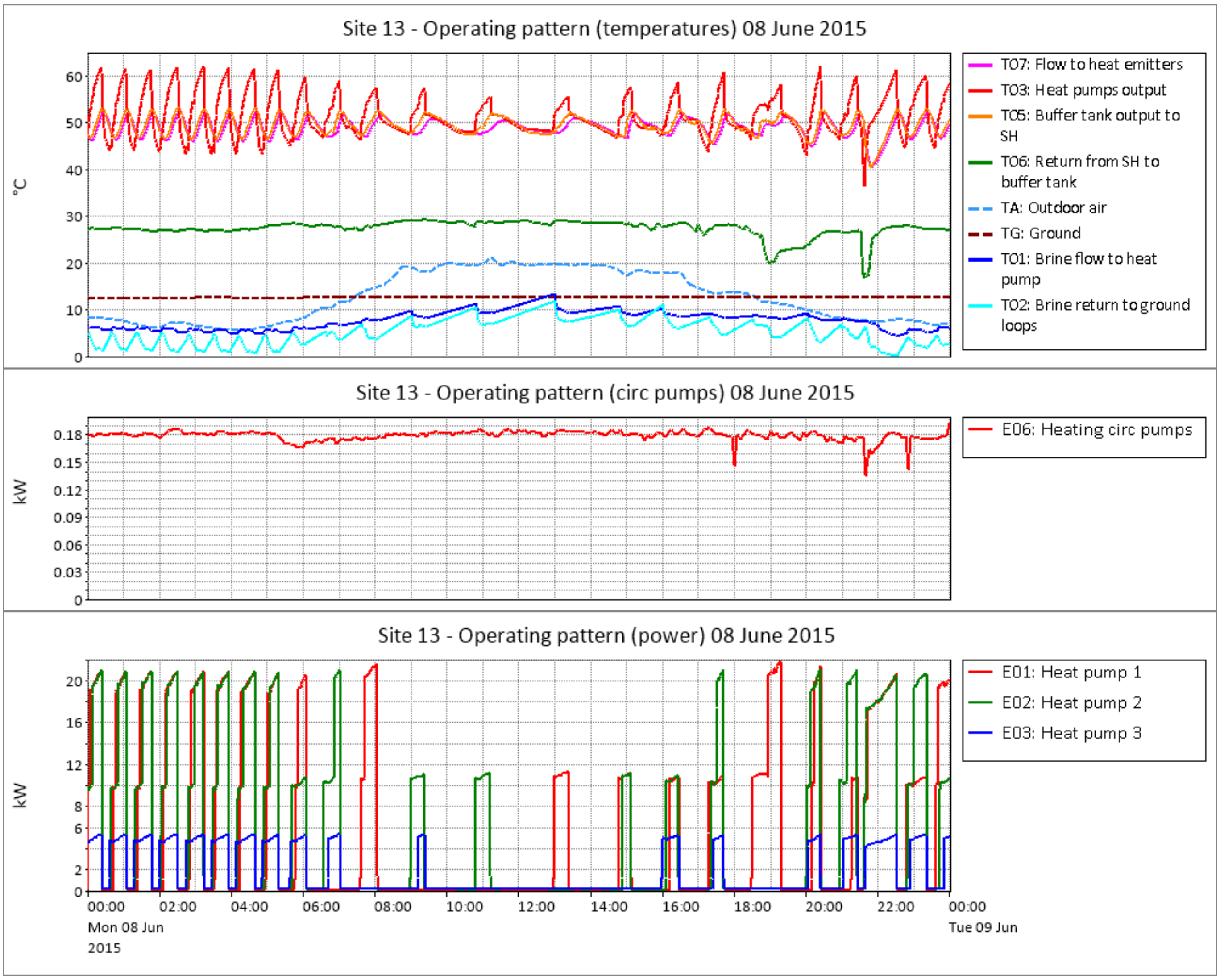

Figure 7 – Operating pattern on 8th June 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, ground, brine from the ground loops, the output from the heat pumps and the output to the heat emitters, plotted over the year[5]. The brine and heat pump output temperatures are plotted only for times when the heat pump was running.

The temperature of the output to the heat emitters was boosted at times by the oil-fired boiler to 70 °C, as shown by the top graph.

The heat pump output temperature was up to 62 °C at times when there was significant heat demand. However, the output from the buffer tank to the heat emitters was rarely above 53 °C. This suggests that there is a significant amount of mixing taking place in the buffer tank, which would have had a negative influence on the system performance.

The lower output temperature during the summer months was due to the heat pumps running for very short times only when there was little or no heat demand. The output temperature was also reduced during November and December. The reason for this is not known, but it may have been due to changed use of the greenhouse requiring a lower indoor temperature.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. Indoor and outdoor temperatures were recorded every 15 minutes and the ground temperature every hour.

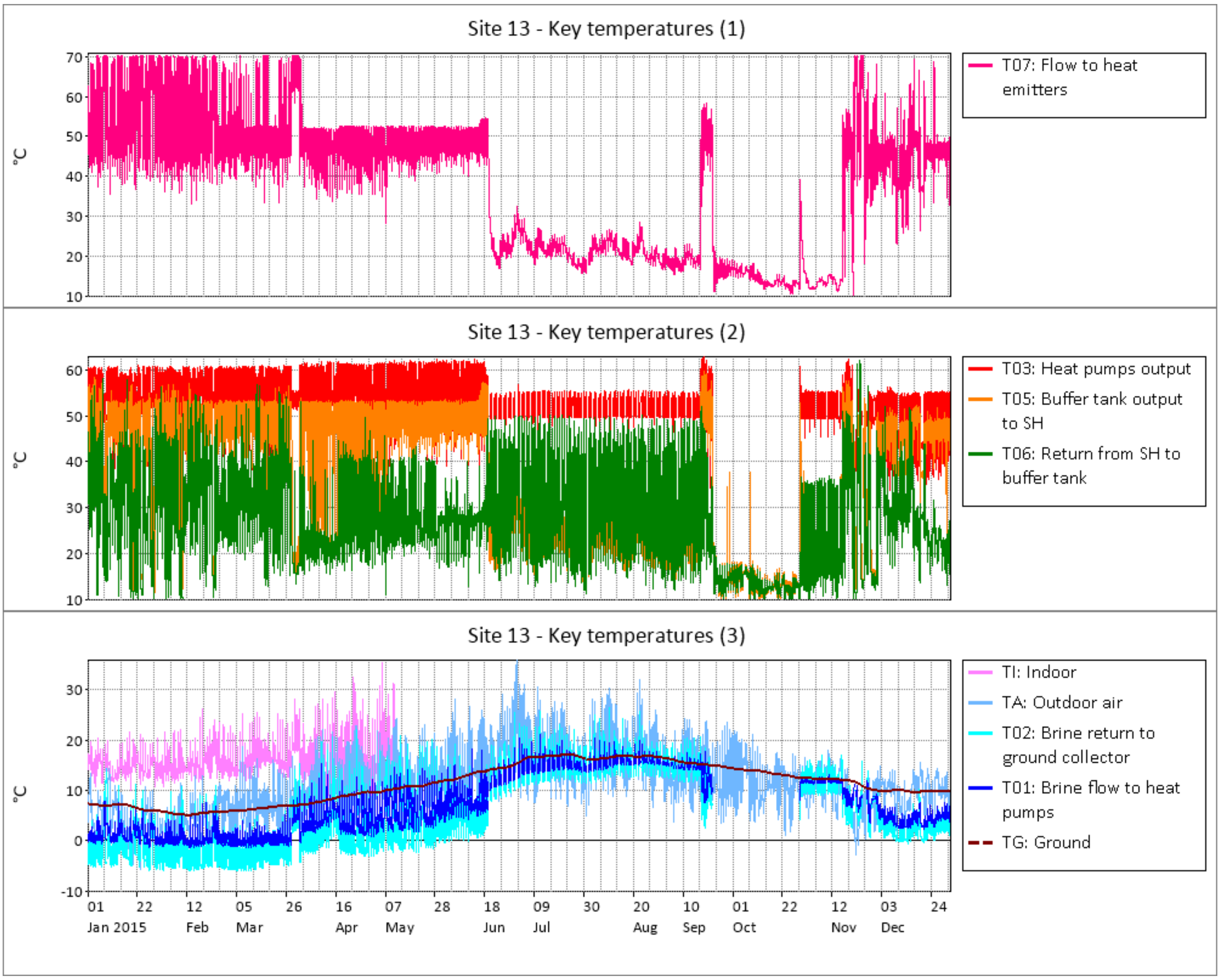

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

The temperature of the brine flow to the heat pumps was minimum (down to -1.2 °C) during the first three months of the year when the heat demand was high. The daily mean brine flow temperature during this period was approximately 6 °C below the ground temperature.

The range of temperature difference between the ground and the brine was above average compared to other horizontal-loop ground-source systems monitored in this project, as shown in Figure 9. This suggests that the ground collector may be undersized – although the design calculations would need to be reviewed to confirm this.

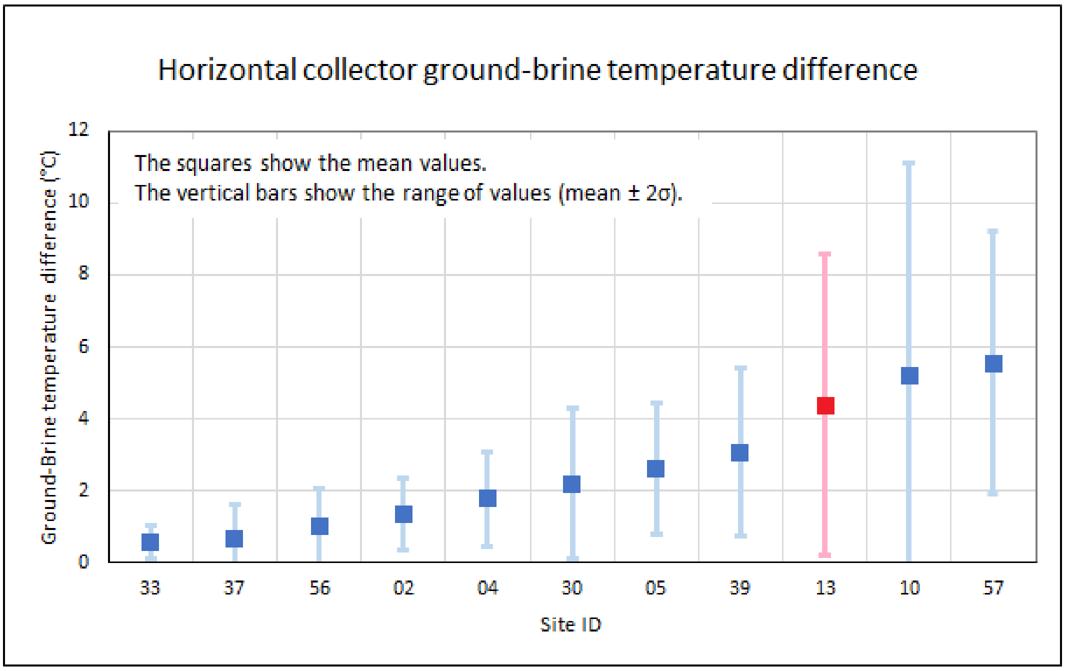

Figure 9 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 13 is shown in red)

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were below average, which would have had a negative influence on system performance.

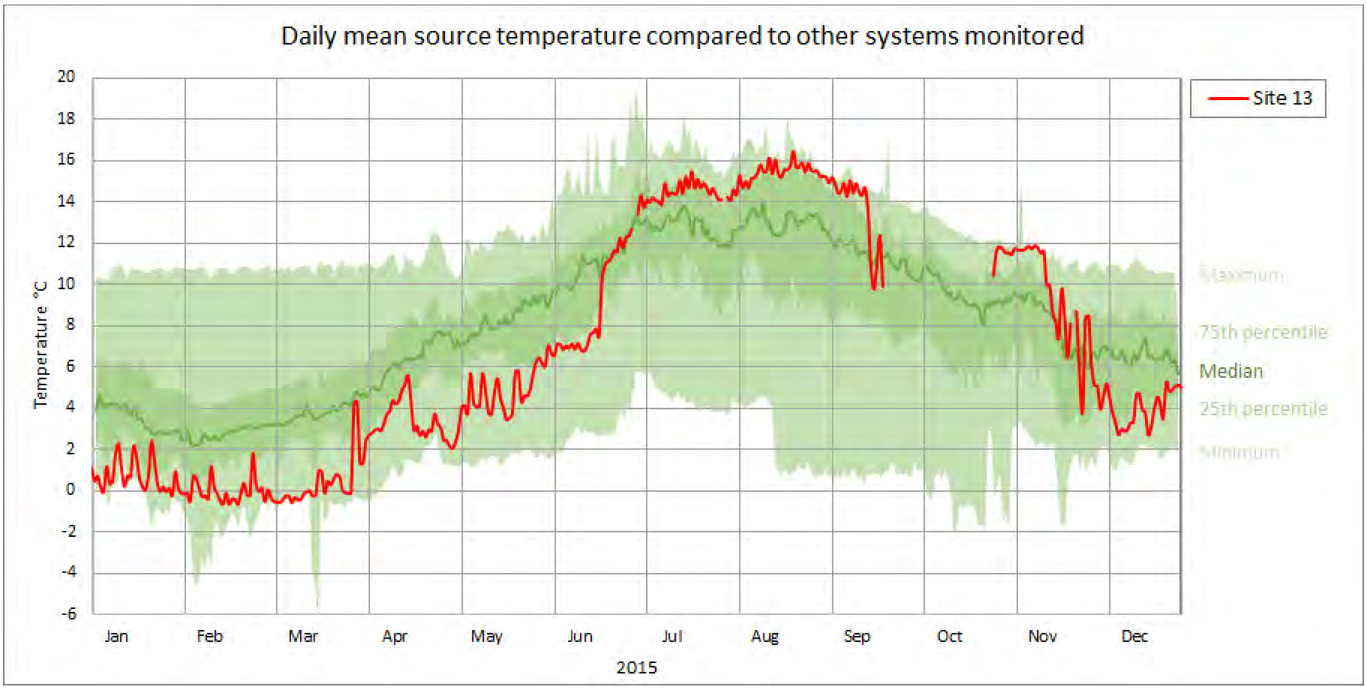

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 13 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were at the upper end of the values observed on other installations. This would have had a negative influence on the system performance.

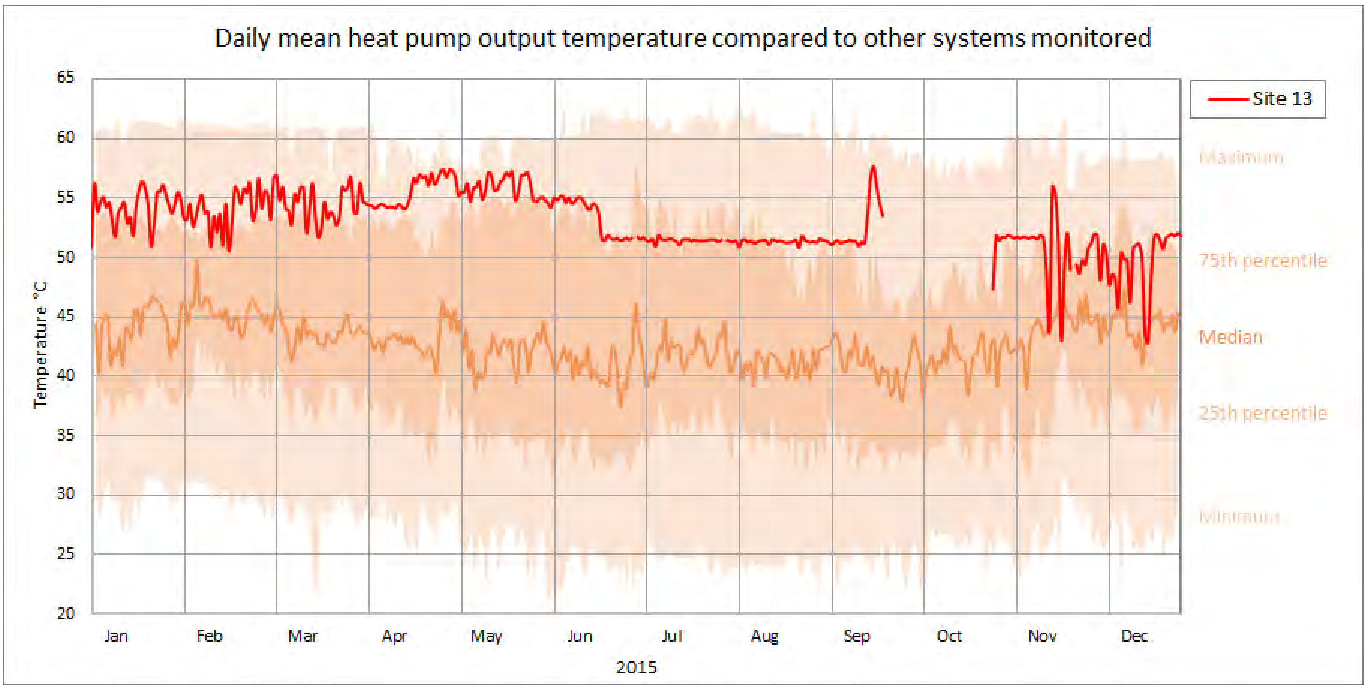

Figure 11 – Daily mean heat pump output temperature compared to those of other systems monitored in this project (site 13 is shown in red)

Comments

The performance of this system (SPF_{H4} = 1.42) was lower than for other systems providing space heating only that were monitored in this project (SPF_{H4} range: 1.42 to 4.10, median value 2.23).

However, this system is quite different in character to the others monitored in this study. The building is poorly insulated, has low thermal inertia and is strongly affected by direct sunlight. The required indoor temperature is lower than typically required for occupied buildings, but the temperature needed by the heat emitters is considerably higher than required by other systems.

The system has been analysed as a bivalent system, with the energy supplied (as gas oil) to the oil-fired boiler being accounted for in the denominator of the SPF_{H4} calculation. The effect of the oil-fired boiler on the SPF_{H4} is very significant, resulting in the lowest value of all systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The mean temperature difference between the ground and the brine flow to the heat pumps was above average compared to other horizontal collector systems monitored. It may be worth installing additional ground loops to increase the brine temperature. From the heat pump manufacturer's performance data, it is estimated that an increase in the brine flow temperature of 2 °C during the winter period would give an improvement in SPF_{H2} of around 3 – 4%.
- The type of heat emitter used requires high temperatures. It would be worth investigating whether the performance of the heat emitters could be improved – e.g. by adding additional emitters, perhaps of a different type – so that more of the heat could be supplied using lower temperatures. This would improve the overall system performance and would reduce the use of the oil-fired boiler.
- The temperature loss between heat pump output and buffer tank output was high – typically around 6 – 7 °C and at times up to 12 °C. It is possible that a different buffer tank arrangement would yield higher system performance. However, the design of buffer tank systems is a complex topic that is beyond the scope of this report.

The proprietor of the system has commented that he believes that a much larger thermal store (buffer tank) would be useful, to allow the heat pumps to store more heat during the warmer part of the day when the space heating demand is low, and for this then to be available during colder hours. This may be worth investigating as a means of increasing the proportion of renewable energy used.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 14

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 14 and performance results from 12 consecutive months of monitoring data.

Site 14 is a healthcare services building, constructed in 2011, in a suburban location. Two heat pumps (total thermal capacity 60 kW) extract heat from groundwater pumped from two boreholes, and provide space heating via underfloor heating pipes.

The seasonal heating performance factors measured over a year of operation
(1st January 2015 to 31st December 2015) were:

SPF_{H2}	[Total heat delivered by the heat pumps (excluding buffer pumps)] -- [Electricity used by the heat pumps (excluding buffer pumps) + source pumps]	2.31
SPF_{H4}	[Total heat delivered by the heat pumps] + [Immersion heater in buffer tank] -- [Electricity used by heat pumps + source pumps + circ pumps + immersion heater in buffer tank]	2.08

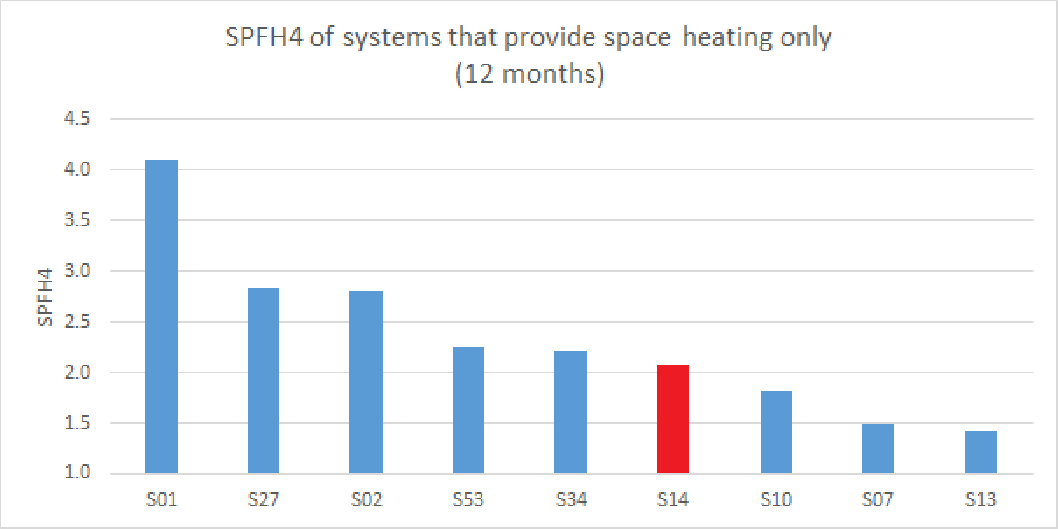


Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

An aspect of this system that positively influenced its performance was:

- The source temperature was generally higher during the winter months than on most other systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The energy used by the source pumps was the highest of all systems monitored: 32% of the total electricity used by the heat pump system. The borehole pumps were often run continuously during warm weather when the demand for heat was low and the heat pumps were used only intermittently.

- Low water levels in the boreholes, or possibly problems with the borehole pumps, at times led to poor heat transfer from the groundwater to the brine loop, with brine temperatures falling to very low levels – resulting in low system performance.
- The control strategy was not optimal during warm-weather, low-load conditions. Better use could be made of the 4-stage capacity control available by running only the minimum number of compressors needed to satisfy the heat demand.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	14
Survey date	07/04/2014
Monitoring installed	09/07/2014
G/WSHP	GSHP
Building type	Healthcare clinic
Location	Suburban
Heat pump capacity kWTH	60
Number of heat pumps	2
Number of compressors	4
Heat source	Groundwater from 2 boreholes
Heat emitters	Underfloor heating pipes
DHW	No
Auxiliary heat	21.6 kW electric boiler + 6 kW immersion heater in buffer tank. Both manually switched, used for backup only.
Source water pumps	2 down-hole pumps 2.1 kW & 1 kW variable-speed
Brine pumps	2 internal pumps of 600 W fixed-speed
Buffer pumps	4 pumps of 170 W (2 in each heat pump)
Buffer tank	500 litre 4-pipe
SH circulating pumps	Dual pump set: each pump 250 W max variable-speed (duty & standby)
DHW cylinder	N/A
Control	Control system in panel in ground floor switch room + heat pump controller
Weather compensation	Yes
Heat meter type	Vortex
No. of heat meters	1
Heat meter interface	M-Bus
Comments	

Table 1 – System details

This site is a building used for a healthcare clinic with offices and laboratories. The heat pump system was installed at the time of construction of the building in 2011.

This application entails the extraction of heat from groundwater pumped from two boreholes to provide space heating via underfloor heating pipes in a modern well-insulated building, located in an area with slightly below-average outdoor temperatures – annual mean 9.2 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C).

Heat pump and monitoring systems

Two heat pumps with a total thermal capacity of 60 kW are installed in a first-floor plant room inside the building. Each heat pump is equipped with two compressors each in a separate vapour-compression circuit, an arrangement that provides four steps of capacity control.

The heat source is groundwater pumped from two boreholes through a plate heat exchanger and returned to the aquifer. Brine is circulated through the heat exchanger to the heat pumps.

A 500-litre 4-pipe buffer tank is installed between the heat pumps and the underfloor heating circuits.

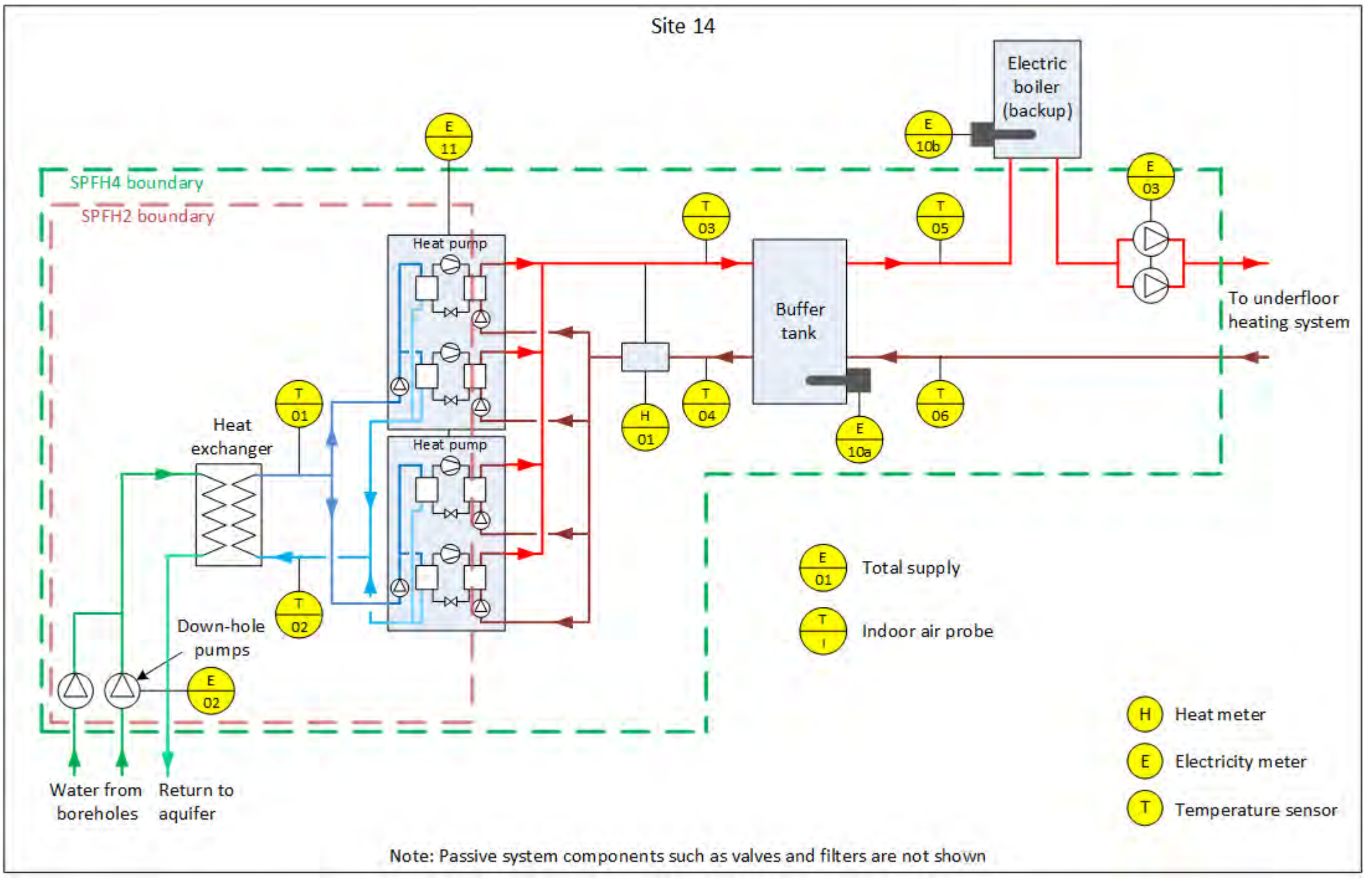
A 22 kW electric boiler is installed for back-up service only. It is not used in tandem with the heat pumps. A 6 kW immersion heater in the buffer tank is also only used for back-up service. Inspection of the recorded 1-minute data showed that the back-up electric heaters were not used at the same time as the heat pumps during the monitoring period.

The system is controlled by a custom building-services control panel.

Domestic hot water is provided separately using electric immersion heaters.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating (SH), and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1].



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses a vortex flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is mains-powered. Monitoring was via the M-Bus interface of the meter.

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[1] The temperature probes were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

The vortex flow meter is installed in a horizontal pipe with the sensor head on top of the pipe. This is not according to the manufacturer's instructions. This position is not advised as it renders the flow sensor susceptible to interference from air bubbles that may collect in the pipe. Previous research on heat metering accuracy [1] has shown that incorrect orientation of a vortex flowmeter can lead to increased error at high flow rates. The actual effect on this system is not known.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source water and brine pumps.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and the immersion heater in the buffer tank.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [2].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature readings from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump, the downhole pumps and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

$$\mathrm{SPF}_{H2} = \frac{\text{[Heat output of heat pumps]} - \text{[heat added by buffer pumps]}}{\text{Electricity used by: [heat pumps]} - \text{[buffer pumps]} + \text{[source pumps]}}$$

- This calculation required the electrical energy used by the buffer pumps inside the heat pumps to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running.

- The heat added by the buffer pump was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pump.

$$\mathrm{SPF}_{H4} = \frac{\text{[Heat output of heat pumps]} + \text{[heat added by SH circ pumps]}}{\text{Electricity used by: [heat pumps]} + \text{[source pumps]} + \text{[SH circ pumps]}}$$

- The heat added by the SH circulating pumps was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was not subtracted from the calculated heat output of the system because the buffer tank is located inside the building, within the heated envelope. During periods when there was no demand for heat, the buffer tank temperature dropped (within 6 hours) to below the indoor air temperature, so there would have been very little undesirable heat loss from the buffer tank during these periods.

- The SPF_{H4} equation does not include the electric boiler or buffer tank immersion heater as these were used only for back-up duty (verified by inspection of the recorded data).

The number of 1-minute intervals selected as valid for analysis was 506 142, which represents 96.3% of the 12-month period.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	2.31
SPF_{H4}	2.08

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 2.08 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. The data used to calculate these values does not include the electricity used by the backup heaters, as these heaters were used only for emergency backup and not for supplementary heat while the heat pumps were working.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

The SPF values were lower during warmer weather. This can be explained by the reduced performance of the heat pumps when operating at part load and the high power needed for pumping water from the boreholes becoming a very high proportion of the total electricity use.

The low SPFH4 values during the summer have a small influence on the overall annual performance because the total heat delivered under these conditions is small.

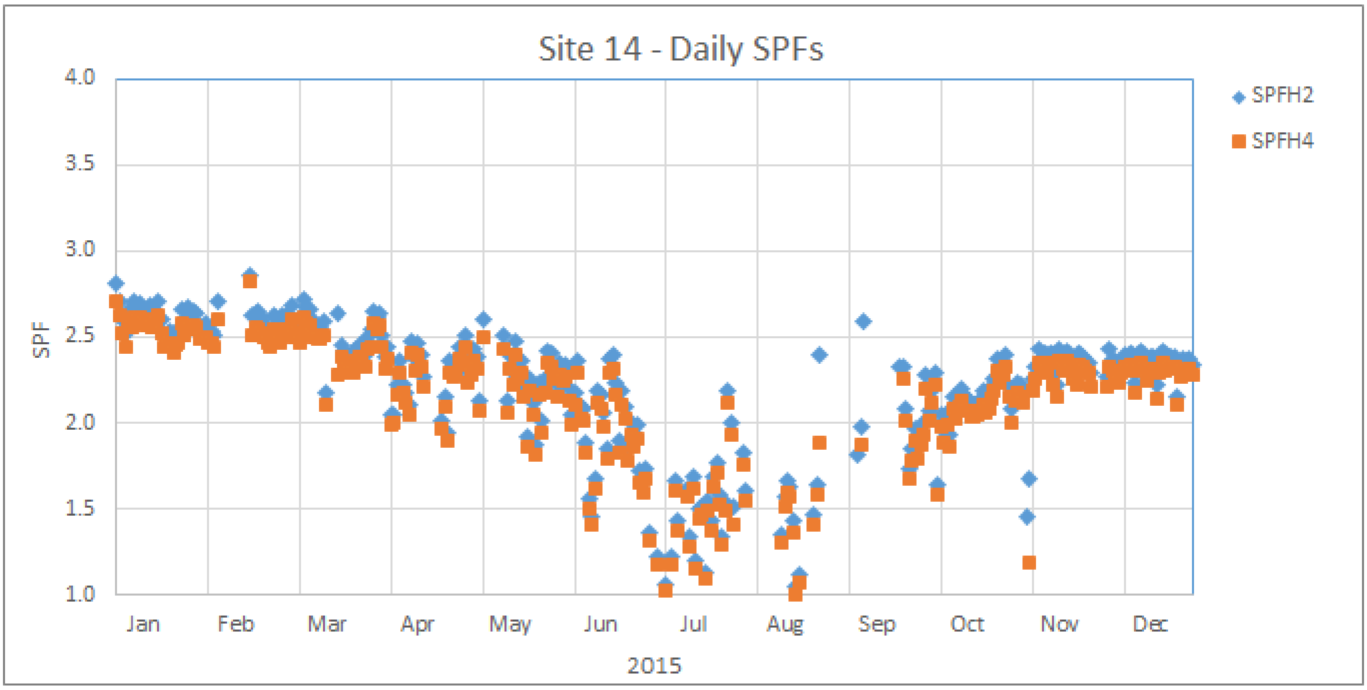

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the groundwater and the sink is the space being heated.

Heat extraction from the source to the heat pump is via an open-loop circuit from the boreholes, through a water-to-brine heat exchanger, and through a brine circuit to the heat pump. The brine will always be colder than the source, because a temperature difference between the groundwater and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. This water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the source water at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump water from the source, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [3] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The backup boiler was used during September, apparently because of a fault with the heat pumps. It was used again on 5th – 6th November for short periods. The reason for this is not known.

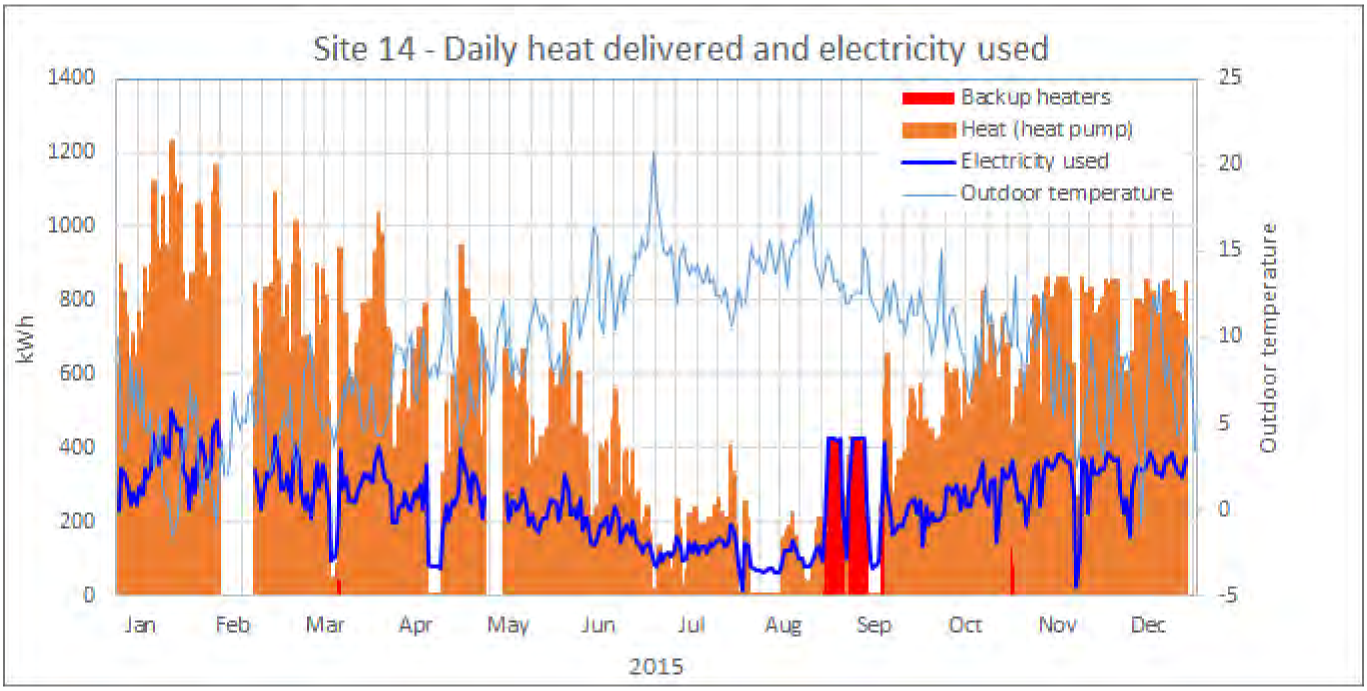

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The data for weeks 7, 19, 48 and 49 was incomplete, so these have not been shown.

The use of the backup heaters during March, September and in November is clearly seen (the red bars).

The borehole pumps and the brine pumps together accounted for 29.8% of the total electricity use (32.1% of electricity if the backup heaters are excluded). This was the highest of all systems monitored (range 2.3% - 29.8%, median 7.6%), and is presumably because downhole pumps are open-circuit lift pumps, rather than circulators as would be the case on systems with closed-loop source circuits. This would have had a negative influence on system performance.

It is also notable that the electricity used by the borehole pumps did not reduce in proportion to that used by the heat pumps during warmer weather.

The buffer pumps and space heating circulating pumps together accounted for 3.5% of electricity used (3.8% of electricity excluding the backup heaters), which is below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on system performance.

As noted above, the energy used by and the heat provided by the backup heaters (electric boiler and immersion heater) has been excluded from the performance calculations.

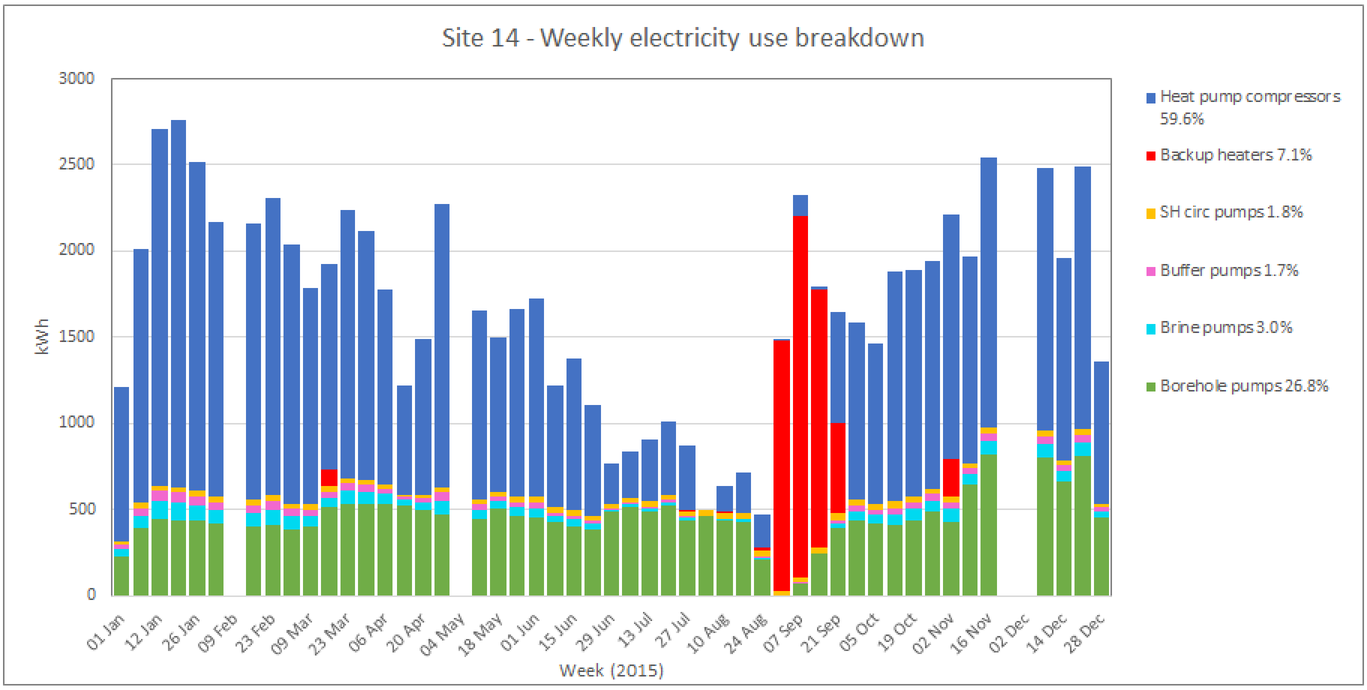

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the typical operating pattern during a cold day, on 20th January 2015, when the outdoor temperature[4] was between -4 and +1 °C. The temperature of the brine flow to the heat pump was between 4 and 10 °C.

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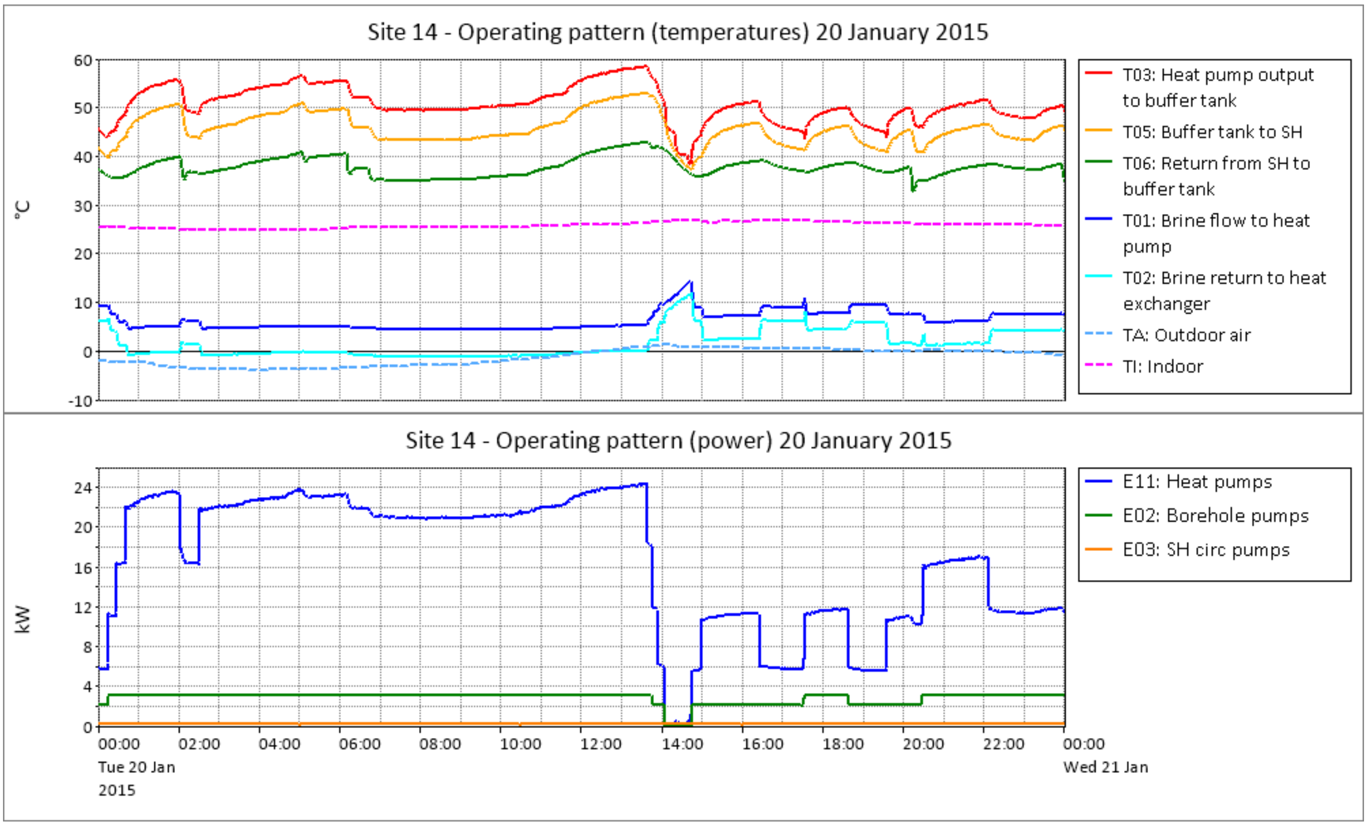
[4] The outdoor temperature was not recorded at this site. The temperature data is taken from another nearby site.

The temperature of the output from the heat pumps to the buffer tank varied between 38 and 58 °C. The output from the buffer tank to the underfloor heating circuits was between 37 and 53 °C. The temperature loss through the buffer tank was 4 °C when one heat pump compressor was running, and 6 °C with all four compressors running.

Both heat pumps were running from 00:30 until 14:00 when they stopped for 35 minutes. The load reduced during the afternoon, with one heat pump being sufficient for most of the rest of the day.

The two borehole pumps were also in use all morning, with one or both of them used at different times for the rest of the day.

The SPF_{H4} on this day was 2.41.



Site 14 - Operating pattern (temperatures) 20 January 2015

Site 14 - Operating pattern (power) 20 January 2015

Figure 6 – Operating pattern on 20th January 2015

Figure 7 shows the typical operating pattern during a moderately warm day on 9th July 2015. The outdoor temperature was between 7 and 15 °C, and the brine flow temperature between 4 and 12 °C while at least one heat pump was running.

All four heat pump compressors were running between 03:00 and 05:30. This appears to have been in response to the fairly low outdoor temperature at that time. The brine return temperature dropped to -6.5 °C although there is no evidence of the water freezing in the heat exchanger. The heat pump output temperature was up to 46 °C.

The indoor temperature was never below 23 °C, so there was no urgent need for heat. It would probably have been adequate to use only one heat pump for a longer time, which should have given better performance with a higher brine temperature and lower heat pump output temperature. Both borehole pumps were running all day.

The SPFH4 on this day was only 1.61. A different control strategy should be able to improve this significantly, by running the borehole pumps only when needed and by using only one heat pump, possibly with only one compressor.

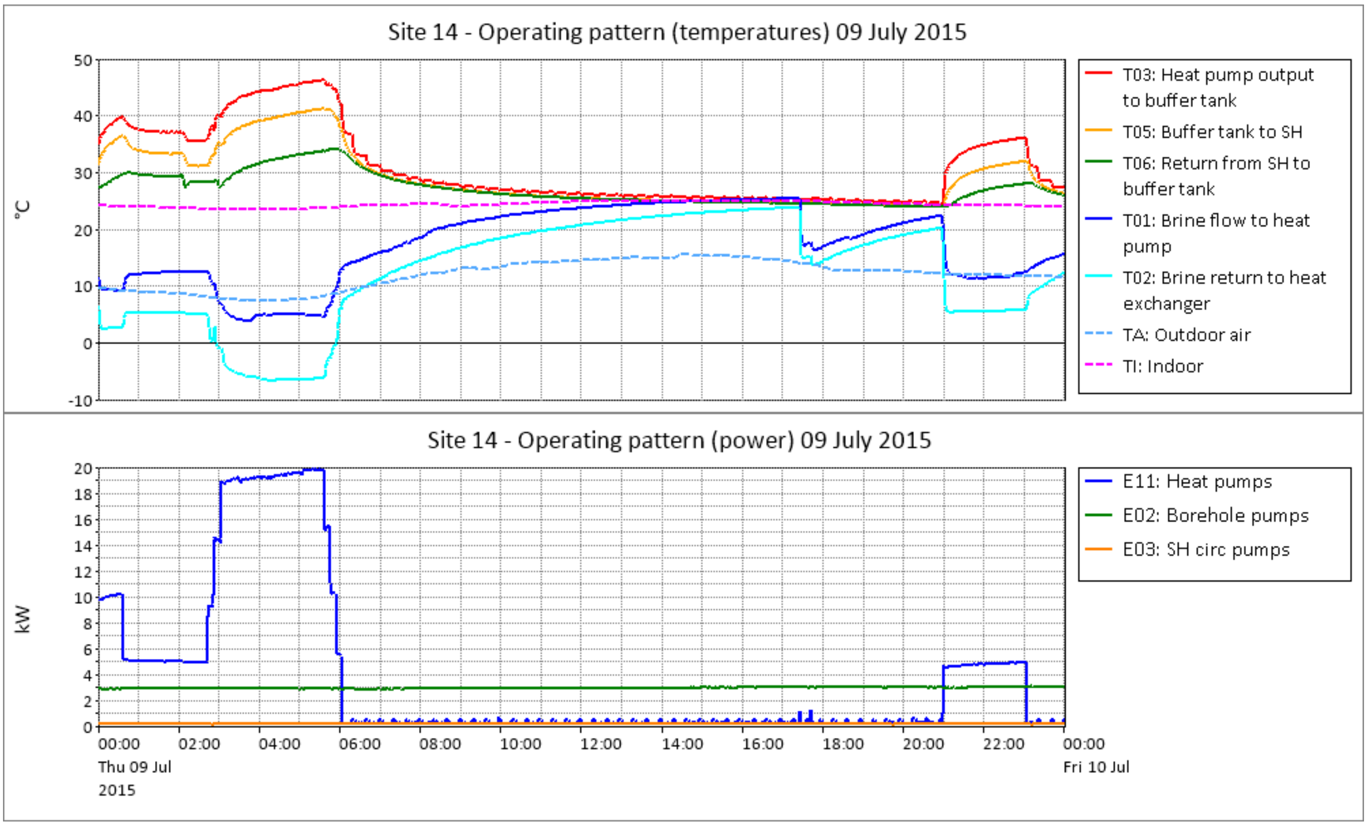


Figure 7 – Operating pattern on 9th July 2015

Problem with borehole pumps in March 2015

There appears to have been a problem with the borehole pumps during periods in March, September, October and November 2015.

Figure 8 shows the system behaviour between 12th and 18th March 2015. On 13th March the brine temperature suddenly dropped from around +4 °C to between -2 and -6 °C and the system heat output dropped to a very low level, with the heat pumps short-cycling. This behaviour continued until 16th March when the backup electric heater was switched on. Normal operation resumed on 17th March.

Similar behaviour occurred between September and November – as seen in Figure 9.

The nature of the problem is not known. One possibility is that the water level in the boreholes fell below the pump inlets.

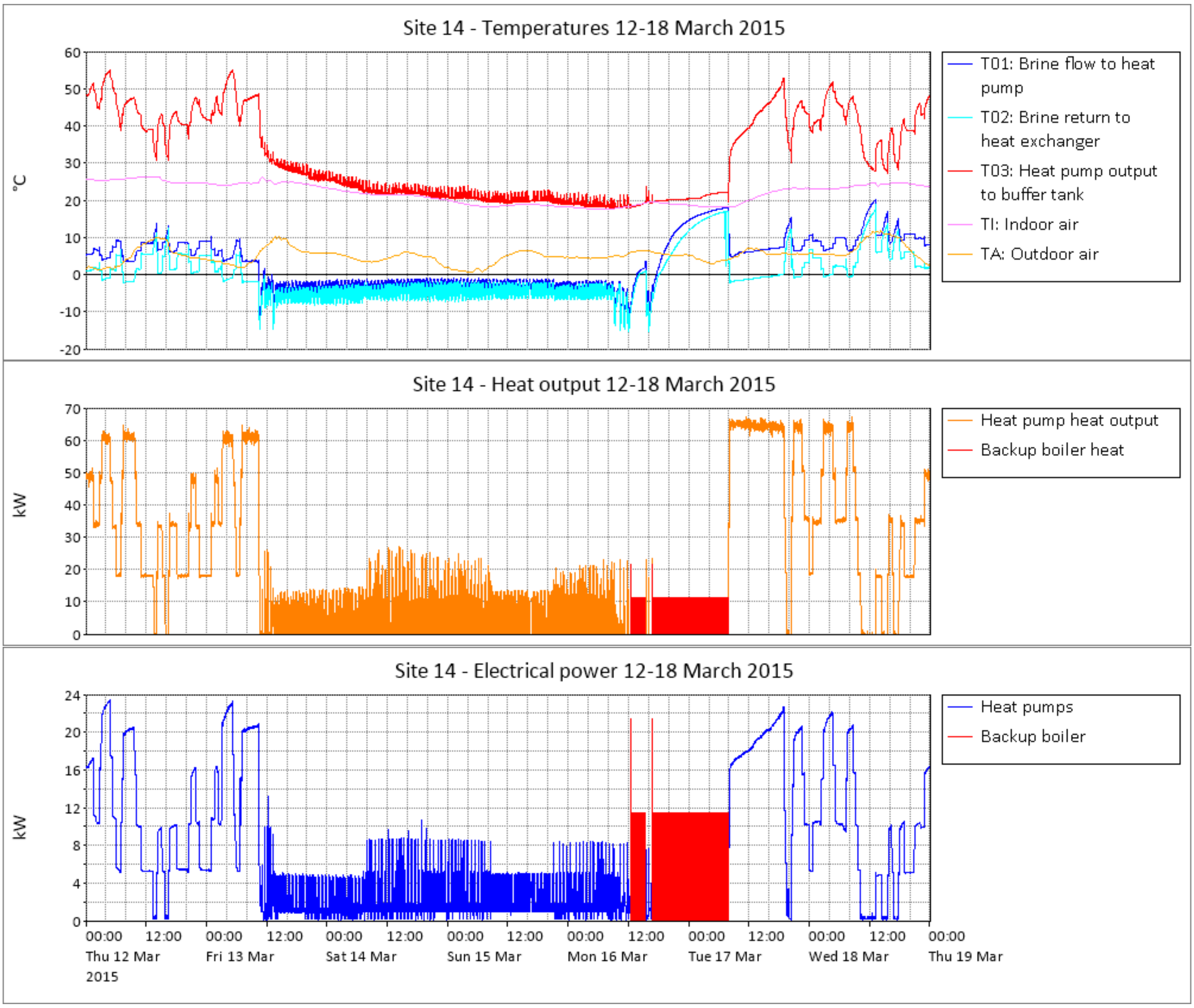


Figure 8 – Borehole pump problem on 13th – 16th March

Source and sink temperatures

Figure 9 shows the principal temperatures of the outdoor air, source water and the outputs from the heat pump, plotted over the year[5]. For clarity, the source and heat pump output temperatures have been plotted only for times when the heat pump was running.

The temperature of the output from the heat pumps was highest during January, rising to just over 60 °C on 19th January when the outdoor temperature was lowest and falling to a daily maximum of 35 °C during July. This illustrates the operation of the weather compensation function.

The borehole pumping problems noted above can be seen, where the brine flow temperature was below zero.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

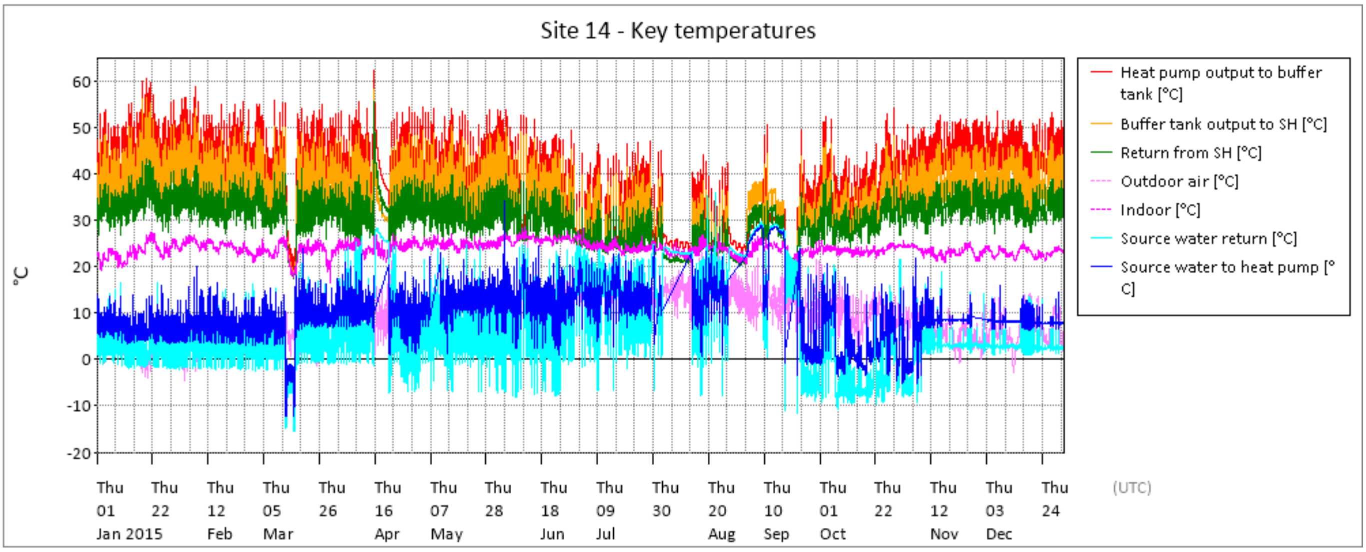

Figure 9 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were above average, especially during the winter months. The gaps in the data correspond to periods when the heat pumps were not in use.

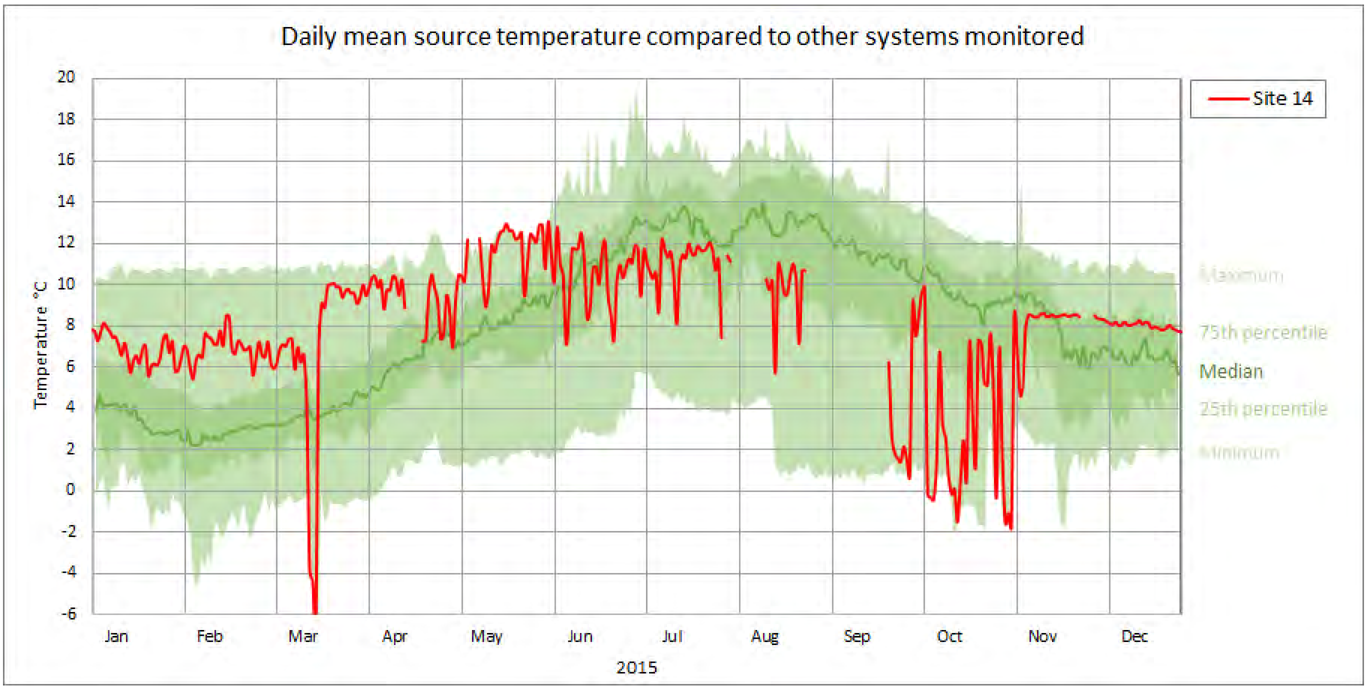

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 14 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. Ignoring the times of the borehole pumping problems, the output temperatures on this system were average.

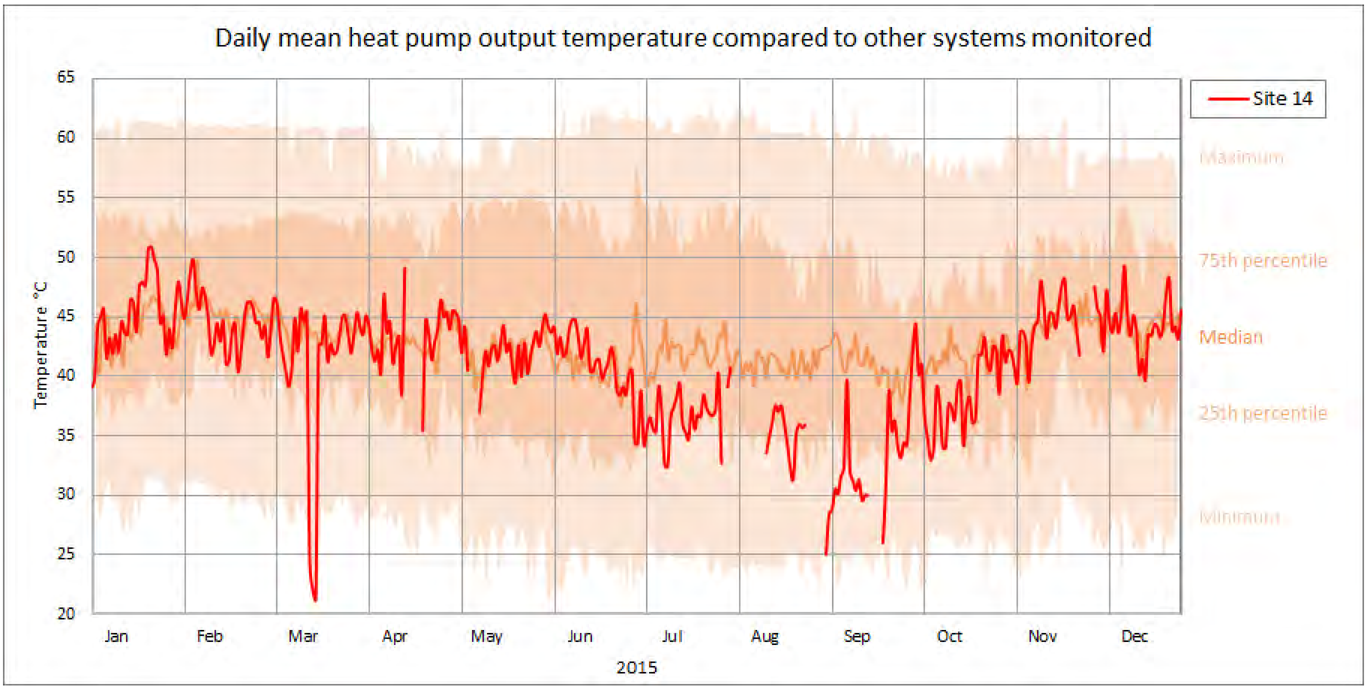

Figure 11 – Daily mean heat pump output temperature (to SH) compared to those of other systems monitored in this project (site 14 is shown in red)

Comments

The performance of this system (SPFH4 = 2.08) was below average compared to other systems providing space heating only that were monitored in this project (SPFH4 range 1.42 to 4.10, median 2.23).

An aspect of this system that positively influenced its performance was:

- The source temperature was generally high. Except at times when there were problems with the borehole pumps, the source temperature was higher during the winter months than most other systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The energy used by the source pumps was the highest of all systems monitored: 32% of the total electricity used by the heat pump system (excluding the backup heater). The borehole pumps were often run continuously during warm weather when the demand for heat was low and the heat pumps were used only intermittently. Not running these pumps when not needed would save energy and improve the overall system performance.
  It may be worth considering replacing the down-hole pumps and plate heat exchanger arrangement with vertical brine loops in the boreholes. The pumping power would be considerably reduced and the overall system performance could be significantly improved. If the electricity used by the source pumps could be reduced to 7% (the median value for other systems monitored) of the total electricity used by the heat pump system and assuming the same source temperatures at the heat pumps as with the present arrangement, the SPFH4 would be increased by around 37%.
- Low water levels in the boreholes, or possibly problems with the borehole pumps, at times led to poor heat transfer from the groundwater to the brine loop, with brine temperatures falling to very low levels – resulting in low system performance.
- The control strategy was not optimal during warm-weather, low-load conditions. Better use could be made of the 4-stage capacity control available by running only the minimum number of compressors needed to satisfy the heat demand.

- The temperature loss through the 4-pipe buffer tank was between 4 and 6 °C. It is possible that a different design or arrangement of the buffer tank would reduce this temperature loss and yield an improvement of the system performance. However, this is a specialised topic and is outside the scope of this report.

Bibliography

[1] D. Butler, A. Abela and C. Martin, “Heat meter accuracy testing (URN: 15D/446),” DECC, 2015.

[2] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[3] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[4] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[5] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 17

Prepared by GRAHAM Energy Management
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January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 17 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 17 is a public hall, refurbished in 2010. A heat pump (thermal capacity 30 kW) extracts heat from vertical boreholes and provides space heating to a combination of underfloor heating pipes in the main hall and radiators in other parts of the building. Some heat is also provided to domestic hot water to top up the heat provided by solar thermal collectors.

Seasonal performance factors are not presented because characteristics of the heat meter previously installed for the Renewable Heat Incentive and used to monitor this system, have led to unacceptably high uncertainties of measurement of the heat delivered.

Aspects of this system that positively influenced its performance are:

- The temperature of the heat pump output to space heating was rarely above 43 °C – below average compared to other systems monitored.
- Weather compensation and night setback were used to keep the output temperature as low as possible.
- The temperature of the output to domestic hot water was below 56 °C most of the time.
- The immersion heater in the domestic hot water cylinder was used minimally (0.5% of total electricity used by the heat pump system).
- A solar thermal collector is used to heat the domestic hot water and may have reduced the requirement for high temperature output from the heat pump.
- The proportion of total electricity used by the brine, buffer and heating circulating pumps was low compared to other systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the brine flow to the heat pump was below average compared to other systems monitored.
- The lack of individual room thermostats may have led to spaces being overheated at times.
- Some heat loss from the buffer tank occurred during the summer months when there was no demand for space heating. This appears to have been due to incorrect positioning of the 3-port valve at the heat pump output during domestic hot water operation.

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[1] The heat meter installation on this system uses strap-on temperature sensors. This technique is known [2] to be prone to unacceptably large measurement errors and the performance values could therefore not reliably be determined.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	17
Survey date	12/03/2014
Monitoring installed	08/07/2014
G/WSHP	GSHP
Building type	Public hall
Location	Urban
Heat pump capacity kW$_{TH}$	30
Number of heat pumps	1
Number of compressors	2
Heat source	Vertical boreholes: 1 x 65m, 6 x 75m
Heat emitters	Underfloor heating pipes + radiators in part of the building
DHW	Yes
Auxiliary heat	3kW immersion heater in DHW cylinder
Source pump	Internal in the heat pump: 2 pumps of 160 W max
Buffer pumps	Internal in the heat pump: 2 pumps of 90 W max
SH circulating pump	1 pump of 85 W max
DHW circulating pump	1 pump of 50 W max
Buffer tank	300 litre 4-pipe
DHW cylinder	450 litre
Control	Heat pump controller
Weather compensation	Yes
Heat meter type	Mechanical multi-jet turbine + strap-on temperature sensors
No. of heat meters	1 (for space heating only)
Heat meter interface	Pulse (100 Wh/pulse)
Comments	A solar thermal collector also provides heat to the DHW cylinder.

Table 1 – System details

Site 17 is public hall which was extensively refurbished in 2010 with solid wall insulation, loft insulation, secondary glazing and underfloor heating pipes.

This application entails extracting heat from vertical boreholes in the ground to provide space heating and part of the domestic hot water requirement. The building is located in an area with above-average outdoor temperatures – annual mean 10.9 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The performance of this system would be expected to be above average.

Heat pump and monitoring systems

A dual-compressor heat pump with a thermal capacity of 30 kW provides space heating (SH) and domestic hot water (DHW). Solar thermal collectors also provide heat to the domestic hot water cylinder.

The heat source is seven vertical boreholes (six of 75 m and one of 65 m depth), using brine circulated through U-tube pipes.

A 300-litre 4-pipe buffer tank is installed between the heat pump output and the heating circuits.

The heat emitters are a combination of underfloor heating in the main hall area and radiators in other parts of the building.

The system is controlled by the heat pump controller. No other programmer or thermostats are installed.

An immersion heater in the domestic hot water cylinder is used principally to raise the temperature once every two weeks for Legionella control.

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. The existing heat meter ("H") installed for the Renewable Heat Incentive (RHI) is monitored via its pulse interface. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2]. The outdoor air and ground temperatures are also monitored.

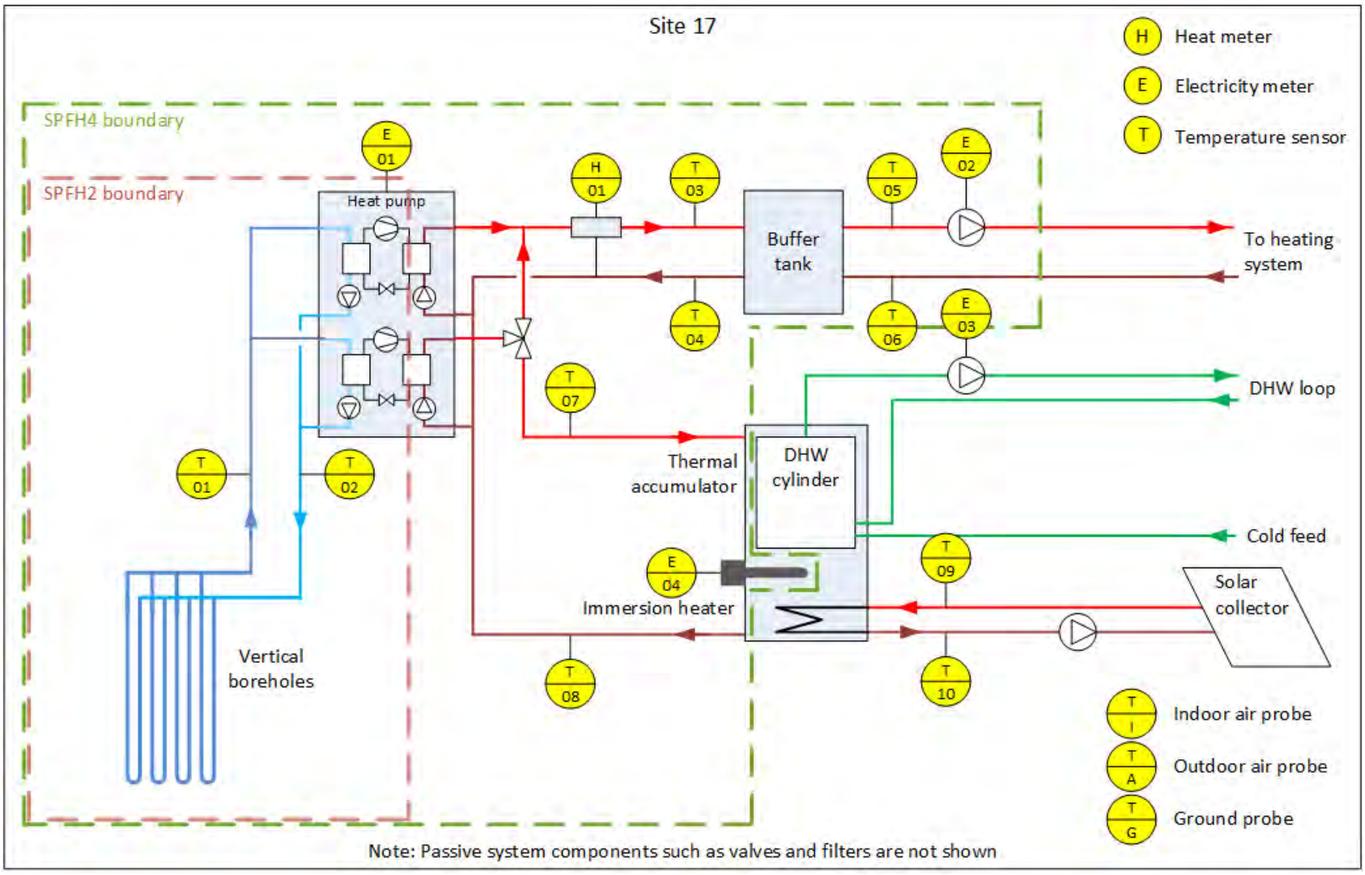

Figure 1 – System schematic showing the monitoring instrumentation installed

Solar collector

A solar thermal collector is installed, and is understood to be intended as the principal source of heat for domestic hot water.

A special type of thermal accumulator is installed for the DHW system. This accumulator is specifically designed for integration of a heat pump and solar thermal collector, and comprises a tank within a tank. The outer tank is heated directly by the heat pump, while the solar collector is connected to a heating coil at the bottom of the

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[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [1] for further details. Note that these temperature measurements were not used for heat metering.

outer tank. The inner tank contains the potable water to be heated for supply to the DHW distribution in the building.

The design of the thermal accumulator is such that it can be used for both SH and DHW (when a separate SH buffer tank is not installed), or for DHW duty only. Two sets of fittings are provided for the connections to the heat pump: one set at the bottom of the outer tank is for use in combined SH + DHW operation; the other set is positioned higher up the outer tank for DHW-only operation. On this system, the heat pump is connected to the lower fittings, although the tank is used for DHW only.

It is not known whether this arrangement is intentional, but it may influence the operation of the solar collector: the water at the bottom of the outer tank where the solar heating coil is located will be heated by the heat pump, thereby reducing the efficiency of the solar collector because it will need to work at a higher temperature. On the other hand, the heat pump should be able to operate more efficiently by having a lower return temperature from the accumulator.

The heat provided to DHW is not metered, so it is not possible to report the relative contributions to DHW of the heat pump and the solar collector. However, it is possible to provide an indication of the heat provided by the solar collector using the measured flow and return temperatures (the flow rate is unknown). Figure 22 shows an indication of the solar contribution. The heat from the heat pump was estimated as described in Appendix D of the Interim Report [1]. The contribution of the immersion heater was measured and is estimated to have been less than 0.1% of the total DHW heat.

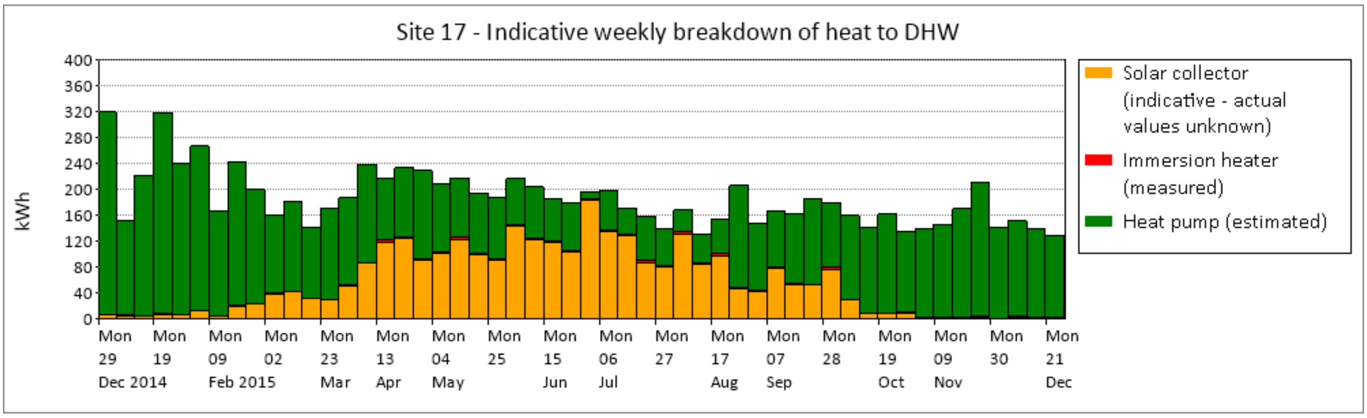

Figure 2 – Indicative weekly breakdown of heat provided to DHW

Heat metering

The heat meter on this system measures only the heat supplied to space heating (for simplified compliance with the RHI scheme). The heat provided to domestic hot water was estimated from temperature data[3].

The heat meter is of a type that uses a mechanical multi-jet turbine flow meter and strap-on temperature sensors. Although the use of strap-on temperature probes was as recommended by the meter manufacturer at the time of installation, it is known from subsequent research [2] that this technique can result in large measurement errors. Therefore, it has not been possible to determine the system performance with any useful degree of accuracy.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

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[3] See Appendix D of the interim report [1] for an explanation of how this was calculated.

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [3].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[4] procedures tailored to suit this heat pump system.

Solar collector excluded from calculation

The SEPEMO project [4] recommends that for this type of bivalent system (heat pump + solar collector) the heat from the solar collector be included in the numerator of the SPF_{H4} calculation and the electricity used by the solar circulating pump in the denominator.

Inclusion of these values in the SPF_{H4} calculation is likely to yield very high SPF_{H4} values that are not very meaningful for comparison with systems without solar collectors – because the ratio of heat to electricity in a solar thermal system can be very high and does not have the same meaning as the SPF of a heat pump.

The (relative) SPF_{H4} results for this system do not include the heat output of or electricity used by the solar thermal collectors.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Metered heat to SH] + [Estimated heat to DHW] – [heat added by buffer pumps]}}{\text{Electricity used by: [heat pump] – [buffer pumps]}}$$

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[4] Structured Query Language: a programming language used for managing data held in a relational database management system.

- This calculation required the electrical energy used by the buffer pump inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pumps, calculated for intervals that the heat pump was running.

- The heat added by the buffer pumps was estimated as 30% (the assumed pump efficiency[5]) of the electrical energy supplied to the pumps.

$$SPF_{H4} = \frac{\text{[Metered heat to SH] + [Estimated heat to DHW] – [heat loss from buffer tank]} \atop \text{+ [heat added by heating circ pump] + [heat from DHW immersion heater]}}{\text{Electricity used by: [heat pump] + [heating circ pump] + [DHW immersion heater]}}$$

- The heat added by the heating circulating pump was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pump.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 524 472, which represents 99.8% of the 12-month period.

SPF results presented as relative values

Because of the heat metering issues noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors SPF_{H2} and SPF_{H4} are therefore presented in this case study as “relative” values, whereby each value is shown as an amount above or below a nominal performance.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} behaviour of the system[6]. The lower values during the summer months are probably a consequence of the heat pump running for short periods, mostly for domestic hot water provision, resulting in lower overall efficiency. However, as the total heat output during the summer is small, the effect on the annual performance is not very significant.

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[5] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [6] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[6] The actual values are not shown because of the high uncertainty of measurement of the heat metering on this system. Relative values are shown to give some indication of the scale of the behaviour.

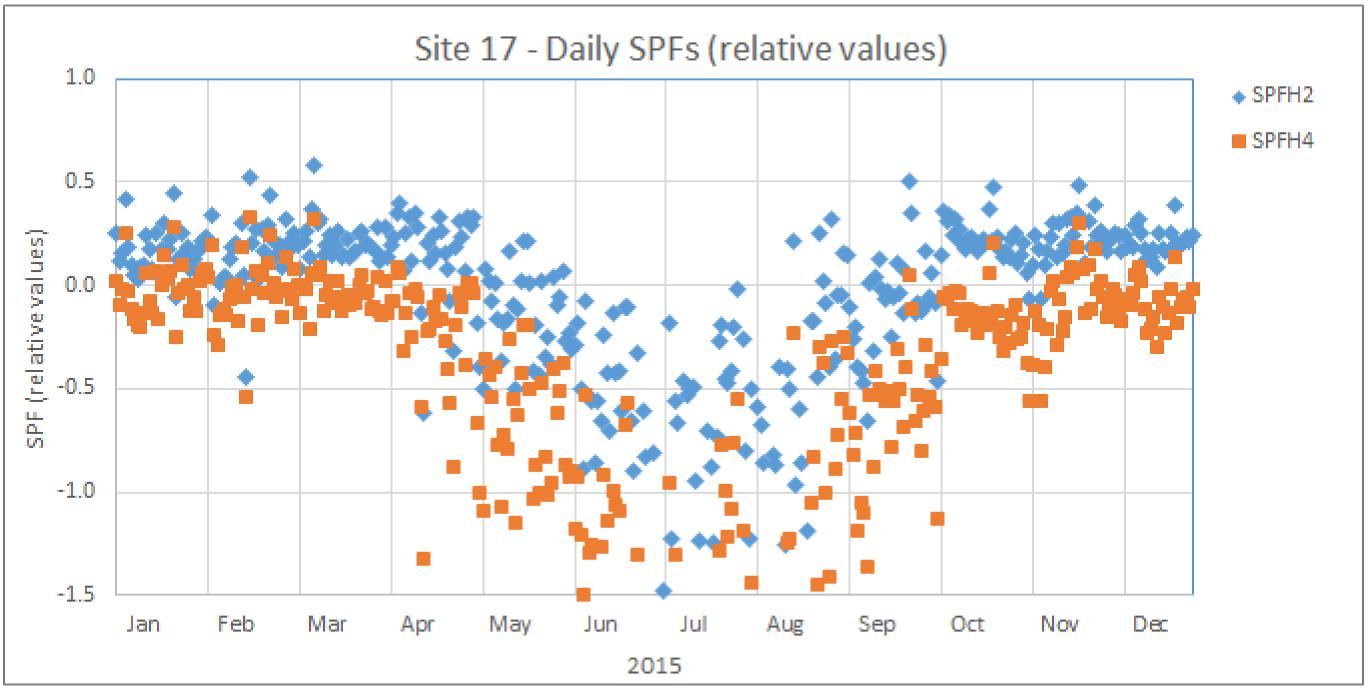

Figure 3 – Relative seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [5] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The heat estimated to have been provided by the heat pump to domestic hot water is shown in green. It is notable that this daily value was lower during the summer months when presumably the contribution from the solar collector would have been greater. Note that the kWh values have been removed from the graph because of the high uncertainty of measurement of the heat meters.

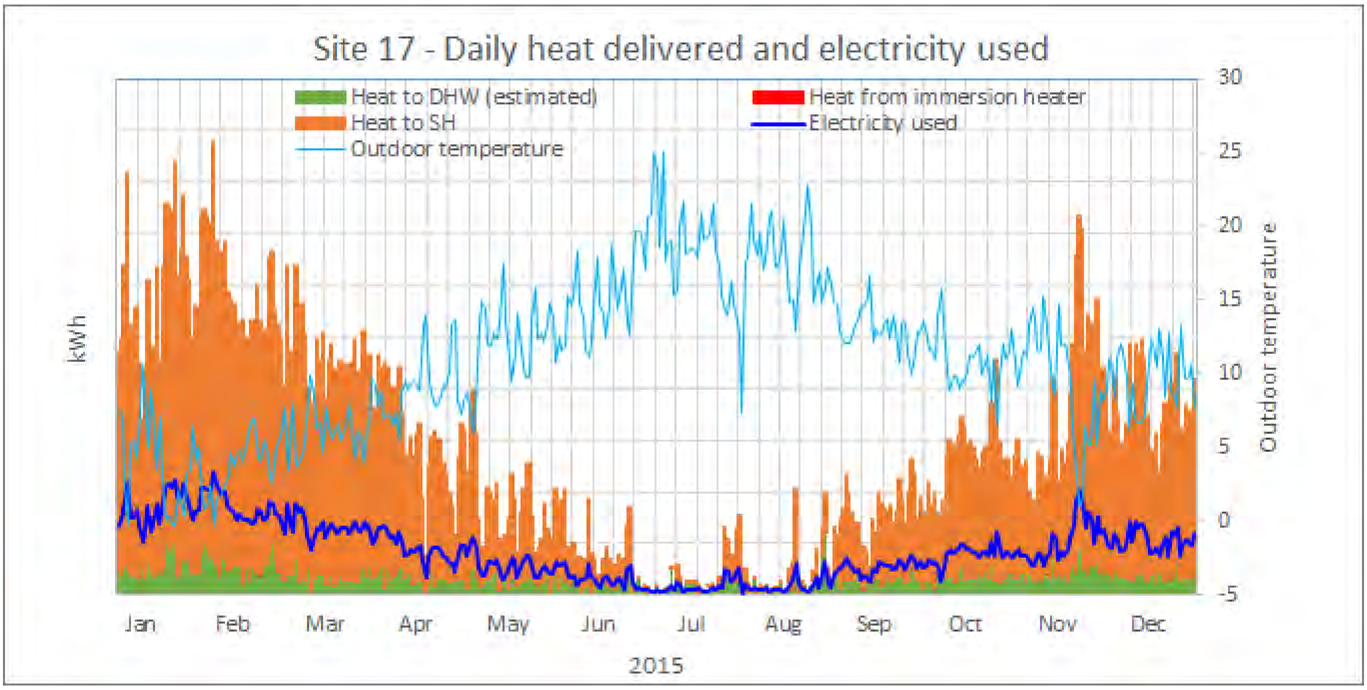

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

Table 2 shows the estimated breakdown of the heat delivered to space heating and to domestic hot water during the period from 1st January to 31st December 2015.

	%
Heat delivered to space heating	83.5%
Heat to domestic hot water (from heat pump)	16.2%
Heat to domestic hot water (from immersion heaters)	0.3%

Table 2 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use.

The brine pump accounted for 3.0% of the total electricity, which is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on system performance.

The buffer pumps and the heating circulating pump together used 9.1% of the total electricity – below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on system performance.

The immersion heater in the domestic hot water cylinder used only 0.5% of the total electricity.

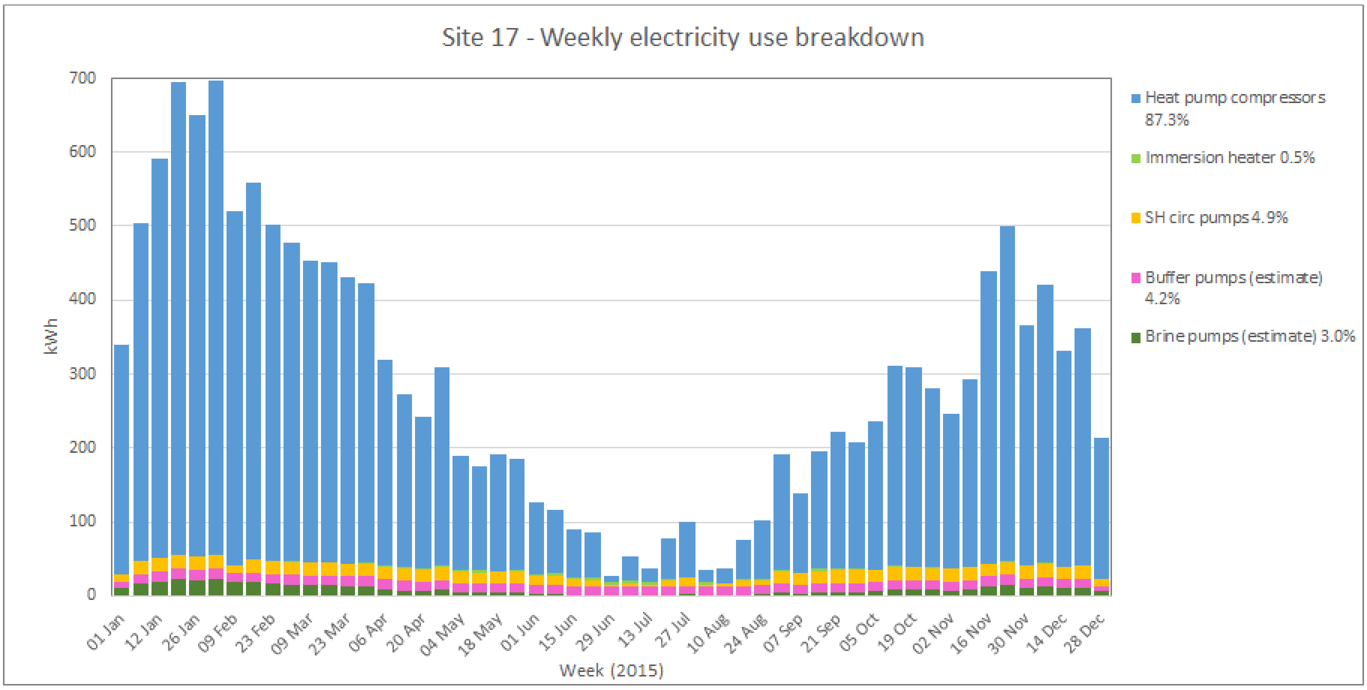

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 21st January 2015 when the outdoor air temperature was between 1 and 3 °C.

The heat pump operated during the full 24 hours, using one or two compressors at different times, as illustrated by the heat pump power graph.

The output to the buffer tank was up to 43 °C during the day, but only 35 °C during the night when the night setback function of the heat pump controller was active.

The loss of temperature through the buffer tank was never more than 2 °C.

Provision of heat to the domestic hot water cylinder was evident twice during the day, with the output temperature at a maximum of 60 °C during the night, presumably intended for Legionella control.

The temperature of the brine flow to the heat pump was between 0 and +4 °C while the heat pump was running. The minimum brine return temperature was -5 °C when both heat pump compressors were running.

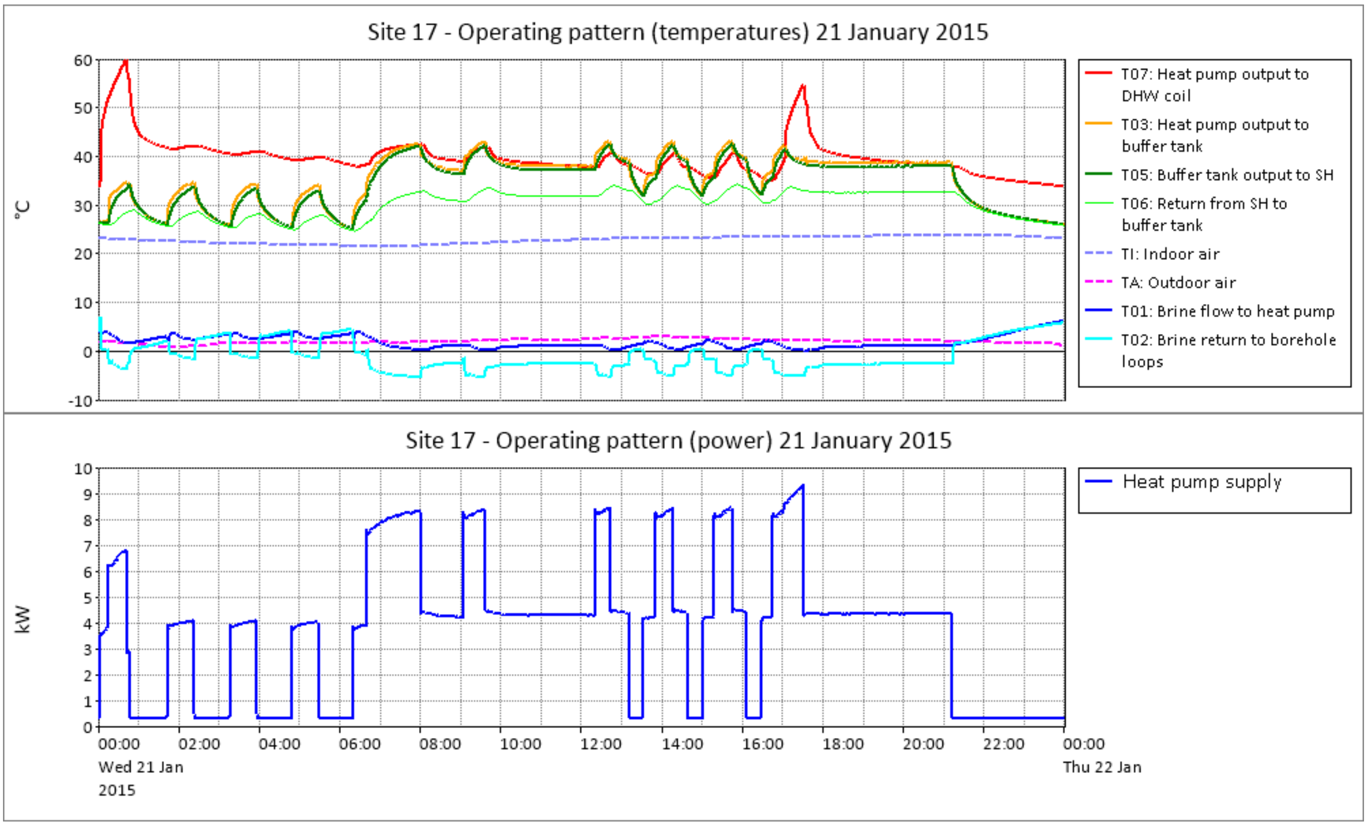

Figure 6 – Operating pattern on 21st January 2015

Figure 7 shows the typical warm-weather operating pattern on 7th July 2015 when the outdoor temperature was between 12 and 25 °C.

The lower graph shows the heat pump running with one compressor four times during the day to provide heat to domestic hot water.

It can be seen that the temperature of the output to the buffer tank also increased while the heat pump was running. This may have been due to the 3-port diverter valve being in the space-heating position when the heat pump started. The total heat measured by the space heating heat meter during the day was only 0.6 kWh. The heating circulating pump was not running at any time during the day, so it can be assumed that there was no demand for space heating, and that this small amount of heat was simply lost from the buffer tank and therefore not included in the SPFH4 calculation. However, the waste of heat is undesirable and it may be worth investigating whether the controls can be adjusted to ensure correct positioning of the 3-port valve.

The temperature of the brine to the heat pump while it was running was between 10 and 11 °C.

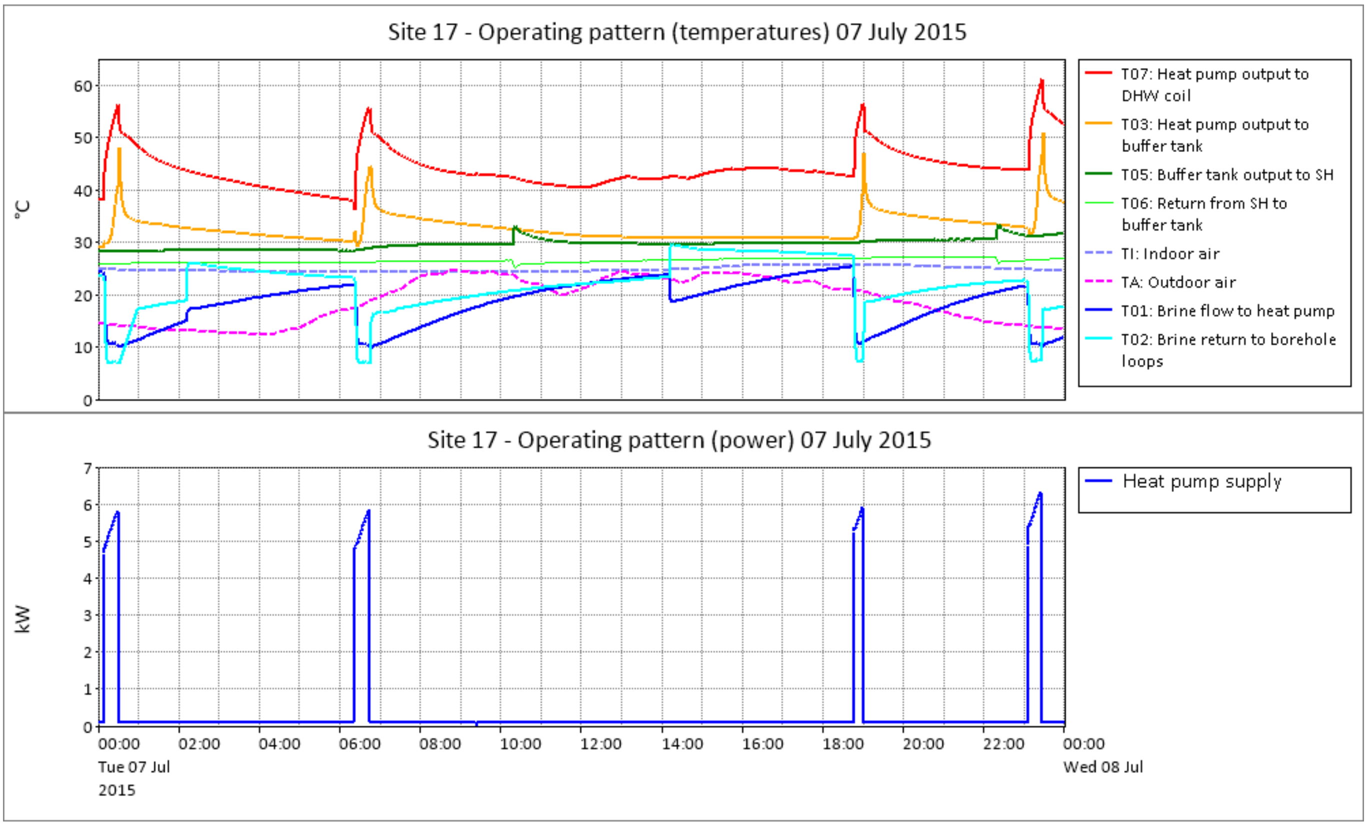

Figure 7 – Operating pattern on 7th July 2015

The cycling behaviour of this system was comfortably within the limits recommended by previous research [5]. The minimum run time was 13 minutes, and there was rarely more than one run cycle per hour.

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[7]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The periodic (every 2 weeks) rise in the temperature of the output to the domestic hot water heating coil to 61 °C can be seen on the top (red) graph. This was presumably for Legionella control. At other times, the output to the DHW coil was generally not above 56 °C.

The temperature of the output from the buffer tank to the heating circuit was at a maximum of 45 °C during January and November when the outdoor temperature was lowest. During warmer weather, the heat pump output temperature was lower as a result of the weather compensation function.

The high temperatures of the heat pump output to the buffer tank (orange graph) during the summer was probably due to the incorrect positioning of the 3-port valve as noted above and as seen in Figure 7.

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[7] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

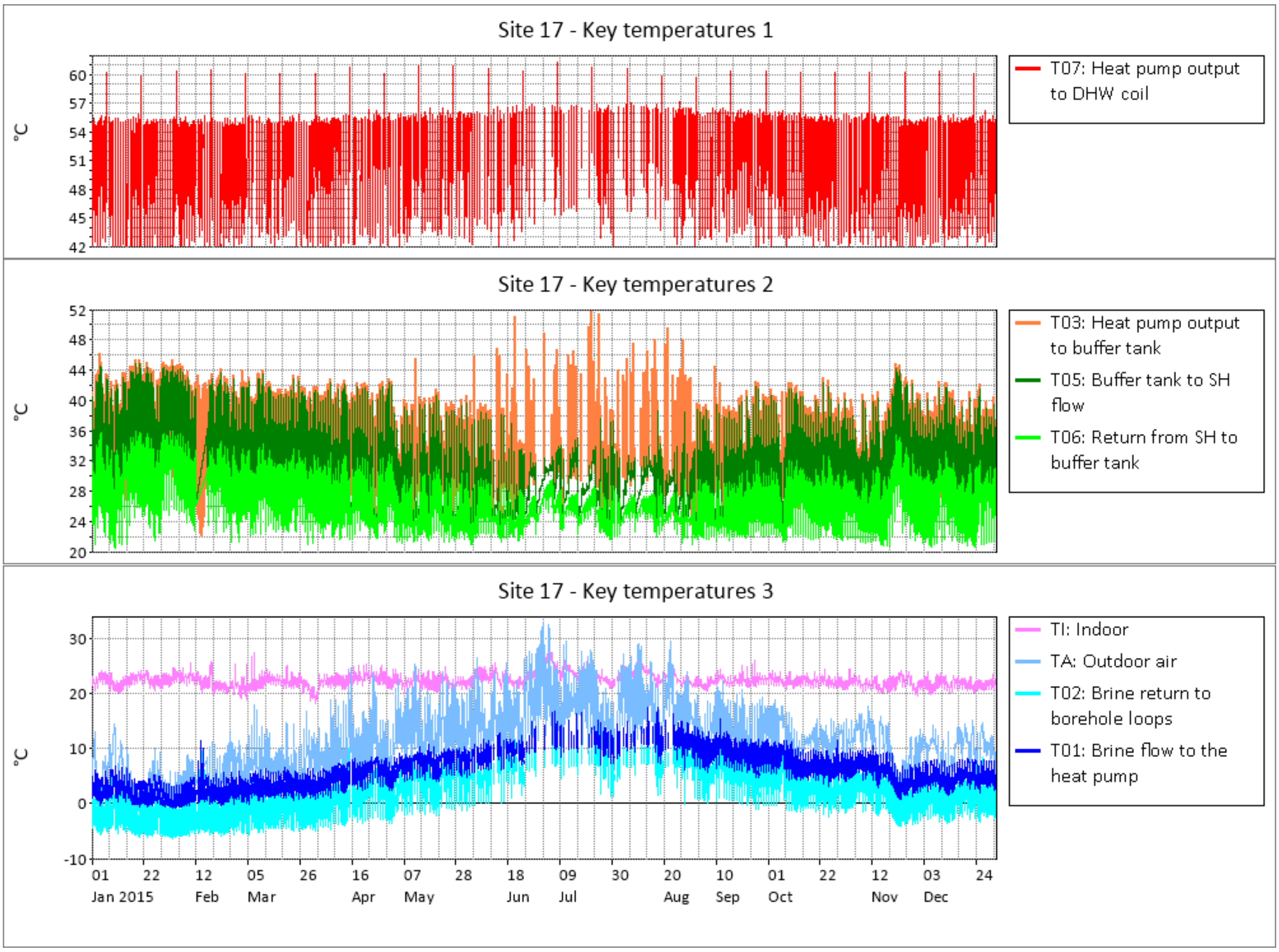

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were slightly below average, which would have had a small negative influence on system performance.

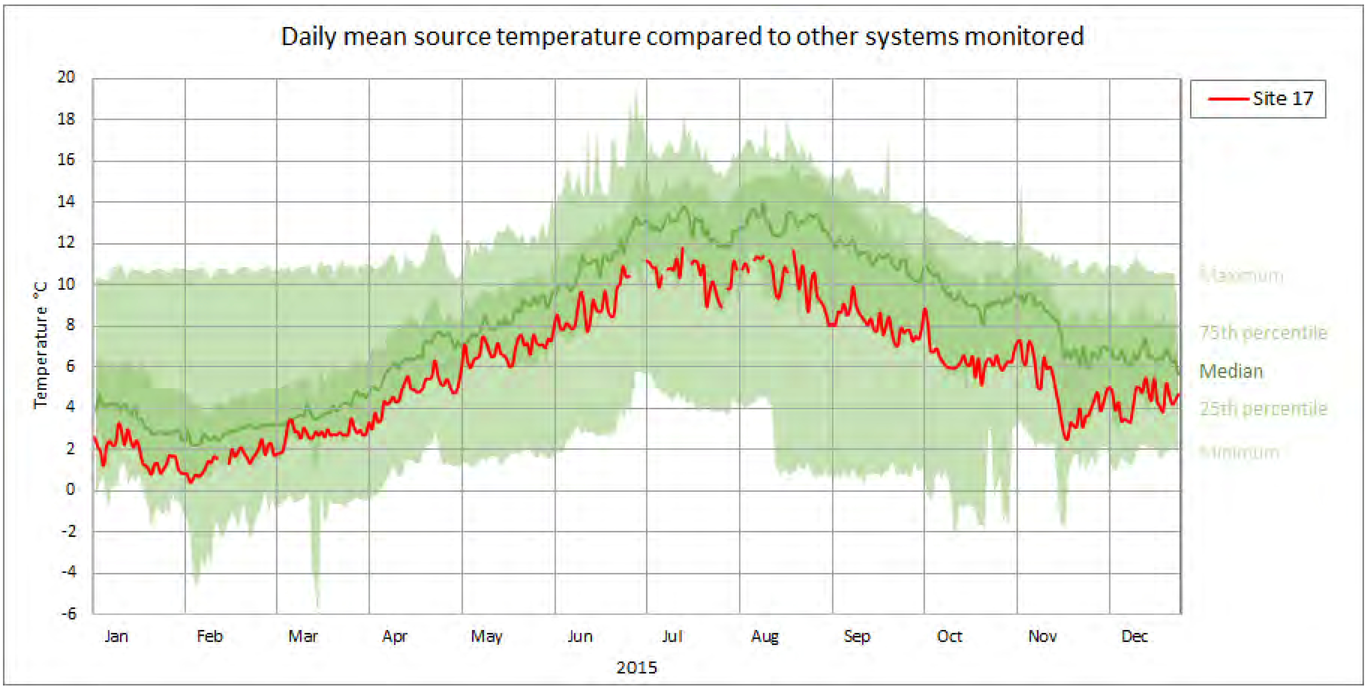

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 17 is shown in red)

Figure 10 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures on this system were below average. This would have had a positive effect on the system performance.

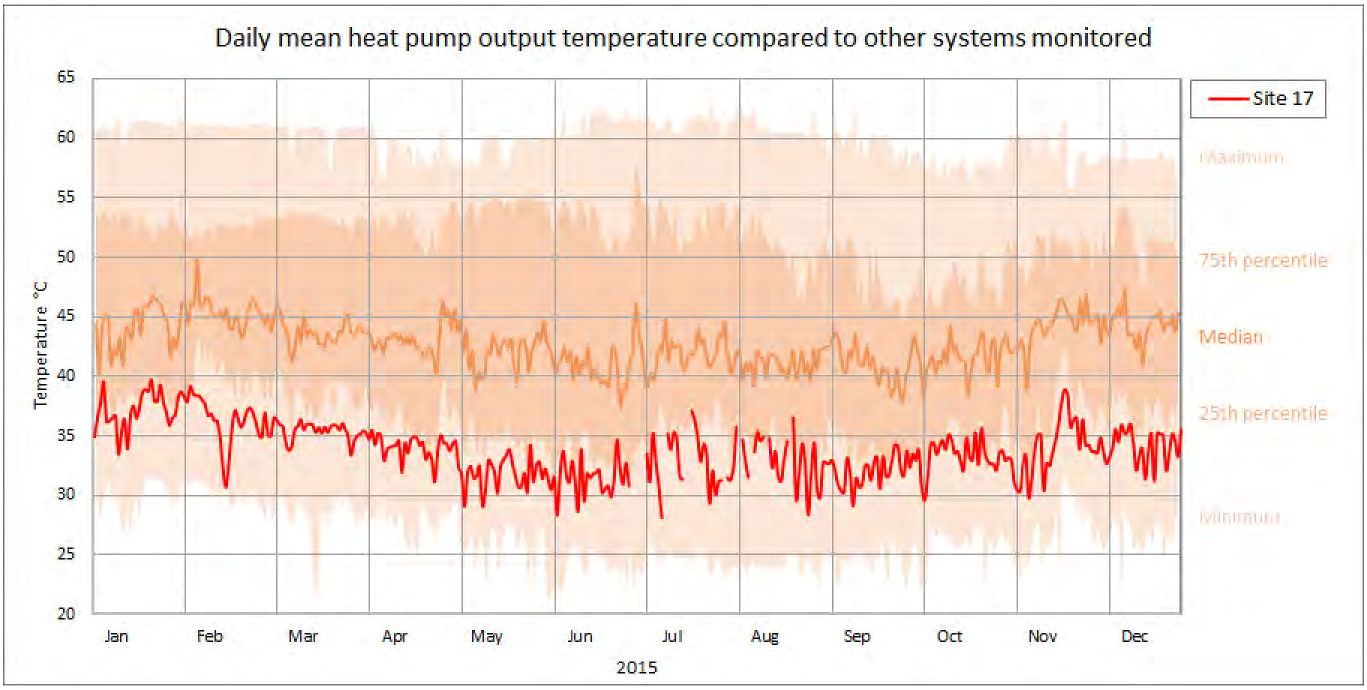

Figure 10 – Daily mean heat pump output temperature (to SH) compared to those of other systems monitored in this project (site 17 is shown in red)

Comments

The large uncertainty of measurement of the heat metering and the need to estimate the heat provided to domestic hot water precluded the determination of the SPF values.

Aspects of this system that positively influenced its performance are:

- The temperature of the output to the buffer tank was rarely above 43 °C – below average compared to other systems monitored.
- Weather compensation and night setback were used to keep the output temperature as low as possible.
- The temperature loss through the buffer tank was generally less than 2 °C. This was lower than most other monitored systems with 4-pipe buffer tanks.
- The temperature of the output to domestic hot water was below 56 °C most of the time.
- The immersion heater in the domestic hot water cylinder was used minimally (0.5% of total electricity used by the heat pump system).
- The solar thermal collector used to heat the domestic hot water may have reduced the requirement for high temperature output from the heat pump to domestic hot water.
- The proportion of total electricity used by the brine, buffer and heating circulating pumps was low compared to other systems monitored.
- The use of just one of the heat pump vapour-compression systems to heat the domestic hot water via a 3-port diverter valve allowed the output to space heating to be provided at low temperatures at all times.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the brine flow to the heat pump was below average compared to other systems monitored. The reason for this is unknown, but the temperatures were not outside the principles of good practice.
- The lack of individual room thermostats may have led to the spaces being overheated at times. This would have wasted energy and increased the running costs.
- Some heat loss from the buffer tank occurred during the summer months when there was no demand for space heating. This appears to have been due to incorrect positioning of the 3-port valve at the heat pump output during DHW operation.

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[2] D. Butler, A. Abela and C. Martin, “Heat meter accuracy testing,” DECC, 2015.

[3] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[4] R. Nordman, “SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector,” SEPEMO-Build project, 2012.

[5] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[6] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 18

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 18 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 18 is an apartment complex with two 4-storey buildings built in 2011.

A ground-source heat pump, installed as original equipment, extracts heat from vertical boreholes beneath the outdoor car park and provides space heating and domestic hot water to all apartments. Underfloor heating is used throughout, and there are no hot water storage cylinders in the apartments.

Seasonal performance factors are not presented because characteristics of the heat meters, previously installed for the Renewable Heat Incentive and used to monitor this system, have led to unacceptably high uncertainties of measurement of the heat delivered.

There were some evident problems with the operation of the system during the period of monitoring. As discussed in this case study, the performance of the system when operating correctly could potentially yield improved results.

Aspects of this system that positively influenced its performance are:

- Weather compensation provided a very effective reduction in output temperature during warmer weather.

Aspects of the system that may have negatively influenced its performance include:

- The domestic hot water immersion heaters were used extensively for reasons that are unknown.
- The heating circulating pumps did not operate before 5th August 2015. This may well have resulted in the apartments not being heated properly during that period.
- The temperatures of the output to space heating (up to 62 °C in December) were very high compared to those observed on other underfloor heating systems in the monitored sample.

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[1] The heat meter installation on this system uses strap-on temperature sensors. This technique is known [1] to be prone to unacceptably large measurement errors and the performance values could therefore not reliably be determined.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	18
Survey date	07/04/2014
Monitoring installed	12/06/2014
G/WSHP	GSHP
Building type	Apartment complex: two 4-storey buildings
Location	City
Heat pump capacity kW$_{TH}$	79
Number of heat pumps	2
Number of compressors	4 (2 vapour-compression circuits in each heat pump)
Heat source	Vertical boreholes below outdoor car park. 12 x 100m
Heat emitters	Underfloor heating pipes
DHW	Yes
Auxiliary heat	3 x 9kW immersion heaters in the DHW cylinders
Source pumps	2 x 750W (1 in each heat pump)
Buffer pumps	4 x 170W (2 in each heat pump)
Buffer tank	500 litre 4-pipe
SH circulating pumps	2 twin pump sets: 1 x 180W max; 1 x 430W max
DHW cylinders	3 x 1000 litre
Control	Heat pump controllers
Weather compensation	Yes
Heat meter type	Mechanical multi-jet + strap-on temperature sensors
No. of heat meters	2
Heat meter interface	Pulse (100 Wh/pulse)
Comments	

Table 1 – System details

Site 18 is an apartment complex with two 4-storey buildings. The apartments were designed and built in 2011 by a European construction company using materials supplied from mainland Europe. All heating and domestic hot water is provided from a single plant room in the basement. Space heating is via underfloor pipes, and there are no domestic hot water storage tanks in the apartments.

This application entails extracting heat from the ground to provide space heating and domestic hot water via separate circuits to a modern building with reportedly very good standards of insulation. The building is located in an area with below-average outdoor temperatures – annual mean 9.2 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The use of underfloor heating should allow the heat pumps to operate with low output temperatures, although the domestic hot water requires higher temperatures. The performance of the system would be expected to be at least average compared to other systems monitored.

Heat pump and monitoring systems

Two heat pumps are installed in the basement plant room. Each of these has two vapour-compression circuits, and is designed to provide heat output at up to 65 °C. One of the heat pumps provides heat to space heating (SH) and to domestic hot water (DHW). The other one has both outputs connected together and provides space heating only.

The heat source is 12 x 100 metre boreholes beneath the outdoor car park.

Three 1000-litre domestic hot water cylinders are installed, each equipped with a 9 kW immersion heater for auxiliary heat.

The output to the underfloor heating system is via a 500-litre 4-pipe buffer tank.

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and to domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. The existing heat meters ("H") installed for the Renewable Heat Incentive (RHI) are monitored via their pulse interfaces. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2]. The outdoor air and ground temperatures are also monitored.

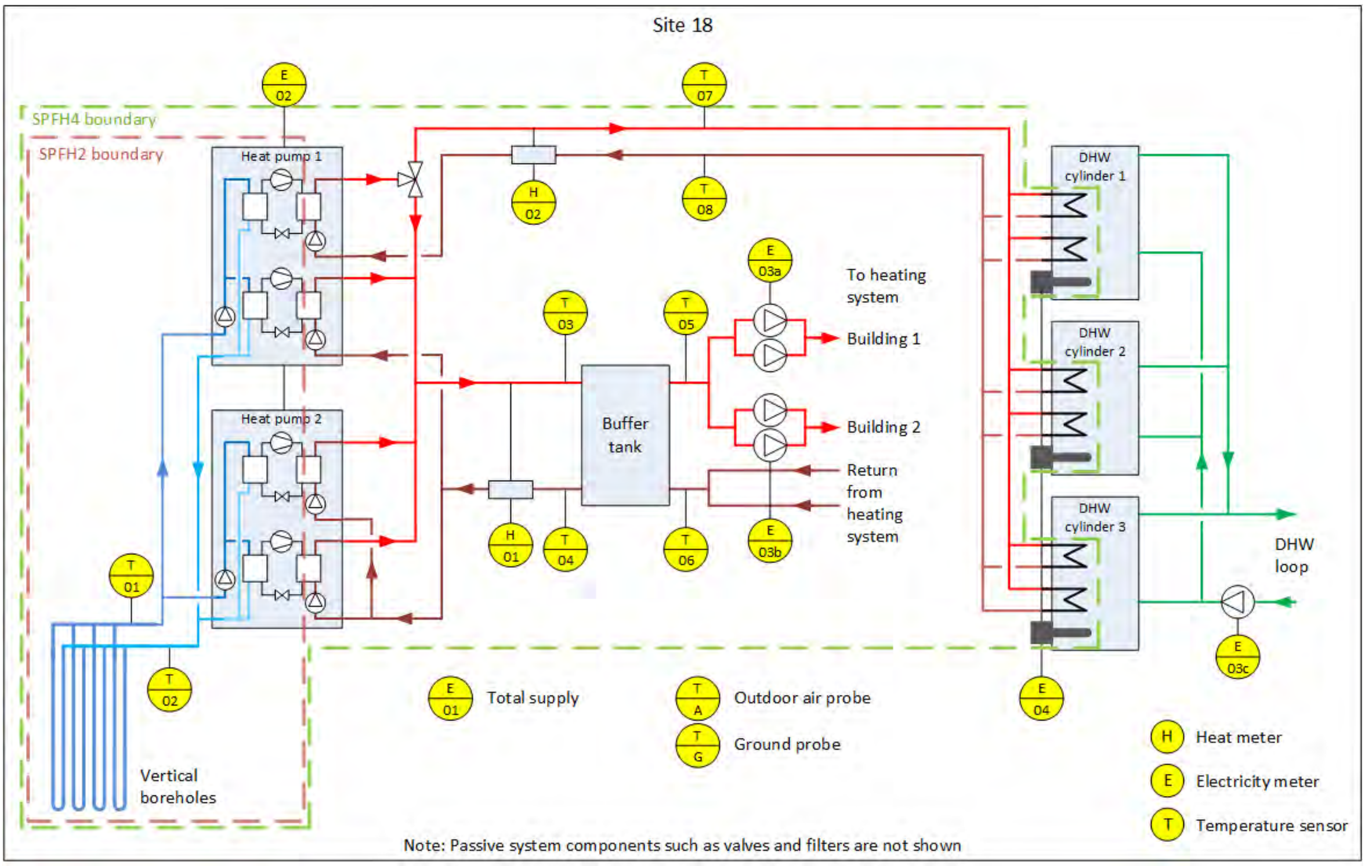

Figure 1 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pumps. Two heat meters are installed: one measures the heat supplied to the buffer tank (space heating); the other measures the heat supplied to the domestic hot water cylinders.

The heat meters are of a type that uses mechanical multi-jet turbine flow meters and strap-on temperature sensors. Although the use of strap-on temperature probes was as recommended by the meter manufacturer at

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[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

the time of installation, it is known from subsequent research [1] that this technique can result in large measurement errors.

The heat calculators on this system were of a type intended for use with antifreeze in the working fluid. However, it is not known whether any antifreeze was present in the heating circuit. This may have caused further error in the heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pumps together with the source pumps.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [2].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counters connected to the heat meters were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pumps and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat outputs recorded by the heat meters were determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pumps to SH \& DHW] – [heat added by internal buffer pumps]}}{\text{Electricity used by: [heat pumps excluding internal buffer pumps]}}$$

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

- This calculation required the electrical energy used by the buffer pumps inside the heat pumps to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running.
- The heat added by the buffer pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pumps.

$$\mathrm{SPF}_{H4} = \frac{\text{[Heat output of heat pumps to SH \& DHW]} - \text{[heat loss from buffer tank]} + \text{[heat added by SH circ pumps]} + \text{[heat added by DHW immersion heaters]}}{\text{Electricity used by: [heat pumps]} + \text{[SH circulating pumps]} + \text{[DHW immersion heaters]}}$$

- The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pumps.
- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 523 019, which represents 99.5% of the 12-month period.

SPF results presented as relative values

Because of the heat metering issues noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors SPF_{H2} and SPF_{H4} are therefore presented in this case study as "relative" values, whereby each value is shown as an amount above or below a nominal performance.

Figure 2 shows the daily SPF_{H2} and SPF_{H4} behaviour of the system (shown as relative values). These values represent the combined space heating + domestic hot water performance.

Both the SPF_{H2} and the SPF_{H4} values were unusually low. As shown in Figure 3, the heating circulating pumps were not operating prior to 5th August 2015[5]. The reason for this is not known, but it can be seen that when the pumps were turned on, the daily SPF values improved significantly because the heat pump output temperature was then lower – although the SPF values were still low compared to other systems monitored.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[5] The heating circulating pumps had previously been operating until 20th October 2014.

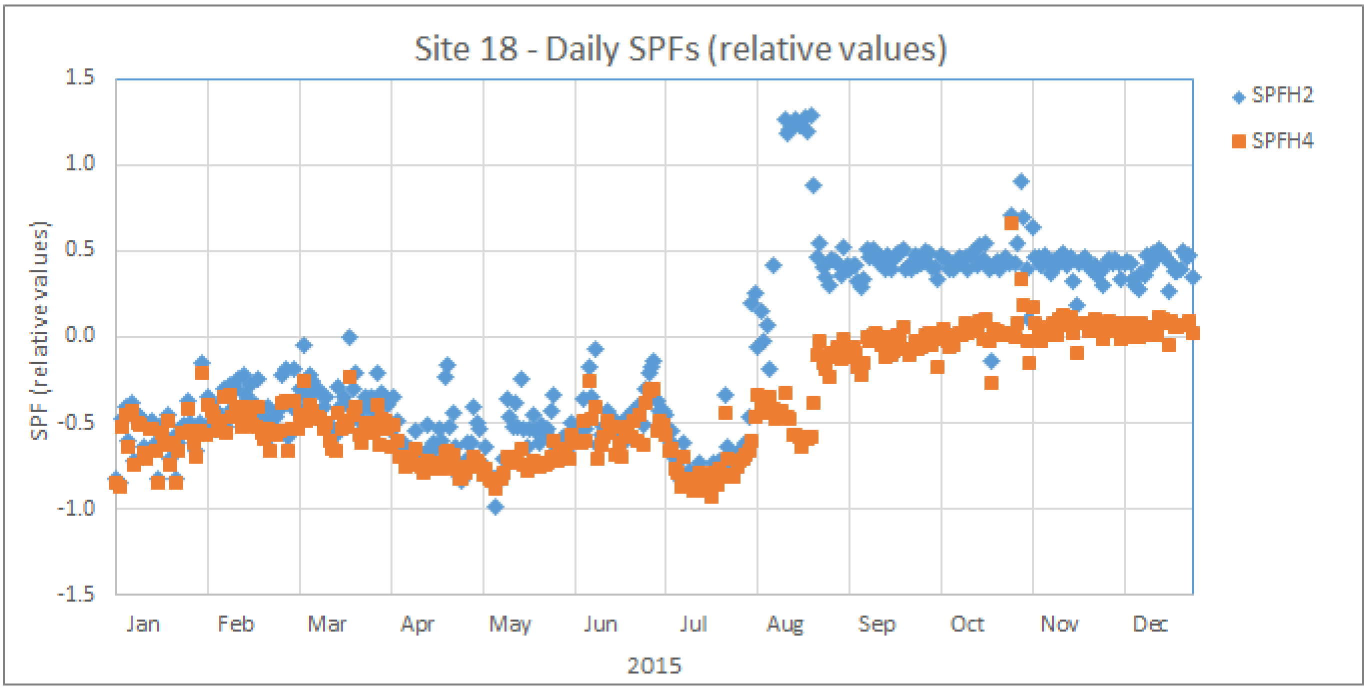

Figure 2 – Relative seasonal performance factors SPFH2 and SPFH4 calculated daily

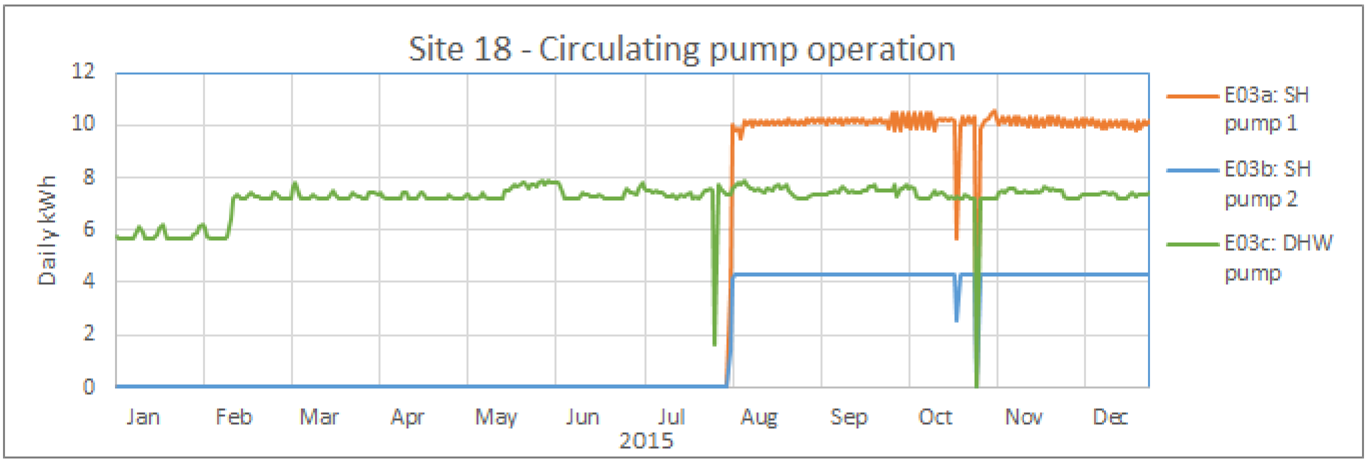

Figure 3 – Circulating pump operation

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [3] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output to space heating and to domestic hot water. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. Note that the kWh values have been removed from the graph because of the high uncertainty of measurement of the heat meters.

The total heat output was highest during the cold weather in November and December. During similar weather in January and February, the heat output to space heating was much lower – almost certainly because the circulating pumps were not operating.

Use of immersion heaters

The very high use of the domestic hot water immersion heaters during April, May and August is shown by the red areas of the graph. The immersion heaters had not been used at all in January and early February, during the coldest part of the year. Then, on 10th February, the immersion heater use jumped from zero to 20% of total electricity use, and on 14th April if increased again to 65% of total electricity. The reason for these sudden changes is unknown and is not apparent from the available data.

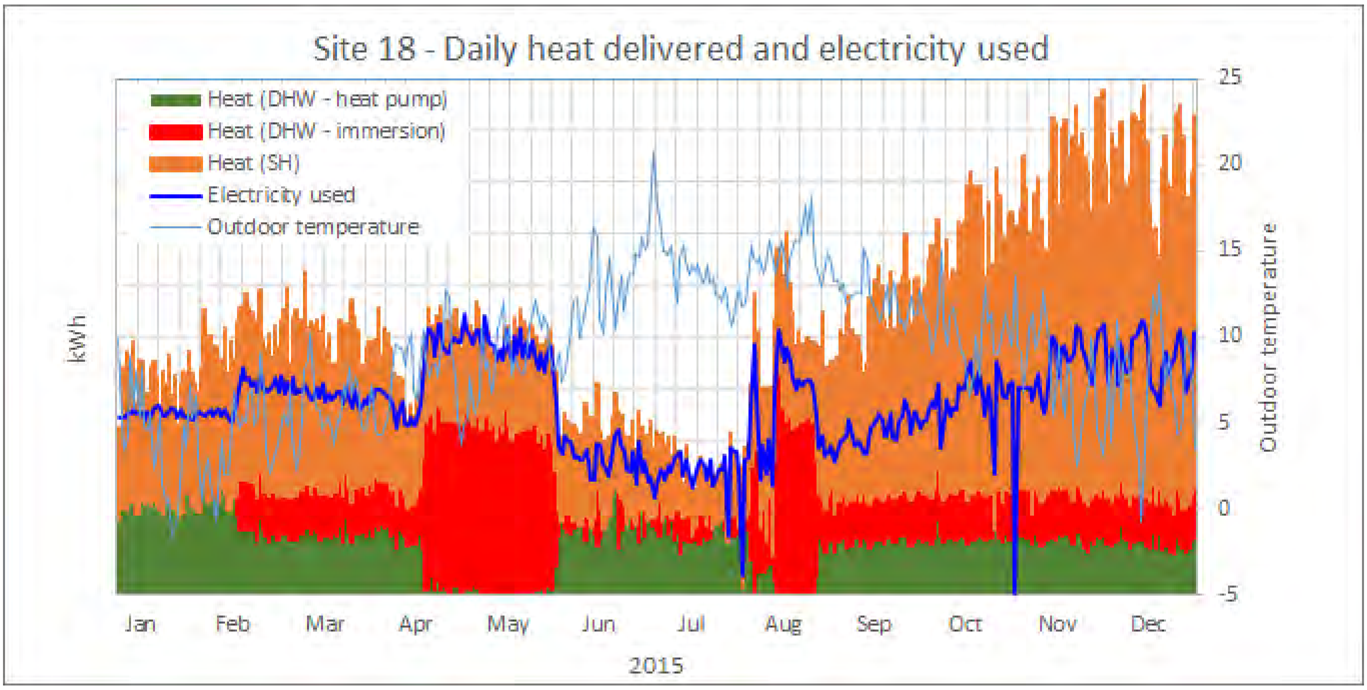

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

Table 2 shows the estimated breakdown of the heat delivered to space heating and to domestic hot water during the period from 1st January to 31st December 2015.

	%
Heat delivered to space heating	60.5%
Heat to domestic hot water (from heat pump)	19.3%
Heat to domestic hot water (from immersion heaters)	20.2%

Table 2 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The high use of the domestic hot water immersion heaters can be seen: 27.5% of total electricity use.

The brine pumps[6] accounted for 4.3% of the total electricity use, which is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

The buffer[6], space heating and domestic hot water circulating pumps accounted for 4.6% of electricity, which is also below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%) – although the heating circulating pumps were only used from week 32.

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[6] Electricity used by the brine and buffer pumps was estimated using digital filtering of the detailed data from the electricity monitor.

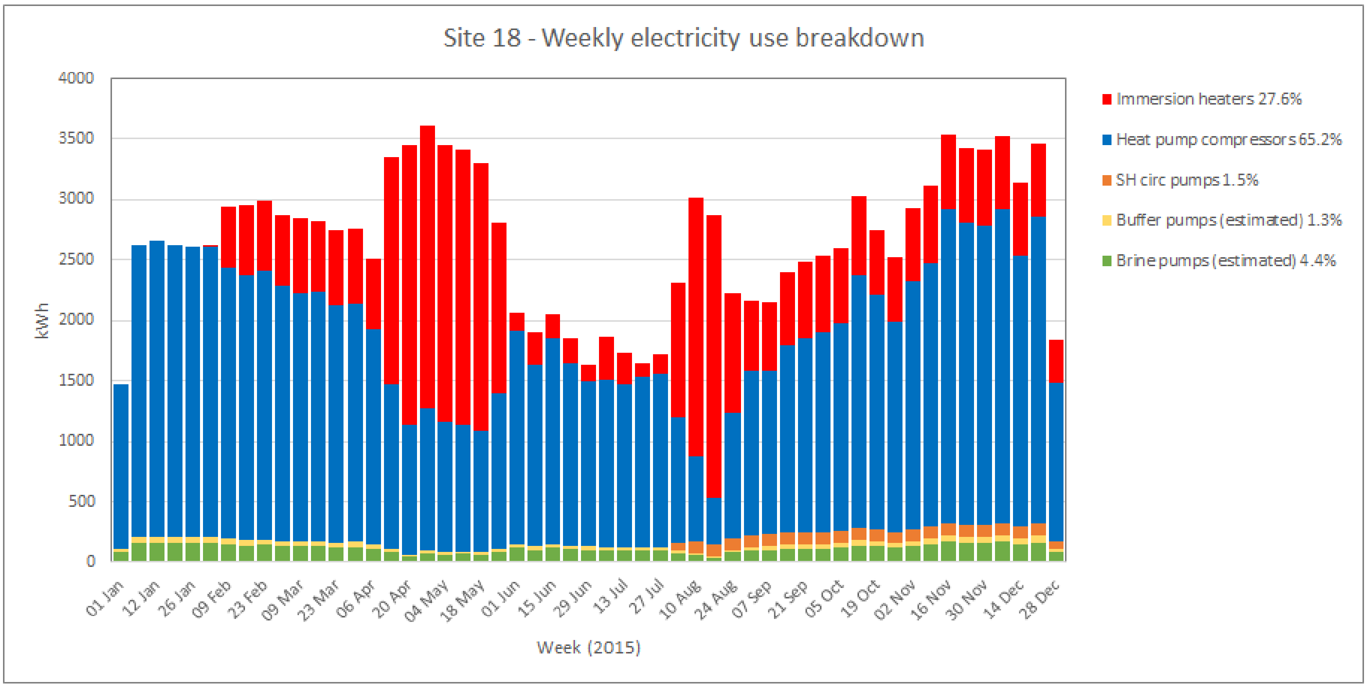

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 1st January 2015, when the outdoor temperature was between 6 and 13 °C and the heating circulating pumps were not operating. The temperature of the output from the heat pump to the buffer tank was high (44 - 62 °C) and the output to the underfloor heating system was up to 58 °C with the return temperature between 40 and 50 °C. It is not clear how the heat was being circulated to the underfloor heating: possibly natural convection with some assistance from the heat pump buffer pumps.

The loss of temperature through the 4-pipe buffer tank varied between 2 and 6 °C, depending on the number of heat pump compressors running.

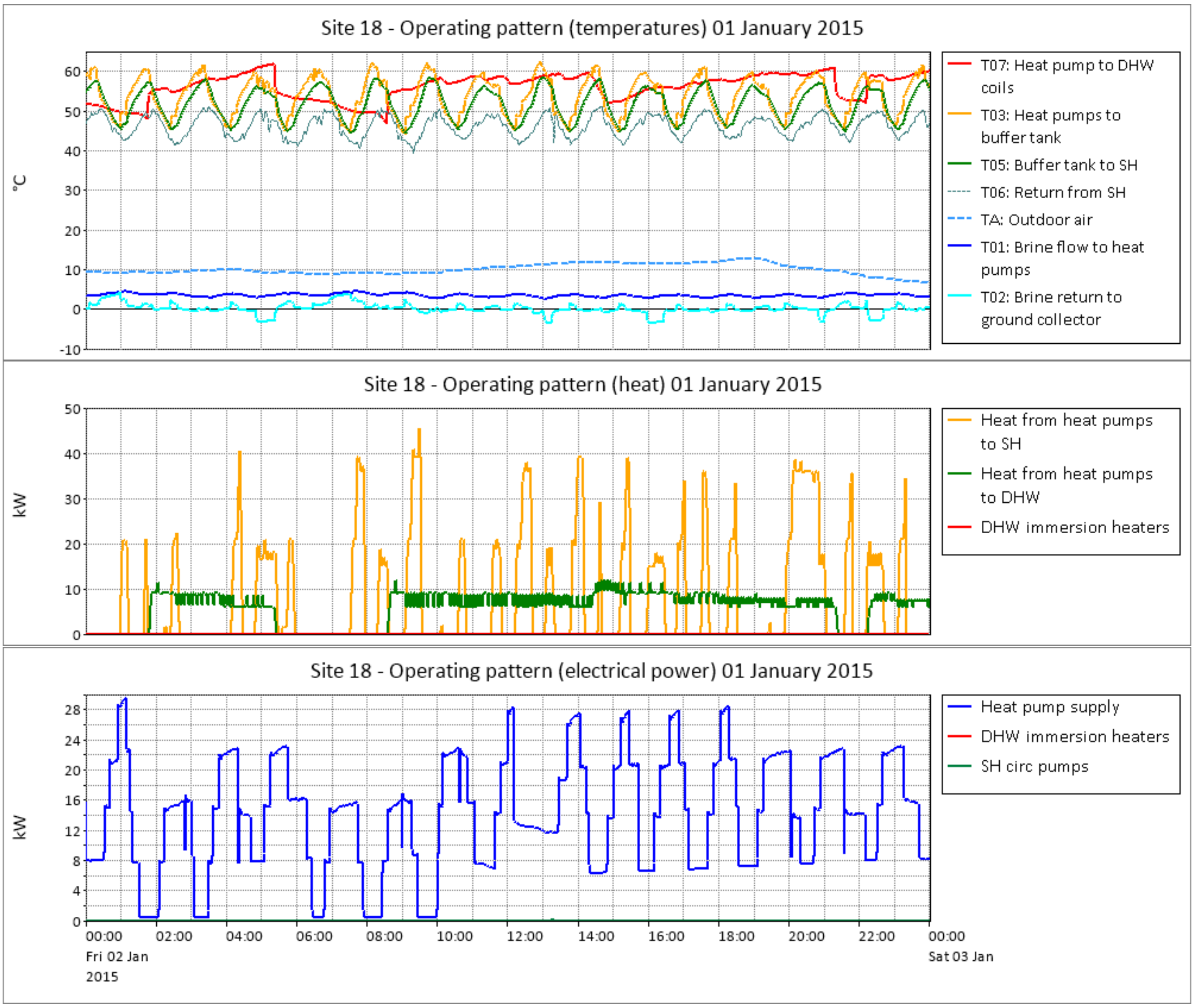

Figure 6 – Operating pattern on 1st January 2015

Unexplained use of immersion heaters

Figure 7 shows the operating pattern on 10th February 2015 when the outdoor temperature was between 3 and 7 °C. This was the day that the domestic hot water immersion heaters were suddenly switched on, and thereafter used approximately 20% of the total electricity. There is no indication from the available data why the immersion heaters were switched on.

The heat pump used for domestic hot water would have been capable of meeting the domestic hot water demand[7], unless the temperature required was over 60 °C, in which case the immersion heaters would have been needed.

Figure 8 shows the daily heat provided to domestic hot water by the heat pump and by the immersion heaters between January and March 2015. When the immersion heater was used, the heat pump provided less heat to domestic hot water than when working on its own.

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[7] The heat pump is rated at 37 kW$_{TH}$ at a source temperature of 0 °C and an output temperature of 50 °C (from the manufacturer's published performance data).

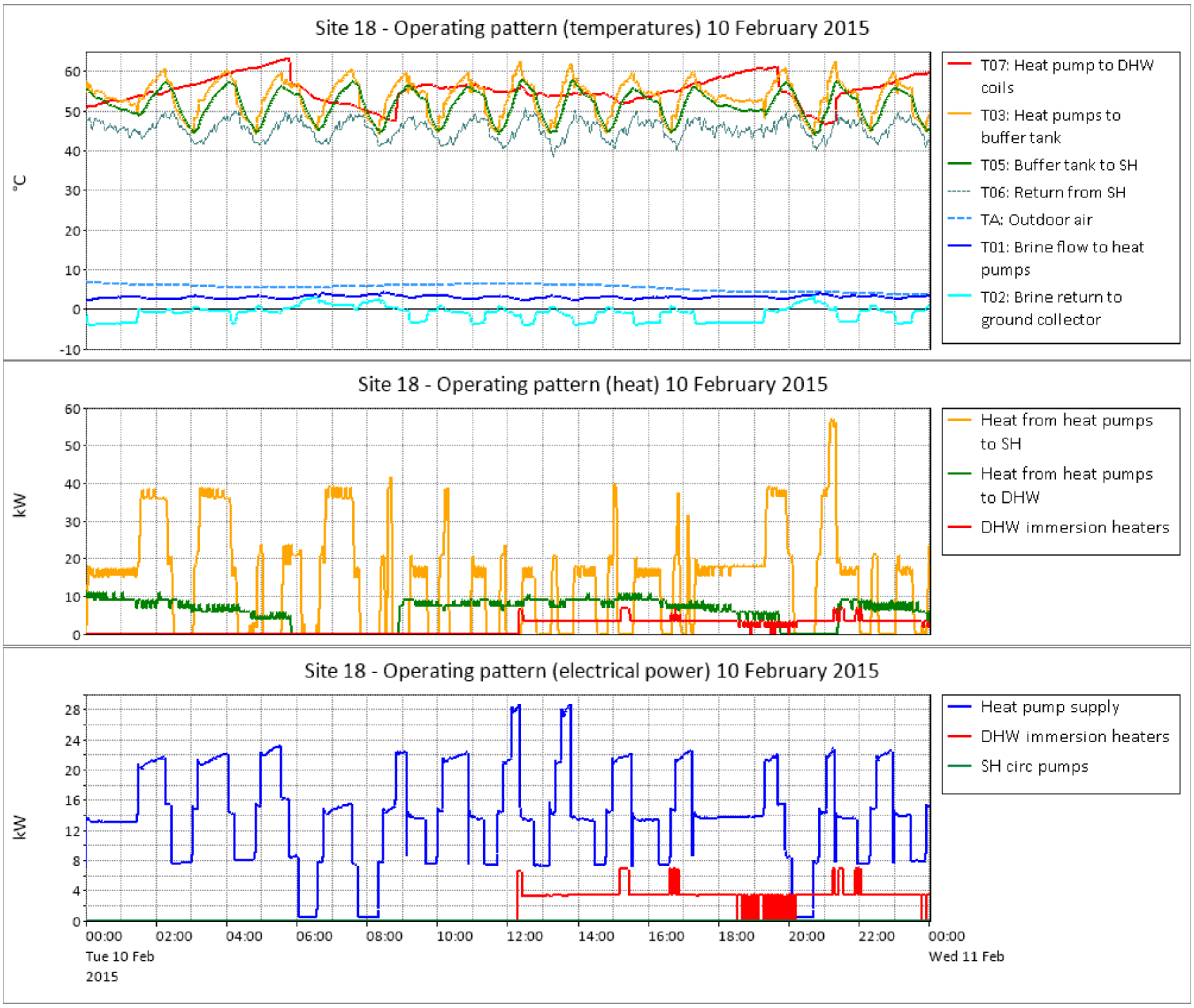

Figure 7 – Operating pattern on 10th February when the DHW immersion heaters were switched on

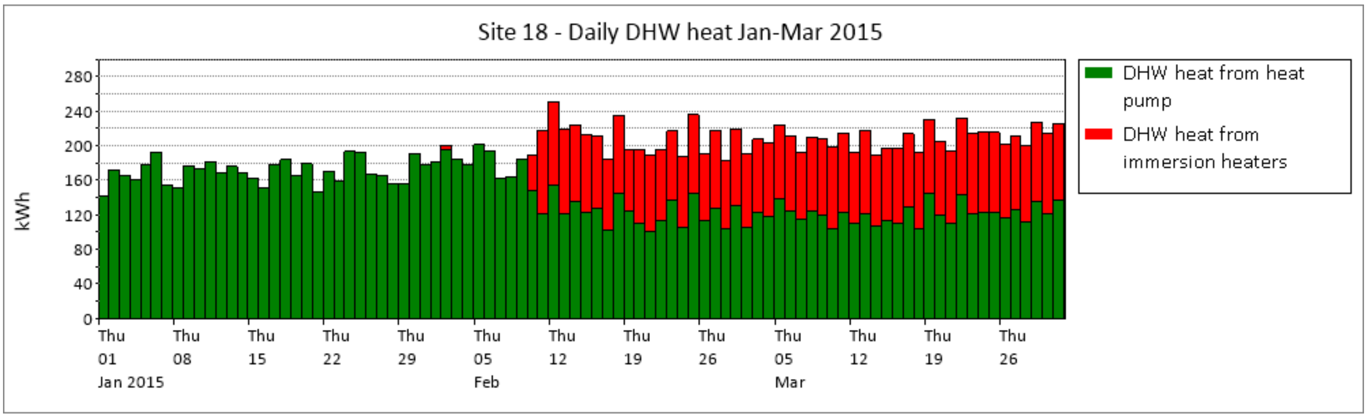

Figure 8 – Daily DHW heat January to March 2015

Figure 9 shows the situation on 14th April when the outdoor temperature was between 10 and 12 °C. On this day, the use of the domestic hot water immersion heaters again changed suddenly – this time to approximately 65% of the total electricity. On this occasion, the heat output from the heat pump to domestic hot water reduced to almost nothing, with the domestic hot water demand being met mainly by the immersion heaters – as shown in

Figure 10. The reason for this change in operation is not known, and the available data offers no obvious explanation[8]. It is assumed that the system operator manually switched on the immersion heaters.

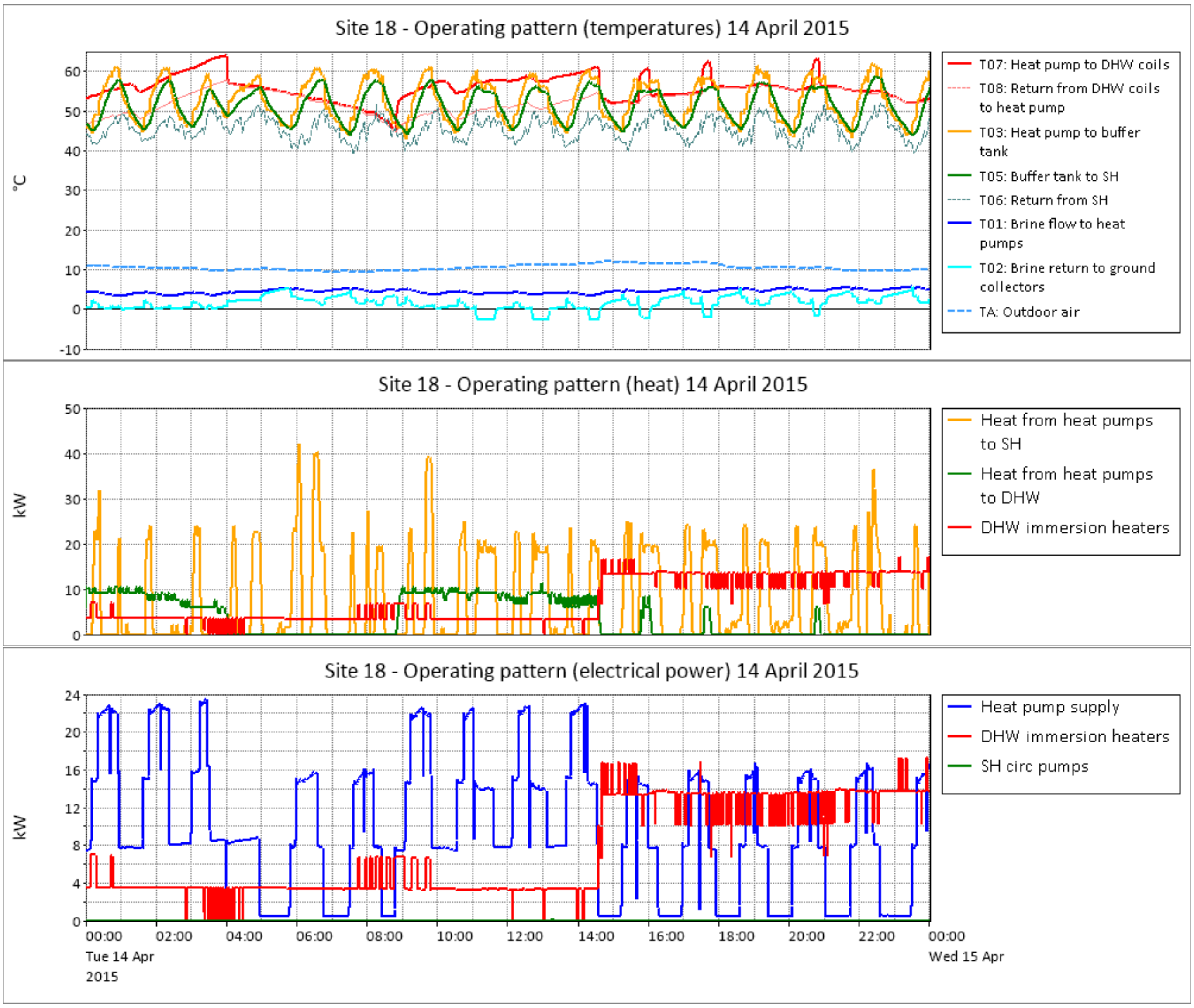

Figure 9 – Operating pattern on 14th April when the immersion heater use increased to approximately 65% of total electricity use

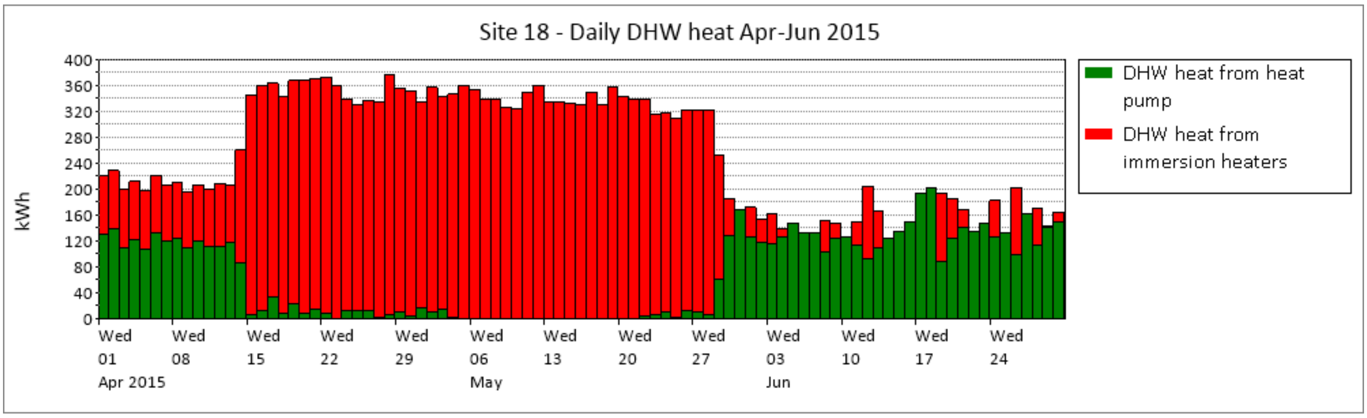

Figure 10 – Daily DHW heat April to June 2015

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[8] The temperature of the output from the DHW cylinders was not measured. It is also suspected that the DHW heat meter may have been faulty: see the discussion of this on page 16.

Space heating circulating pumps restarted on 5th August

Figure 11 shows the change in system behaviour when the heating circulating pumps were started on 5th August 2015 (having evidently[9] been off since 20th October 2014). The heat pump output temperature immediately dropped by around 15 °C, and thereafter started to change with the outdoor temperature in response to the weather compensation function.

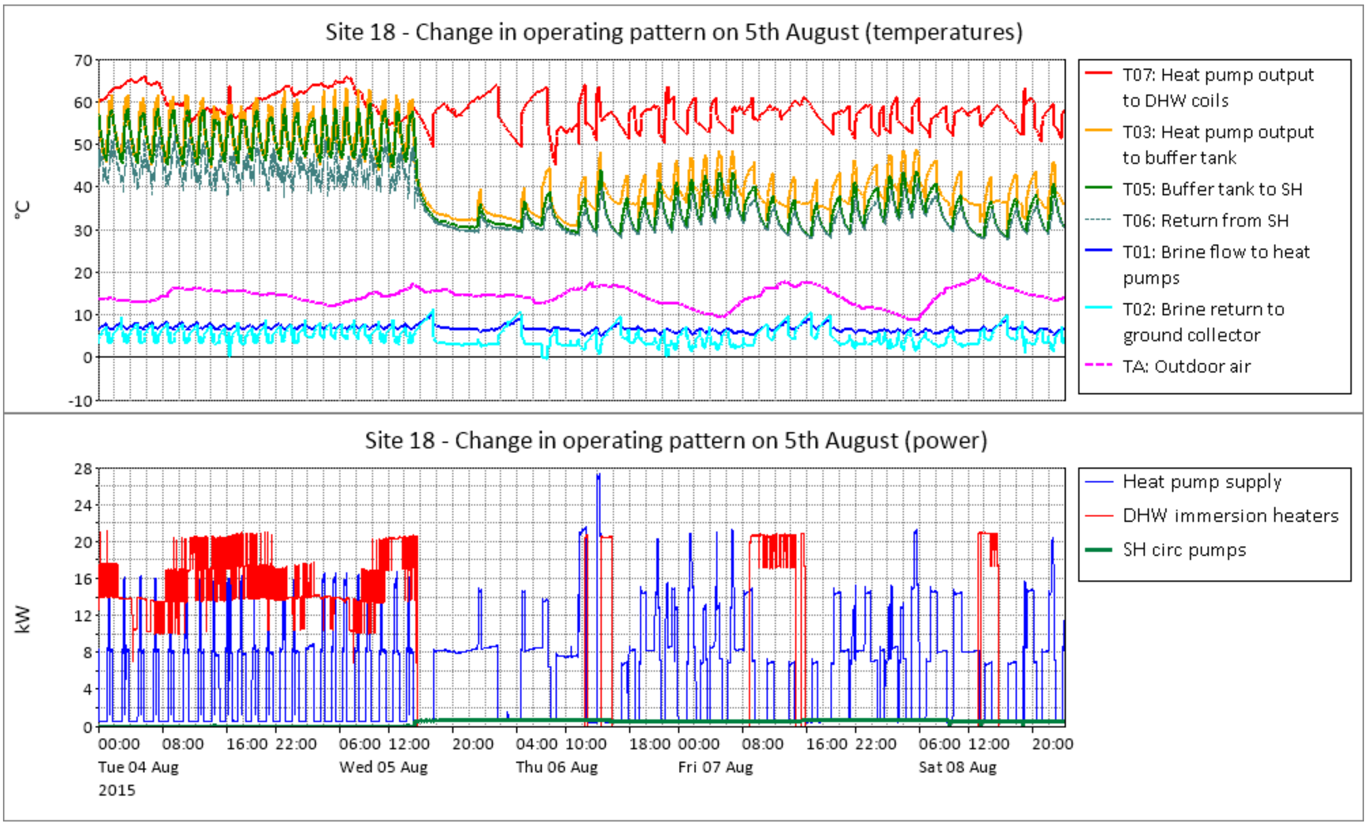

Figure 11 – Change in operating pattern on 5th August 2015

Anomaly in SPFH2 values during August

Figure 12 shows the system behaviour during August 2015, when the daily SPFH2 was unusually high – especially on 13th and 14th August. The SPFH4 values during the same period were not unusually high.

The temperature and power data has been reviewed to identify an explanation for this anomaly. Figure 12 shows the most relevant system monitoring data.

Considering the period from 12th to 24th August:

- The domestic hot water immersion heaters were using 79% of the total electricity and were apparently providing all of the domestic hot water requirements.
- The electrical energy used by the heat pumps was lower than usual (approximately 40% of the daily use earlier in the month) and the total heat output from the heat pumps was to space heating.

The SPFH2 calculation is based on the sum of the heat meters H01 (space heating) and H02 (domestic hot water). As there was evidently no heat being recorded by H02 between 12th and 24th August, the SPFH2 calculation depended during this period on the measurements from H01 only.

This may provide an explanation of the anomaly in the SPFH2 values during this period: if the measurements from H01 were reasonably accurate, while those from H02 were significantly in error (low), then the calculated SPFH2

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[9] This is evident from the recorded electrical power drawn by the pumps (not shown in this report).

values between 12th and 24th August would be more accurate that those calculated at other times when there was also heat being recorded by heat meter H02.

If this hypothesis is true, it offers some explanation of the apparently very low performance of this system – although it does not explain the exceptionally high SPFH2 values on 13th and 14th August.

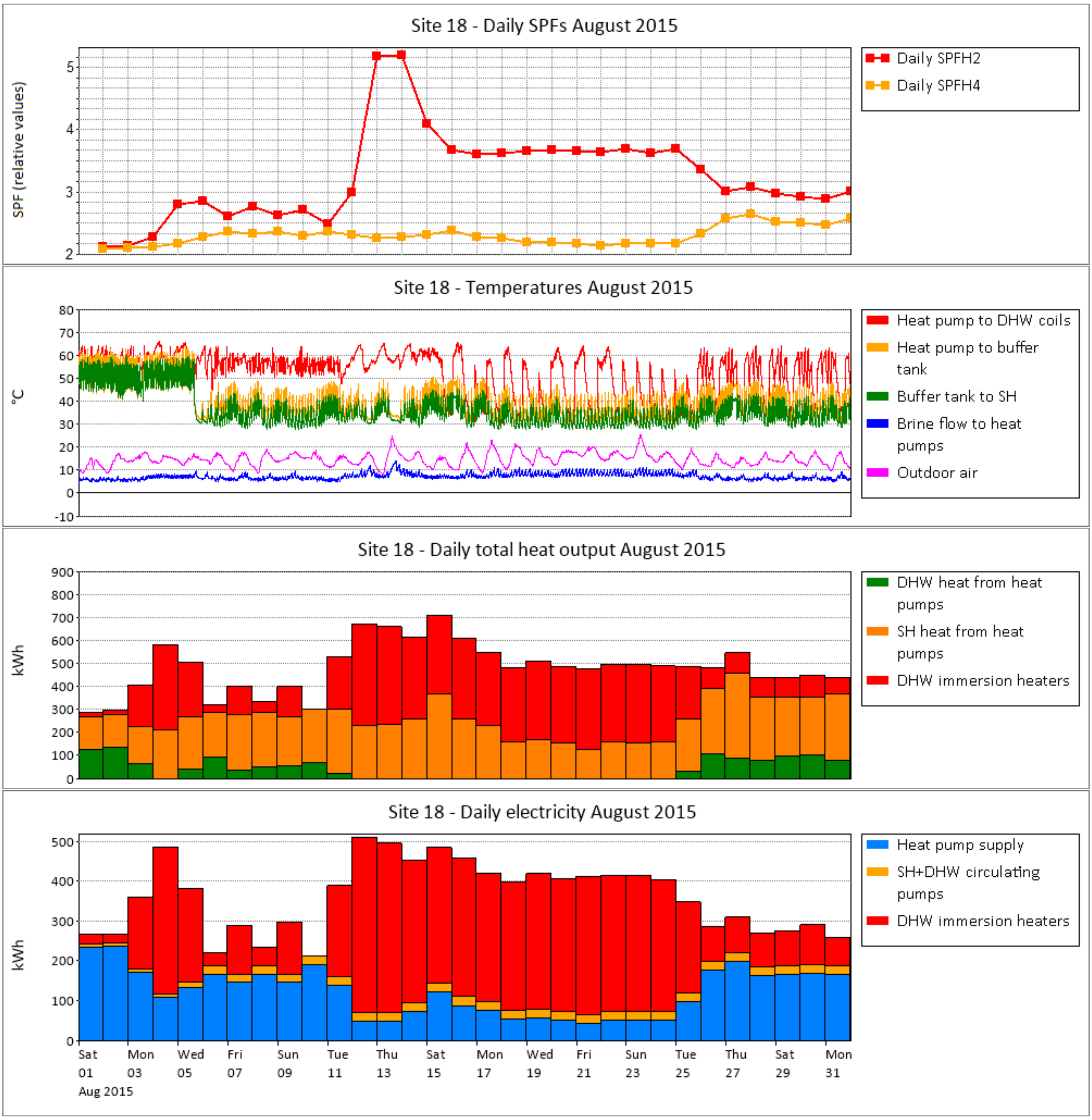

Figure 12 –Site 18 SPFH2 values during August

Source and sink temperatures

Figure 13 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[10]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The temperature of the output to the domestic hot water heating coils was up to 64 °C on most days throughout the year, except for two periods during August when the immersion heaters were used much more than the heat pump for domestic hot water production.

The output to the buffer tank was up to 63 °C most days when the heating circulating pumps were not running – before 5th August. Subsequently, when the pumps were running, the output temperature was apparently controlled by the weather compensation function: between 31 and 51 °C in August, rising to 62 °C during the cold weather in December. This appears to show that the weather compensation mechanism did not or could not operate while the heating circulating pumps were not running.

The minimum temperature of the brine flow to the heat pumps was +1.7 °C on 14th December when the outdoor air temperature was between -3 and +2 °C. The maximum was 9.5 °C on 24th August when the outdoor temperature was between 13 and 18 °C.

It is worth noting that, for much of the year, the temperature of the brine from the borehole loops was below the outdoor air temperature.

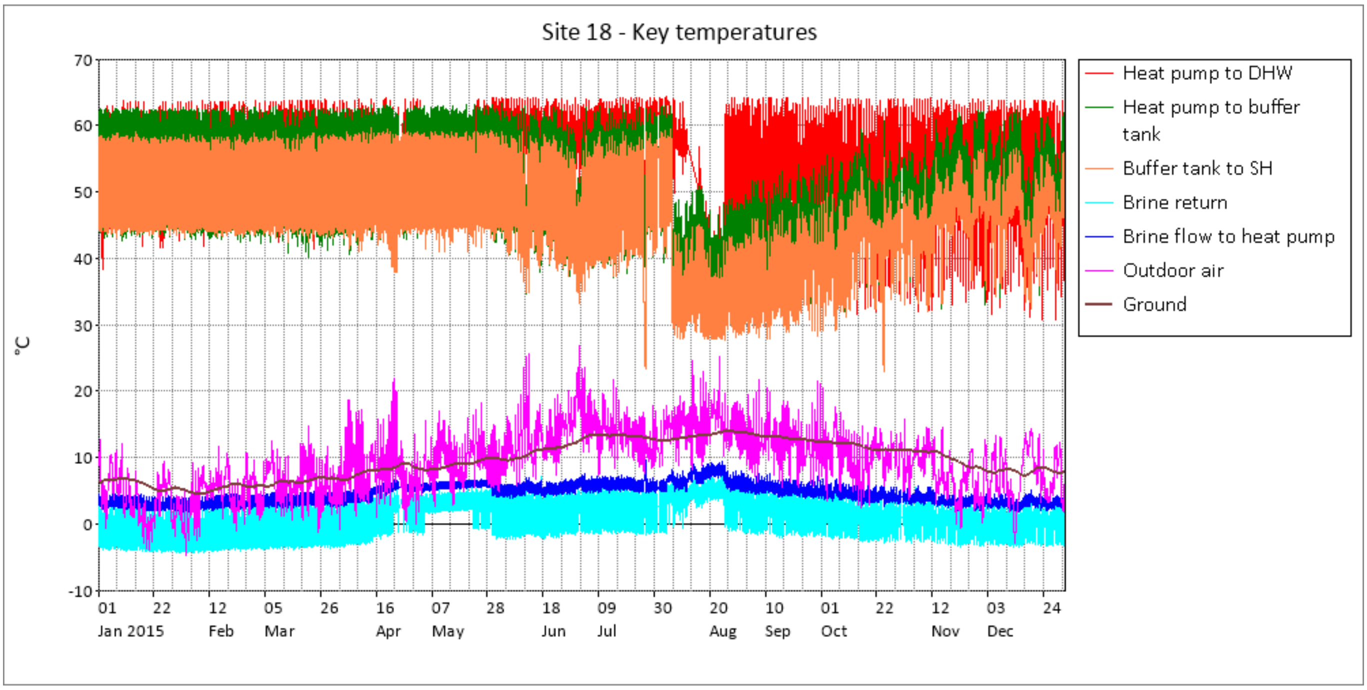

Figure 13 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 14 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system were below the average of other systems, although the variation during the year was much less marked than some systems.

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[10] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

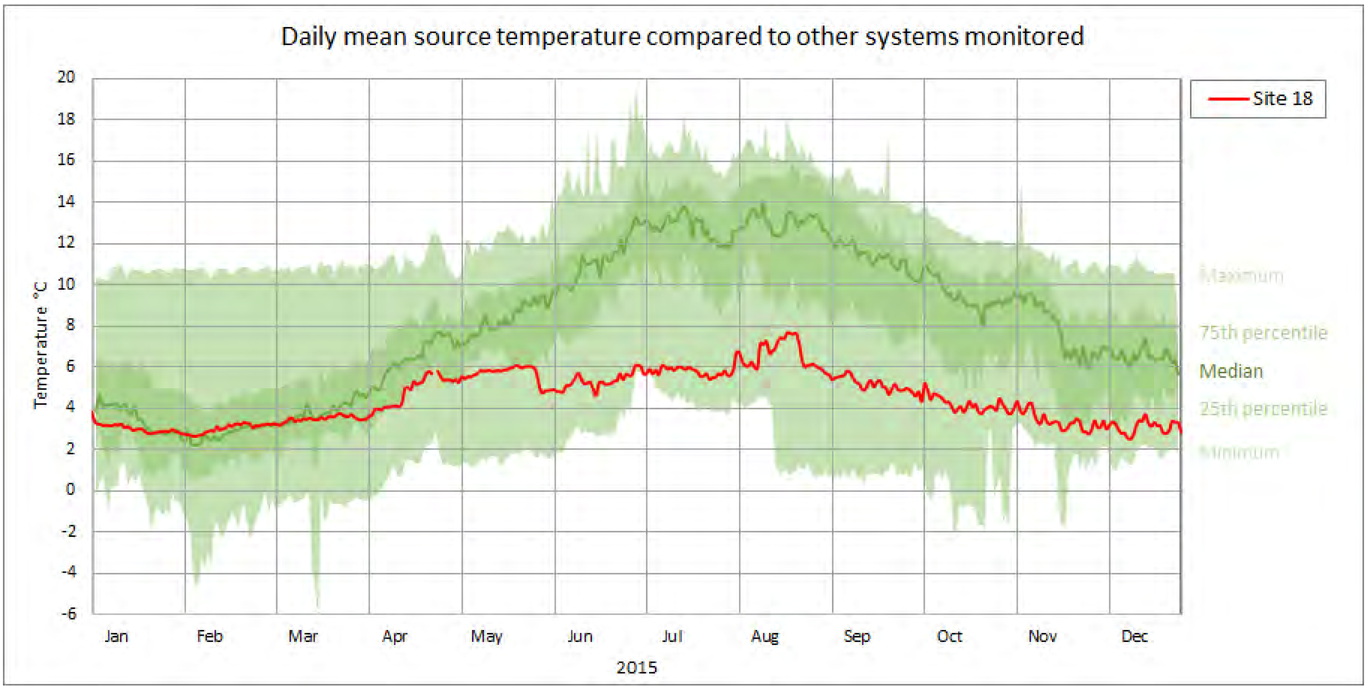

Figure 14 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 18 is shown in red)

Figure 15 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. Prior to 5th August, the space heating pumps were not running and the measured output temperature was not very meaningful. After the space heating pumps were restarted, the output temperature on this system was at first average compared to the values observed on other monitored installations, but during the winter months, it gradually rose to be higher than average (above the 75th percentile). This would have had a negative effect on the system performance.

The high temperatures during November and December are particularly remarkable considering that the heat emitters are underfloor pipes.

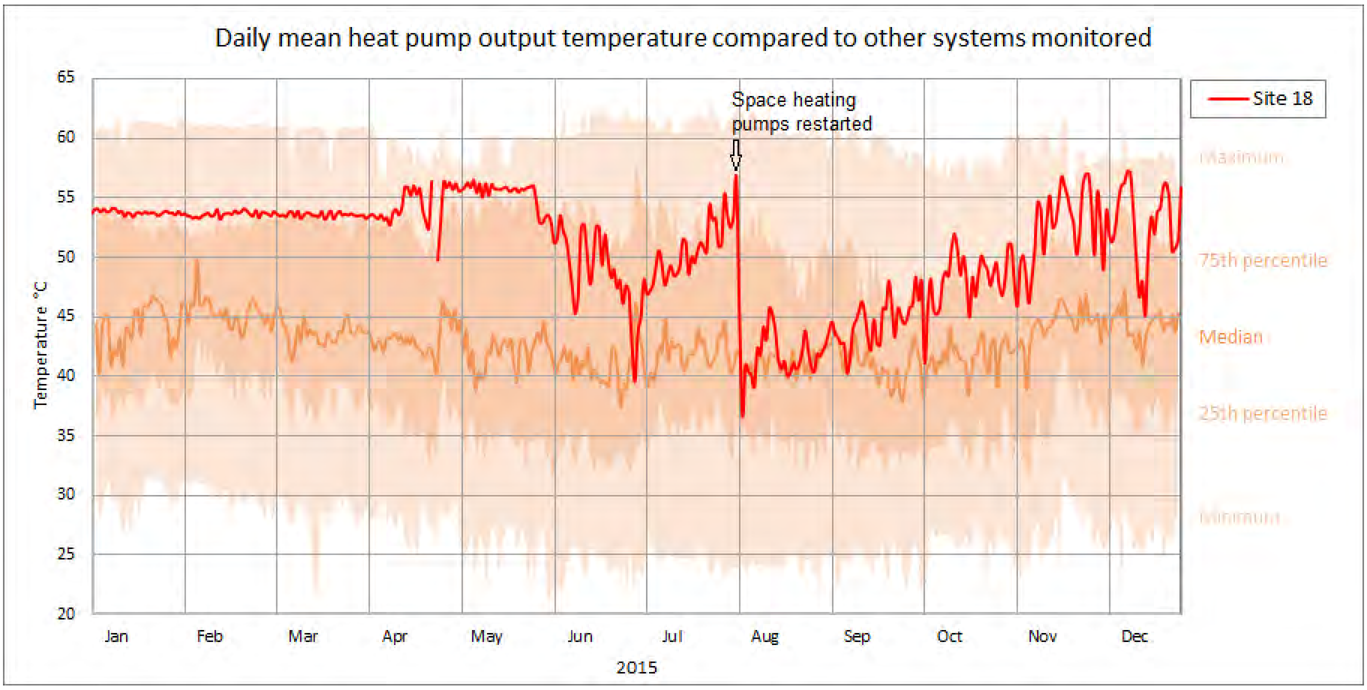

Figure 15 – Daily mean heat pump output temperature (to space heating) compared to those of other systems using monitored in this project (site 18 is shown in red)

Comments

The large uncertainty of measurement of the heat metering on this system precluded the determination of the SPF values.

Aspects of this system that positively influenced its performance are:

- Weather compensation appeared to work well (after the heating circulating pumps were restarted) resulting in a very effective reduction in output temperature during warmer weather.

Aspects of the system that may have negatively influenced its performance include:

- The domestic hot water immersion heaters were used extensively for reasons that are unknown. This will have contributed significantly to the low SPF_{H4} values. It would be worth investigating whether the use of the immersion heaters can be reduced, to improve overall performance.
- The fact that the heating circulating pumps did not operate before 5th August may have resulted in the apartments not being heated properly during that period.
- The temperatures of the output to space heating (up to 62 °C in December) were very high compared to those observed on other underfloor heating systems in the monitored sample. The reason for the high temperatures should be investigated. The type of heat interface units used in the apartments is unknown, but these might be a cause of the problem if they introduce additional temperature losses. A reduction in heat pump output temperature would improve the system performance.
- The temperature losses through the 4-pipe buffer tank were high – between 5 and 7 °C when the heat pumps were running. This is higher than measured on most other systems with 4-pipe buffer tanks in the monitored sample.
  It is possible that a different design or arrangement of the buffer tank would reduce the temperature loss and yield a performance improvement. However, this is a specialised topic and is outside the scope of this report.

Bibliography

[1] D. Butler, A. Abela and C. Martin, "Heat meter accuracy testing," DECC, 2015.

[2] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[3] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[4] D. Hughes, "Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013," DECC, 2016.

[5] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.," EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 27

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the installation at Site 27 and performance results from 12 consecutive months of monitoring data.

Site 27 is a 2-storey accommodation building on a college campus. It is occupied by resident students and is in use 24 hours per day for most of the year.

A single ground-source heat pump of 54 kWTH capacity extracts heat from vertical boreholes in open ground adjacent to the building and provides space heating via underfloor heating pipes.

The seasonal heating performance factors measured over a year of operation (1st January to 31st December 2015) were:

SPFH2	[Heat delivered by the heat pump] -- Electricity used by [heat pump] + [brine pump]	3.09
SPFH4	[Heat delivered by heat pump] + [heat added by buffer & circ pumps] – [buffer tank heat loss] -- Electricity used by [heat pump] + [brine pump] + [buffer & heating circ pumps]	2.84

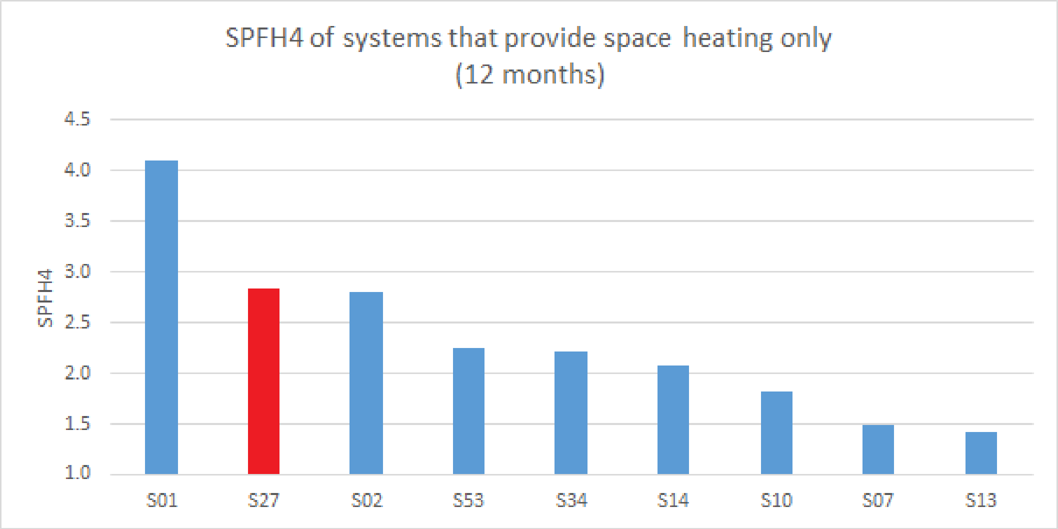

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

Aspects of this system that positively influenced its performance are:

- Electricity use by the brine, buffer and heating circulating pumps was below average compared to other systems monitored.
- Weather compensation was used to reduce the heat pump output temperature when the outdoor temperature was higher.
- No auxiliary immersion heaters are installed on this system.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the brine flow from the boreholes was low compared to other systems monitored.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	27
Survey date	08/04/2014
Monitoring installed	26/06/2014
G/WSHP	GSHP
Building type	Accommodation building
Location	Urban (college campus)
Heat pump capacity kW_{TH}	54
Number of heat pumps	1
Number of compressors	1
Heat source	Vertical boreholes: 10 x 150 metre
Heat emitters	Underfloor heating pipes
DHW	Provided by a separate gas-fired boiler
Auxiliary heat sources	None
Source pump	External to heat pump: 600 W max (variable-speed)
Buffer pump	External to heat pump: 600 W max (variable-speed)
SH circulating pump	Dual pumpset: 2 pumps of 600 W max
Buffer tank	1000 litre 4-pipe
DHW cylinder	N/A
Control	BMS + room thermostats to control underfloor heating zones
Weather compensation	Yes
Heat meter type	Vortex
No. of heat meters	1
Heat meter interface	M-Bus
Building operation and use	The building is occupied by students and is in use 24 hours per day throughout most of the year
Comments	

Table 1 – System details

Site 27 is a 2-storey accommodation building on a college campus. It is occupied by resident students and is in use 24 hours per day for most of the year.

This application entails extracting heat from vertical boreholes in the ground to provide space heating only via underfloor heating pipes in a modern building, located in an area with slightly below-average outdoor temperatures – annual mean 9.7 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The performance of the system would be expected to be good.

Heat pump and monitoring systems

A single heat pump (thermal capacity 54 kW) installed in a basement plant room provides space heating (SH) to underfloor heating, via a 1000-litre buffer tank. Domestic hot water (DHW) is provided by a separate gas-fired boiler.

The heat source is 10 x 150 m boreholes located in a grass-covered area adjacent to the building.

A 1000-litre 4-pipe buffer tank is installed between the heat pump and the underfloor heating circuit.

The system is controlled by a building management system (BMS), with room thermostats controlling the underfloor heating zones.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1]. The outdoor air and ground temperatures are also monitored.

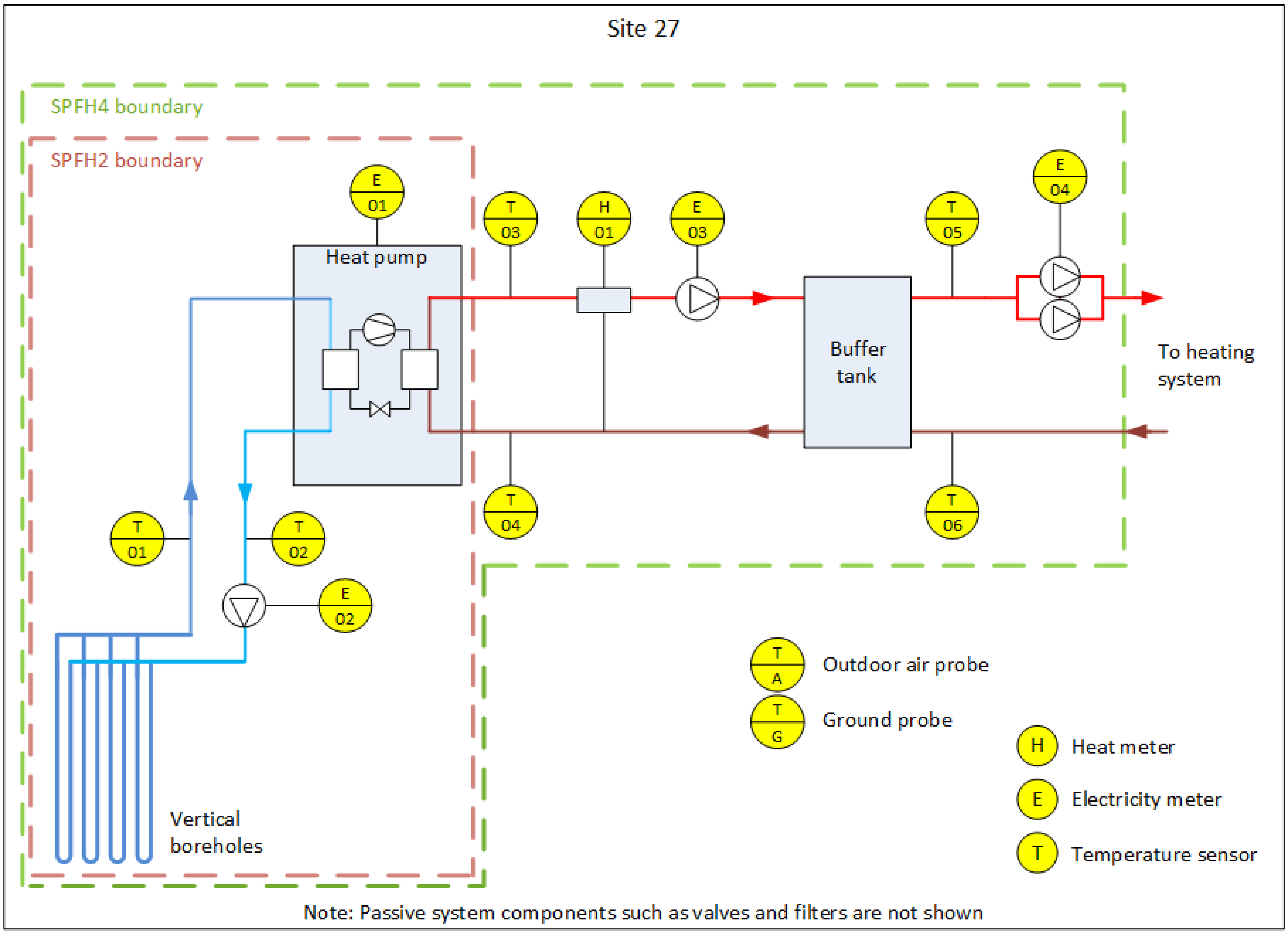

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses a vortex flow meter installed in the flow pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is mains-powered, and monitoring was via the M-Bus interface.

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.
- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump]}}{\text{Electricity used by: [heat pump] + [brine pump]}}$$

$$SPF_{H4} = \frac{\text{[Heat output of heat pump] + [heat added by buffer \& SH circ pumps] – [buffer tank heat loss]}}{\text{Electricity used by: [heat pump] + [brine pump] + [buffer pump] + [SH circulating pumps]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer pump and the heating circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.
- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 522 428, which represents 99.4% of the 12-month period.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	3.09
SPF_{H4}	2.84

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 2.84 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system, for the period 1st January to 31st December 2015.

The low SPF_{H4} values during the summer months are probably a consequence of the heat pump running under conditions of low heat demand: the heat pump was running for short periods, but the heating circulation pumps were running almost continuously, resulting in disproportionately high losses in the heat distribution network. However, as the total heat output during the summer is small, the effect on the annual performance is not very significant.

The high SPF values at the start of January were due to the system having been shut down over the holiday period. When it restarted, the heat pump output temperatures were much lower than normal, resulting in higher than usual performance.

The sudden drop in SPF values in December appears to have been due to a change in the control system, as the mean daily output temperature was higher, and controlled within a smaller range – as shown in Figure 4.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

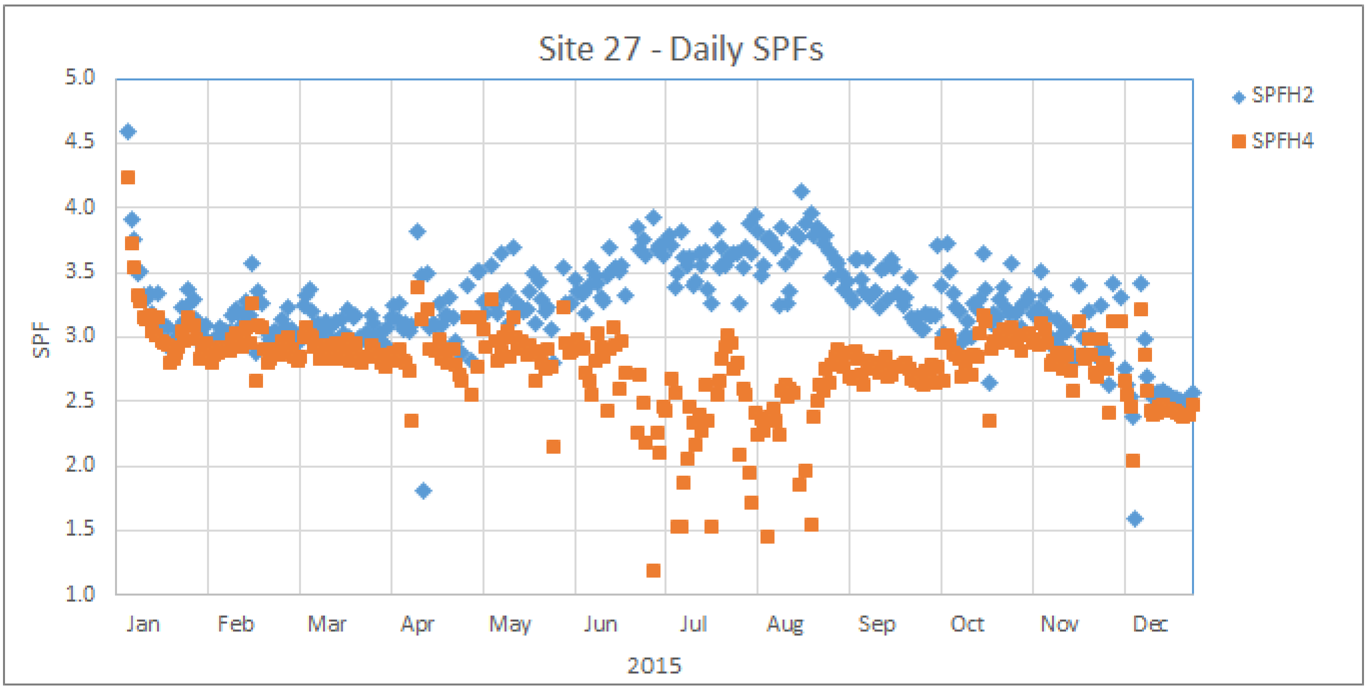

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

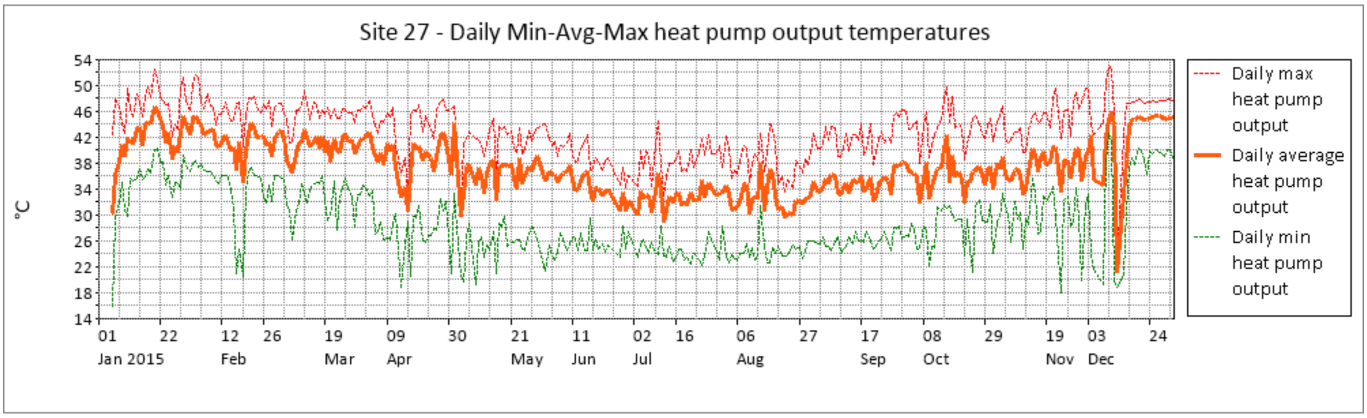

Figure 4 – Daily range of heat pump output temperature

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to circulate the brine through the ground coils and the heat pump, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 5 shows the daily heat output from the heat pump during the year. The outdoor air temperature and the electricity used by the total heat pump system are shown for reference, and it can be seen that the heat demand increased when the outdoor temperature was lower, as would be expected. There was a demand for heat for most of the year, except for a few days when the system was not operating. At the start of January, it seems that the system had been shut down during the holiday period. There were also a few other days during the year when the system was not operating – notably in November and December. The reason for these is not known.

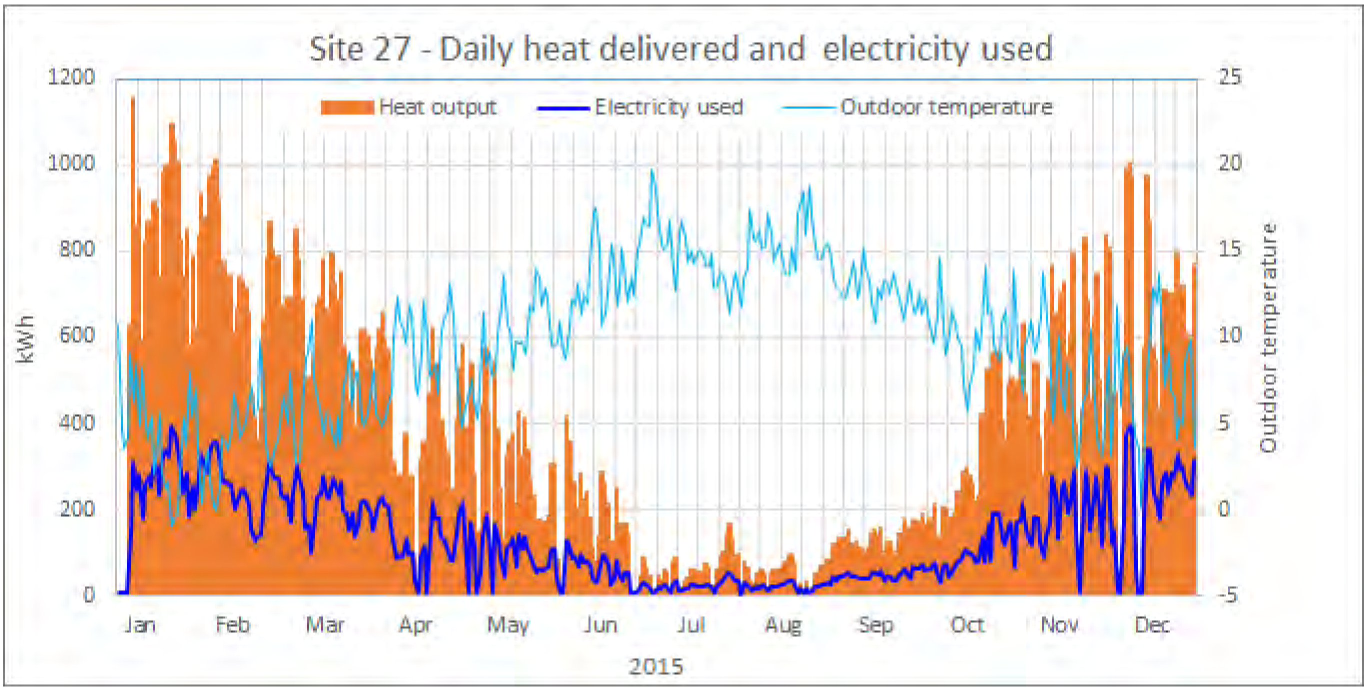

Figure 5 – Daily heat output and electricity used by the total heat pump system

Breakdown of electricity use

Figure 6 shows the weekly breakdown of electricity use. This follows the pattern of heat demand as shown in Figure 5, but it can also be seen that the space heating circulating pumps ran more or less continuously all year. This resulted in their electricity use during the summer period being disproportionately high, and being at least part of the reason for the low SPF_{H4} values during the summer (as noted above).

The brine pump accounted for 3.8% of the total electricity, which was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

The buffer pump and the heating circulating pumps together used 8.3% of electricity, which was also below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance. However, the overall performance could have been slightly better if the heating circulating pumps had only been run when needed[4].

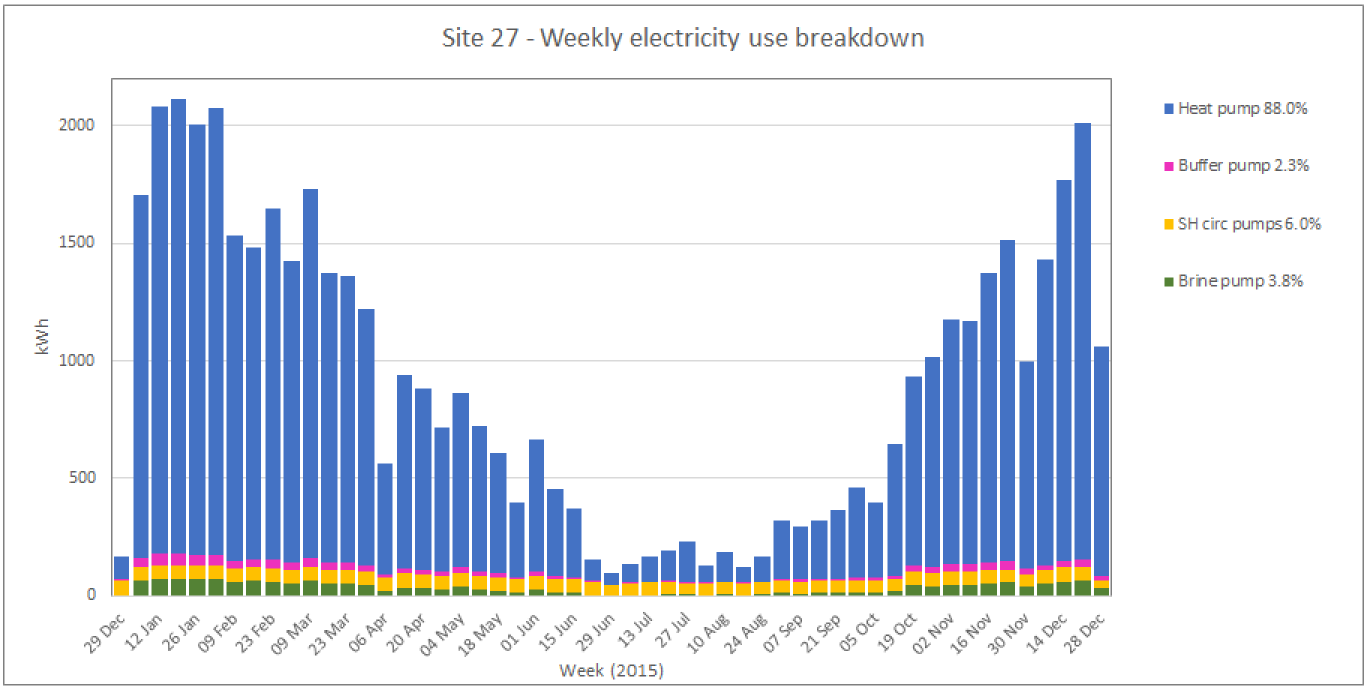

Figure 6 – Weekly electricity use breakdown

Operating pattern

It is interesting to look at the way the system operated under high load during the winter and under light load during the summer. The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 7 shows the operating pattern during Wednesday 14th January when the outdoor air temperature was between 1 and 6 °C.

On this day, the heat pump ran for two periods of approximately 5 hours between midnight and 11:00. The temperature of the output to the buffer tank reached 47 °C at the end of the first run. This was the highest

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[4] If the electricity used by the heating circulating pumps had been reduced by 50% between May and September, a saving of approximately 600 kWh of electricity would have been made, and the overall SPF_{H4} would have improved by 1%.

temperature during the day. After 11:00, the heat pump cycled on/off for the rest of the day, presumably because of the reduced heat demand as the outdoor temperature increased.

The loss of temperature through the 4-pipe buffer tank varied between 0.5 and 2 °C.

The temperature of the brine from the ground collector to the heat pump was between 0.5 and 1.5 °C while the heat pump was running – slightly lower than the outdoor air temperature.

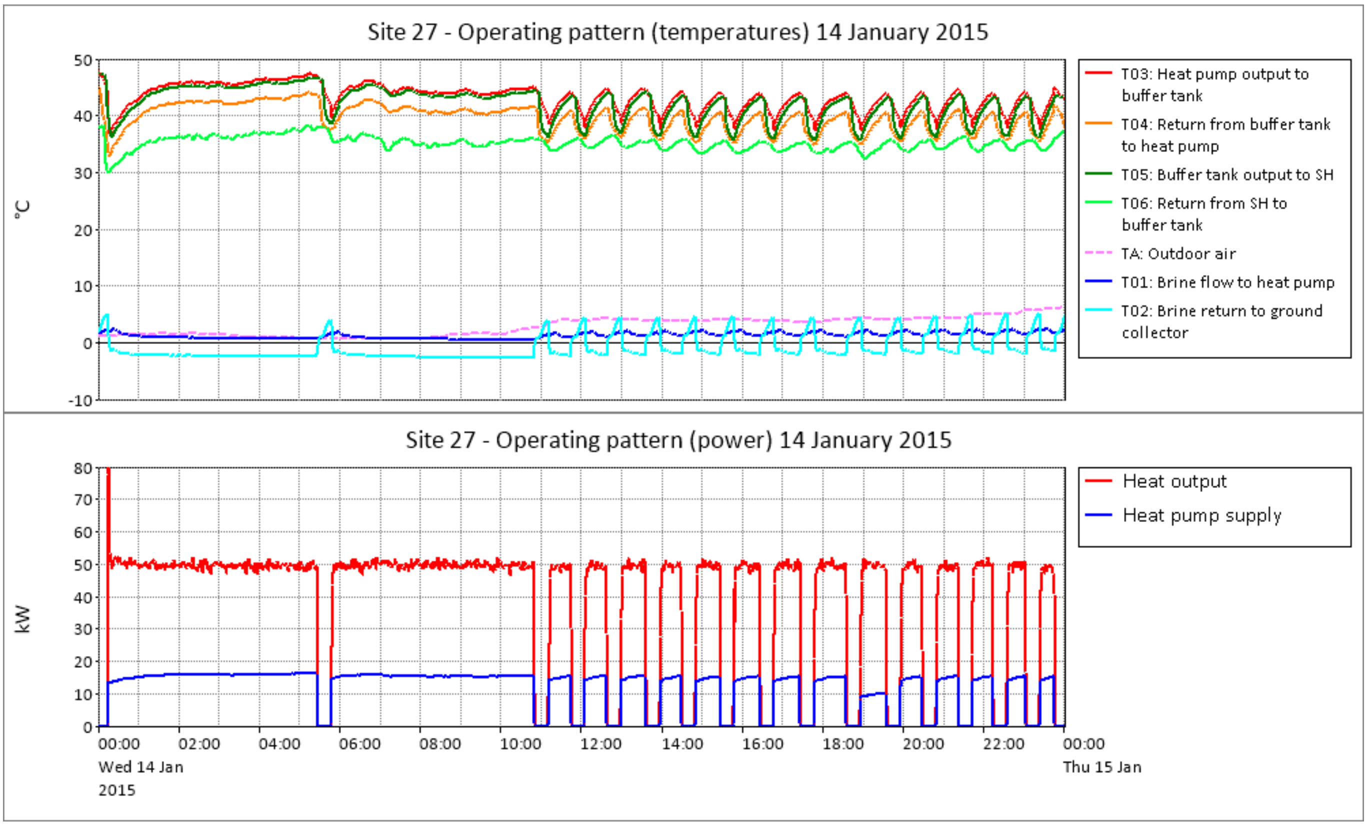

Figure 7 – Operating pattern on 14th January 2015

Figure 8 shows the operating pattern on Thursday 14th July when the outdoor temperature was between 12 and 23 °C. The heat demand was low, and the heat pump operated for six short runs of between 10 and 15 minutes. This is within the cycling parameters recommended from the previous research [2].

The temperature of the output to the buffer tank from the heat pump when it was running varied between 34 and 39 °C. This variation appears to have been a consequence of weather compensation, whereby the output temperature is raised when the outdoor temperature falls.

The temperature of the brine flow to the heat pump when it was running was between 6.5 and 7.5 °C.

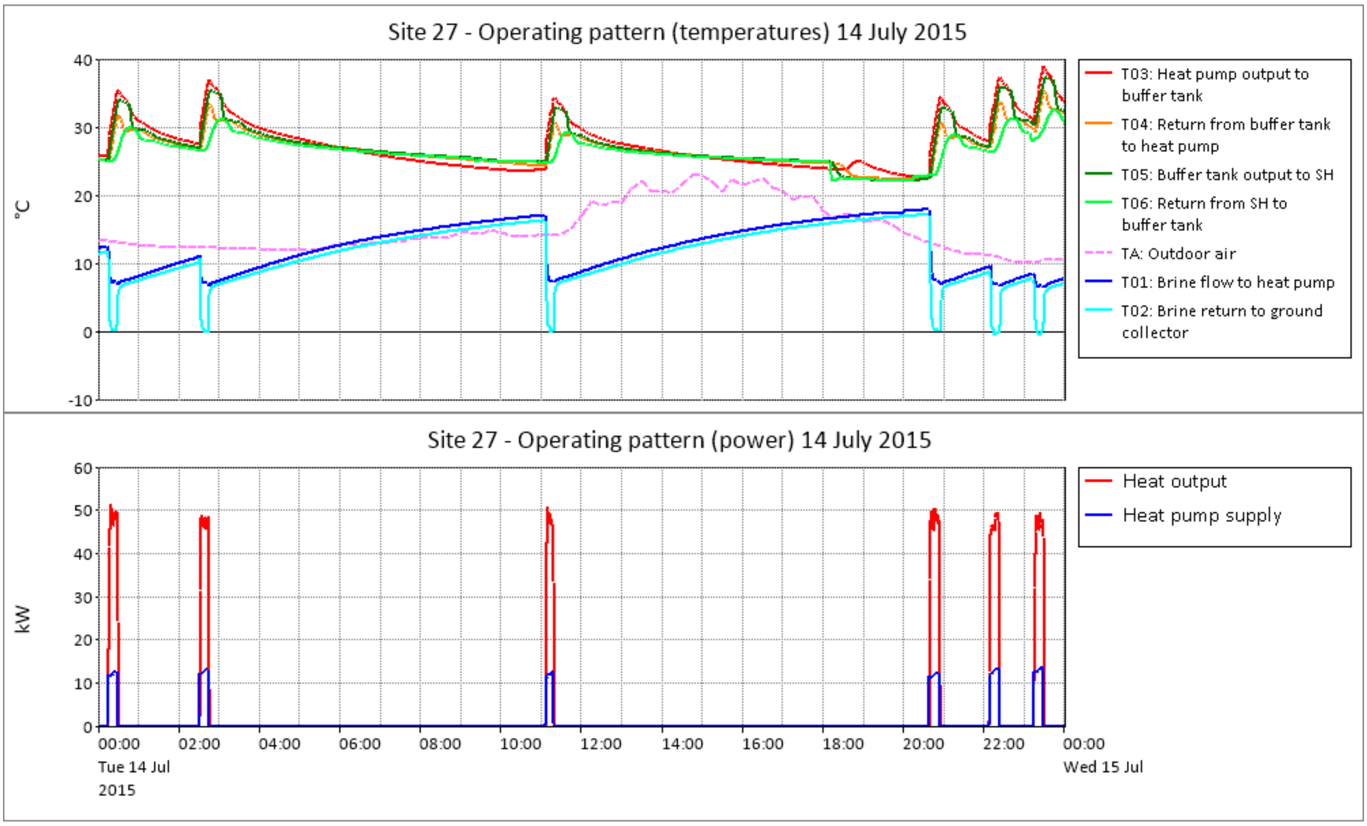

Figure 8 – Operating pattern on 14th July 2015

Source and sink temperatures

Figure 9 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[5]. For clarity, the brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The top chart shows the heat pump output and return temperatures. The maximum output temperature was 53 °C in January and in December on days when the outdoor temperature dropped to -3 °C. The lowest daily maximum output temperature was 34 °C on 28th June, when the outdoor temperature was between 14 and 22 °C.

The second chart shows the temperature of the output from the buffer tank to the underfloor heating circuits and the return to the buffer tank. On average the output from the buffer tank to the heating circuits was no more than 1.2 °C lower than the output from the heat pump. This would have had a positive influence on the system performance.

The third chart shows the brine flow and return temperatures to and from the heat pump. The minimum brine flow temperature was 0 °C on 4th February when the outdoor air temperature had been below -2.5 °C during the previous two nights. The brine return temperature was at its lowest at -3 °C at the same time.

The last chart shows the temperatures of the outdoor air and the ground (1 metre below the surface, remote from the boreholes).

From analysis of the detailed temperature data, the temperature of the brine from the boreholes to the heat pump was below the outdoor air temperature for 91% of the time that the heat pump was running.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

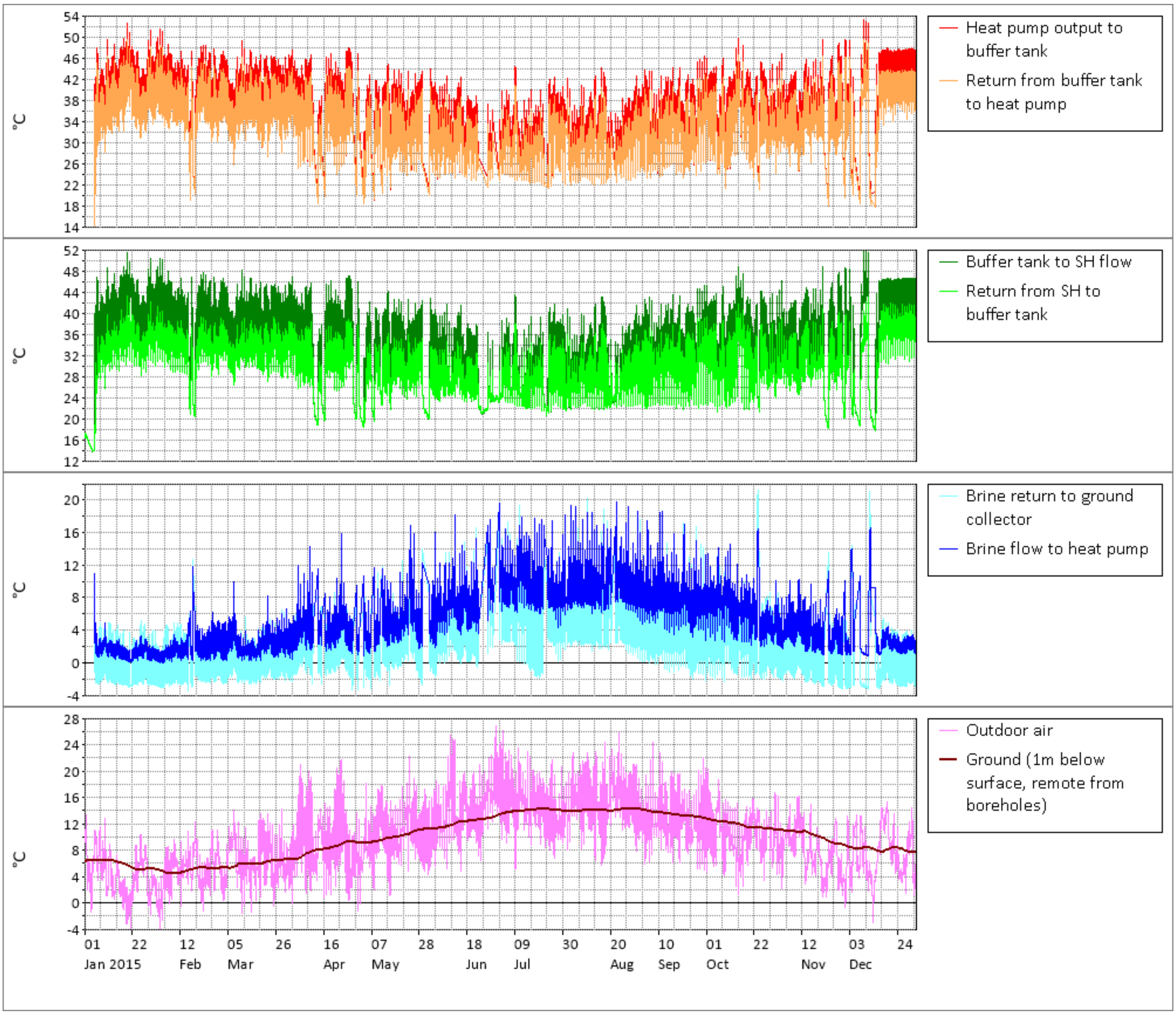

Figure 9 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were below average. This would have had a negative influence on the system performance.

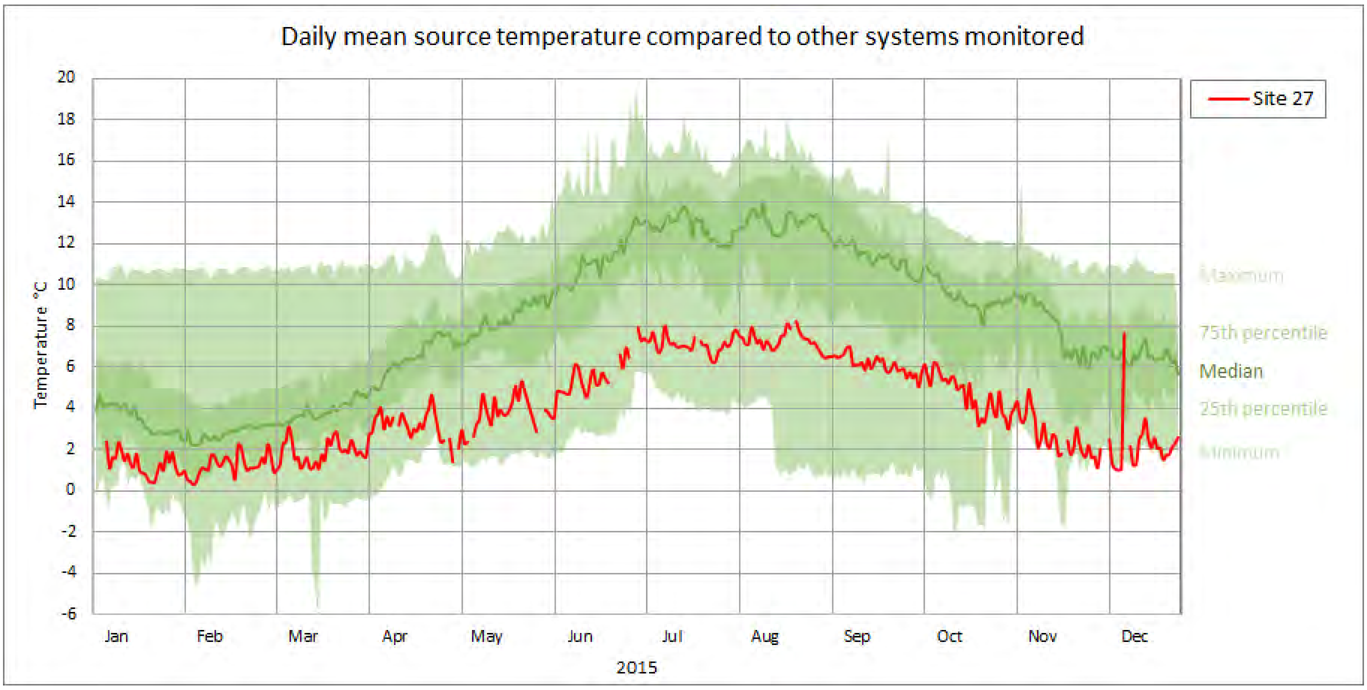

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 27 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system (plotted in red) were below average. This would have had a positive influence on the system performance.

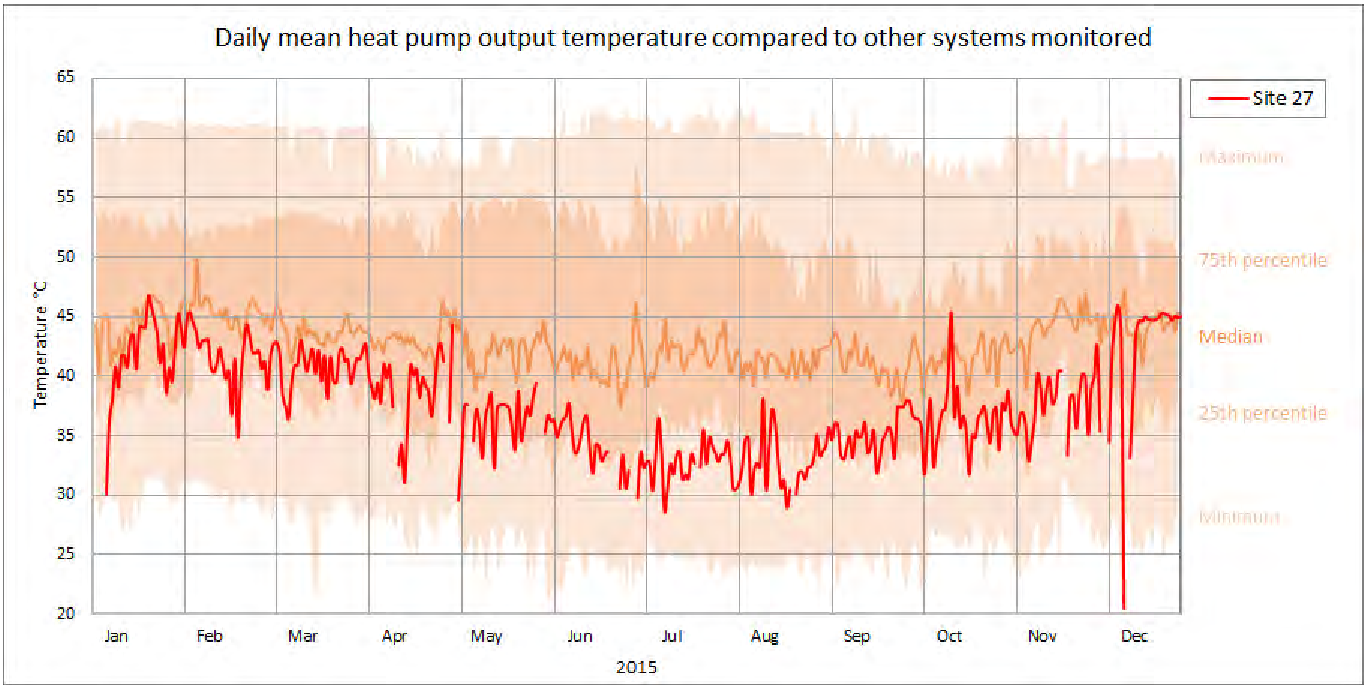

Figure 11 – Daily mean heat pump output temperature compared to those of other systems monitored in this project (site 27 is shown in red)

Figure 12 shows how the output temperature of this system compares to other heat pump systems that use underfloor heating. The output temperatures on this system (plotted in red) were below average, which would have had a positive influence on system performance.

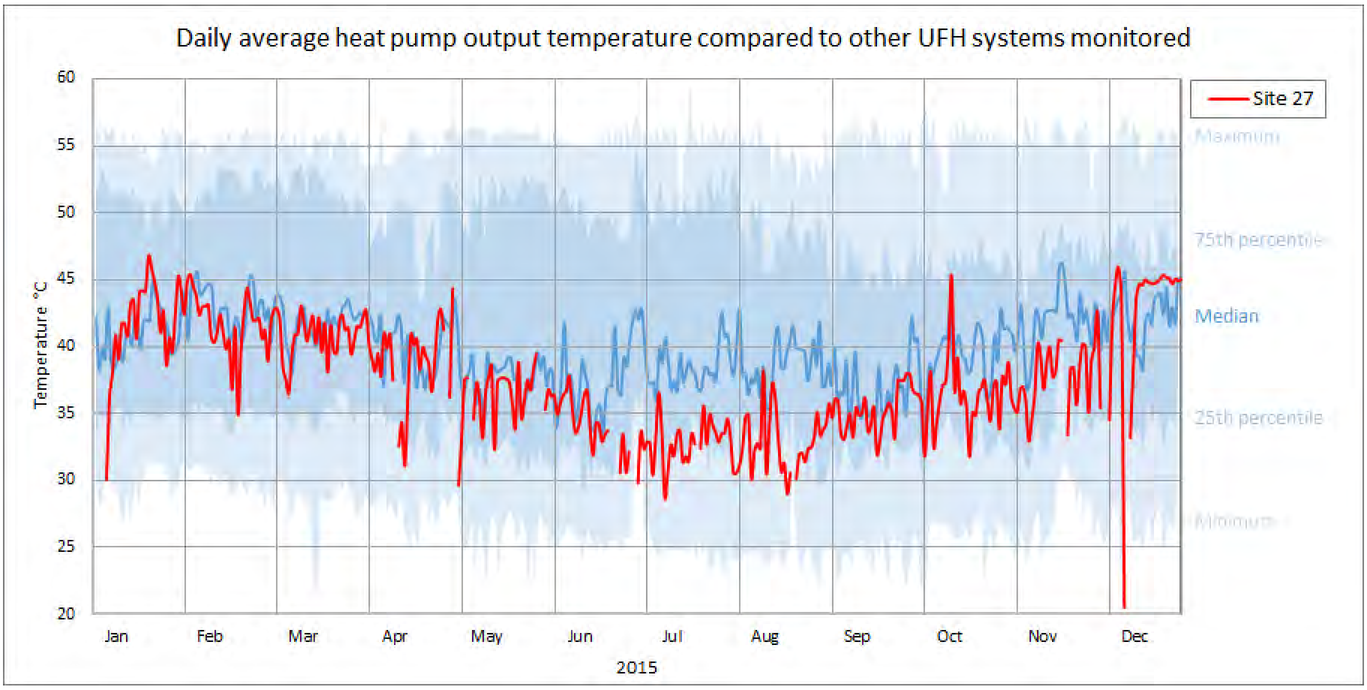

Figure 12 – Daily mean heat pump output temperature compared to those of other underfloor heating systems monitored in this project (site 27 is shown in red)

Comments

This system had the second-best performance (SPF_{H4} = 2.84) of the systems providing space heating only that have been monitored in this project (SPF_{H4} range 1.42 to 4.10, median 2.23). However, its performance was only 72% of that of the system with the best performance.

Aspects of this system that positively influenced its performance are:

- Moderate sink temperatures. The temperature of the output to the heat emitters was generally in the range 30 to 50 °C – although these temperatures were not as low as for some underfloor heating systems monitored. Lower temperatures would improve the system performance.
- Low temperature loss in the buffer tank. The output to the heat emitters was generally not more than 0.5 – 2.0 °C below the heat pump output temperature.
- Reasonably low electricity use by the brine and buffer circulating pumps.
- Weather compensation was used: the heat pump output temperature was reduced when the outdoor temperature was higher.
- No auxiliary immersion heaters are installed on this system.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the brine flow from the boreholes was low compared to other systems monitored.
- The apparent change in the control system in December raised the mean heat pump output temperature. The reason for this is not known, but it should be investigated as the previous operating behaviour apparently gave better performance.

- The heating circulating pumps were run more or less continuously all year. Their use during the summer months could probably be reduced by adjusting the control strategy to switch off or reduce the speed of the pumps at times of low heat demand.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 28

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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Dr David Hughes asserts his moral right under the Copyright, Designs and Patents Act 1988 to be identified as the author of this work.

This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 28 and performance results from 12 consecutive months of monitoring data.

Site 28 is a 19th century hotel, built from cut stone. It is in a rural location with the third lowest average outdoor temperature of the sites monitored.

Two heat pumps (total thermal capacity 71 kW) extract heat from 12 boreholes each 125 metres deep, to provide heat for space heating and domestic hot water. The radiators used for the previous oil-fired heating system have mostly been retained; some have been replaced with larger radiators. One of the oil-fired boilers has been retained for backup duty.

The seasonal heating performance factors measured over a year of operation
(1st March 2015 to 29th February 2016) were:

SPF_{H2}	[Heat delivered by the heat pumps] -- [Electricity used by: [heat pumps] + [brine pumps]	2.76
SPF_{H4}	[Heat delivered by heat pumps] + [heat added by buffer & heating circ pumps] + [heat added by immersion heaters] – [heat loss from buffer tanks] -- Electricity used by: [heat pumps] + [brine pumps] + [heating circ pumps] + [immersion heaters]	2.34

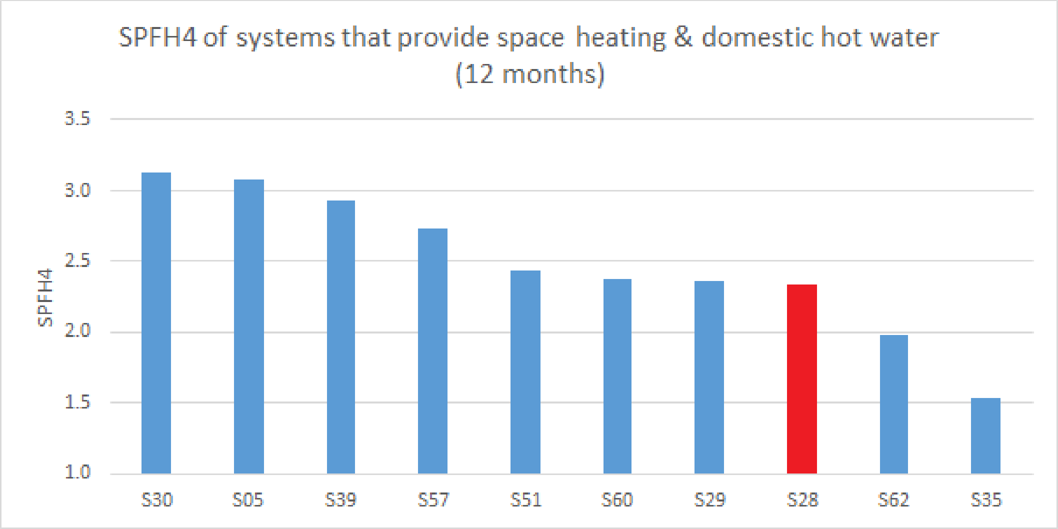


Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influenced its performance are:

- The electricity used by the brine and heating circulating pumps was lower than average for other systems monitored in this study.
- The temperature of the brine from the ground collectors did not decrease as much during the winter as on many other systems in the monitored sample.

Aspects of the system that may have negatively influenced its performance include:

- The domestic hot water immersion heaters were used extensively.
- The temperature of the brine from the ground collectors was generally below average compared to other systems monitored (although did not decrease as much during the winter as on many other systems).
- The temperature of the output to space heating was higher than average (during the winter) compared to other systems monitored.
- The control strategy did not appear to make best use of the heat pumps for providing domestic hot water.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**28**
Survey date	09/04/2014
Monitoring installed	11/07/2014
G/WSHP	GSHP
Building type	19th century cut-stone castle
Location	Rural
Heat pump capacity kWTH	71 total
Number of heat pumps	2
Heat source	12 x 125m vertical boreholes
Heat emitters	Radiators. Some have been upsized from those used for the previous oil-fired heating system. Thermostatic valves are being fitted as areas are refurbished.
DHW	Yes
Auxiliary heat	4 x 6kW immersion heaters in the DHW cylinders. 1 x 7.5 kW immersion heater in the buffer tank.
Source pump	External to heat pumps: 2 pumps of 905 W max
Buffer pumps	External to heat pumps: 2 pumps of 390 W max
DHW primary pumps	External to heat pumps: 2 pumps of 680 W max
SH circulating pumps	1 pump of 390 W (max)
Buffer tank	500 litre 2-pipe
DHW cylinders	2 x 750 litre
Control	Heat pump controller + timeswitches + thermostatic valves on some radiators
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	2
Heat meter interface	Pulse (H01: 100 kWh/pulse; H02: 10 kWh/pulse)
Comments	Oil-fired boiler retained for emergency backup.

Table 1 – System details

Site 28 is a 19th century hotel, constructed from cut stone. It is in a rural location with below-average outdoor temperatures – annual mean 8.8 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The hotel was closed to guests from November to February during the monitoring period.

Heat pump and monitoring systems

Two ground-source heat pumps (total thermal capacity 71 kW) were installed in the hotel to replace an old oil-fired heating system, to provide space heating (SH) and domestic hot water (DHW). Most of the original radiators were retained, although some have been replaced by larger units. Thermostatic valves have been fitted to some radiators, and are gradually being fitted to all of them as areas are refurbished.

Auxiliary heat is provided when needed by immersion heaters in the buffer tank and in the domestic hot water cylinders.

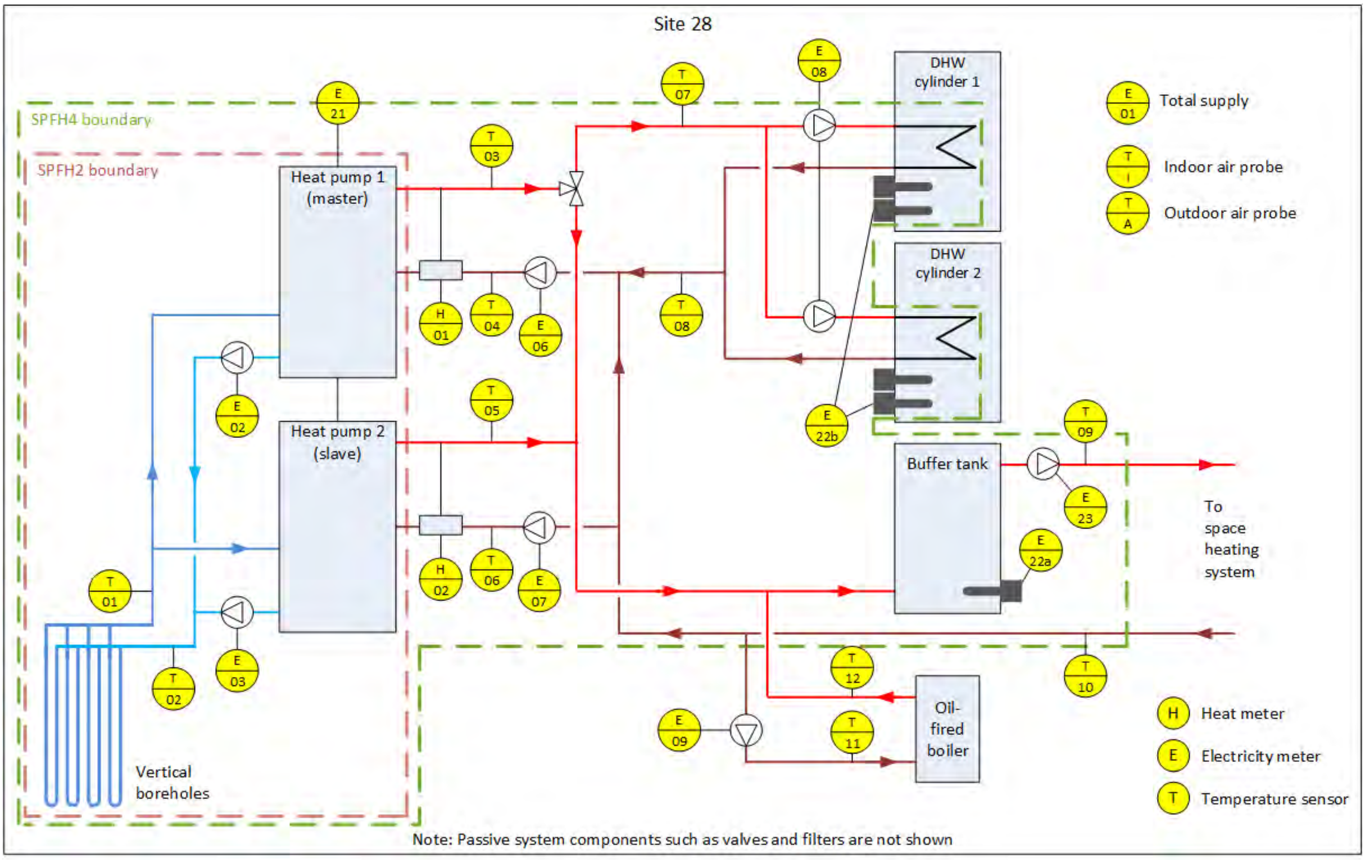
The oil-fired boiler was not used during the monitoring period.

The heat source is a set of 12 boreholes, each 125 m deep, in the grounds of the hotel. Brine is circulated from the heat pump through u-tube pipes in each borehole, to extract heat from the ground.

The two heat pumps are identified as master and slave. The master heat pump provides heat to domestic hot water or to space heating. The slave heat pump supplies space heating only.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and to domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1]. The outdoor air temperature is also monitored.



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pumps. Two heat meters of the same type are installed: one at the output of each heat pump. Ultrasonic flow meters are installed in the return pipes, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculators are battery-powered, and monitoring was via the pulse interfaces.

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pumps together with the source pumps.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and immersion heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.
- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pumps]}}{\text{Electricity used by: [heat pumps] + [brine pumps]}}$$

$$SPF_{H4} = \frac{\begin{array}{c}\text{[Heat output of heat pumps] + [heat added by buffer and heating circ pumps]}\\ \text{+ [heat added by immersion heaters in buffer tank \& DHW cylinders] – [heat loss from buffer tank]}\end{array}}{\text{Electricity used by: [heat pumps] + [brine pumps] + [heating circ pumps] + [immersion heaters]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer pumps and the heating circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.
- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 437 872, which represents 83.3% of the 12-month period.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st March 2015 and 29th February 2016, are shown in Table 2.

SPF_{H2}	2.76
SPF_{H4}	2.34

Table 2 - SPF values measured for the period 1st March 2015 – 29th February 2016

This means that for each unit of electricity used, this system delivers on average 2.34 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. These figures represent the combined space heating + domestic hot water performance.

The daily SPF_{H2} values increased between April and August as the temperature of the brine from the ground collector increased, and the temperature of the output to the radiators reduced. It declined again later in the year as the weather became colder.

The sudden change in performance at the start of November occurred because the hotel was closed to guests from then on: the space heating and domestic hot water loads reduced significantly and the domestic hot water immersion heaters were not used.

The SPF_{H4} values did not increase in line with the SPF_{H2} values during the summer. This can be explained by the high daily demand for domestic hot water, with the immersion heaters being used extensively. While the performance in space heating mode possibly did improve during the milder weather, it was not possible to determine separate performance figures for space heating and domestic hot water operation on this system, because the pipework and heat metering arrangements do not permit the energy inputs and outputs to be determined for each mode of operation.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

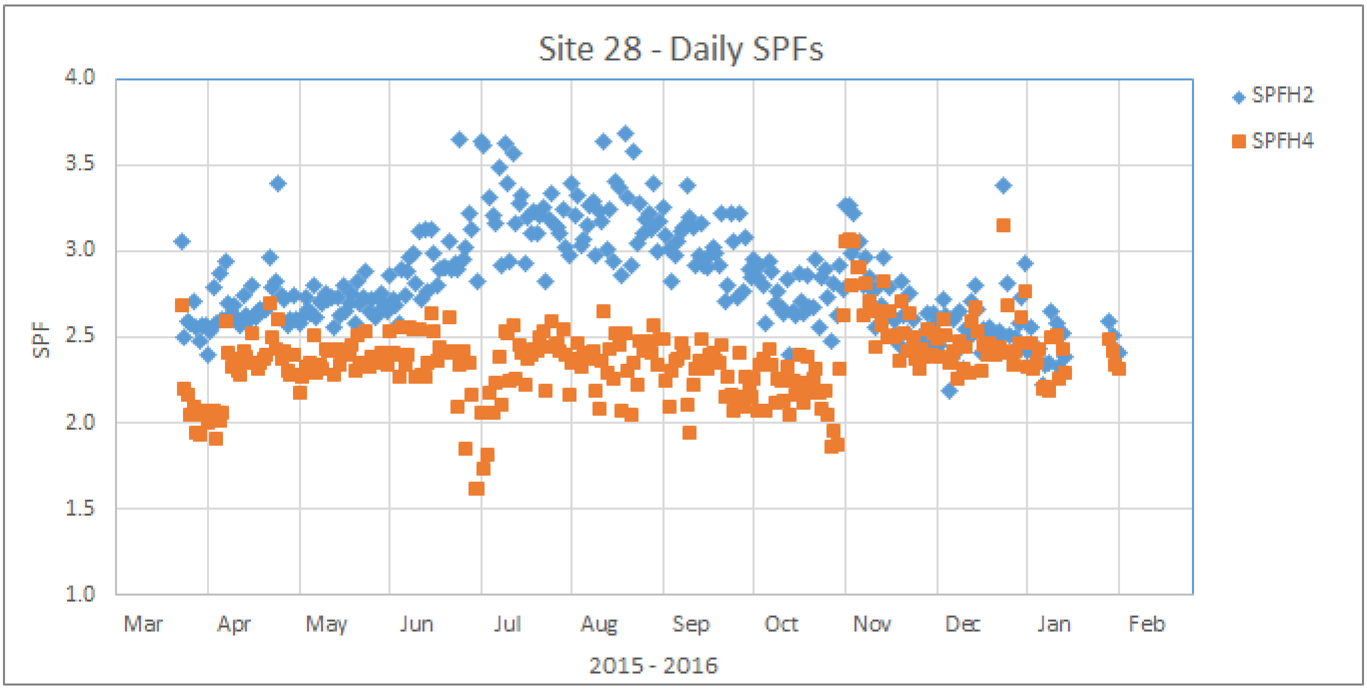

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source is the ground from which heat is being extracted and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output to space heating and to domestic hot water. The electricity used by the total heat pump system and the outdoor temperature are also shown for reference, and it can be seen how the heat demand varies with outdoor temperature. The relatively high demand for heat during the summer is due to the large domestic hot water requirements of the hotel.

The hotel was closed from November to February. During this period the heat pumps were used mainly for space heating.

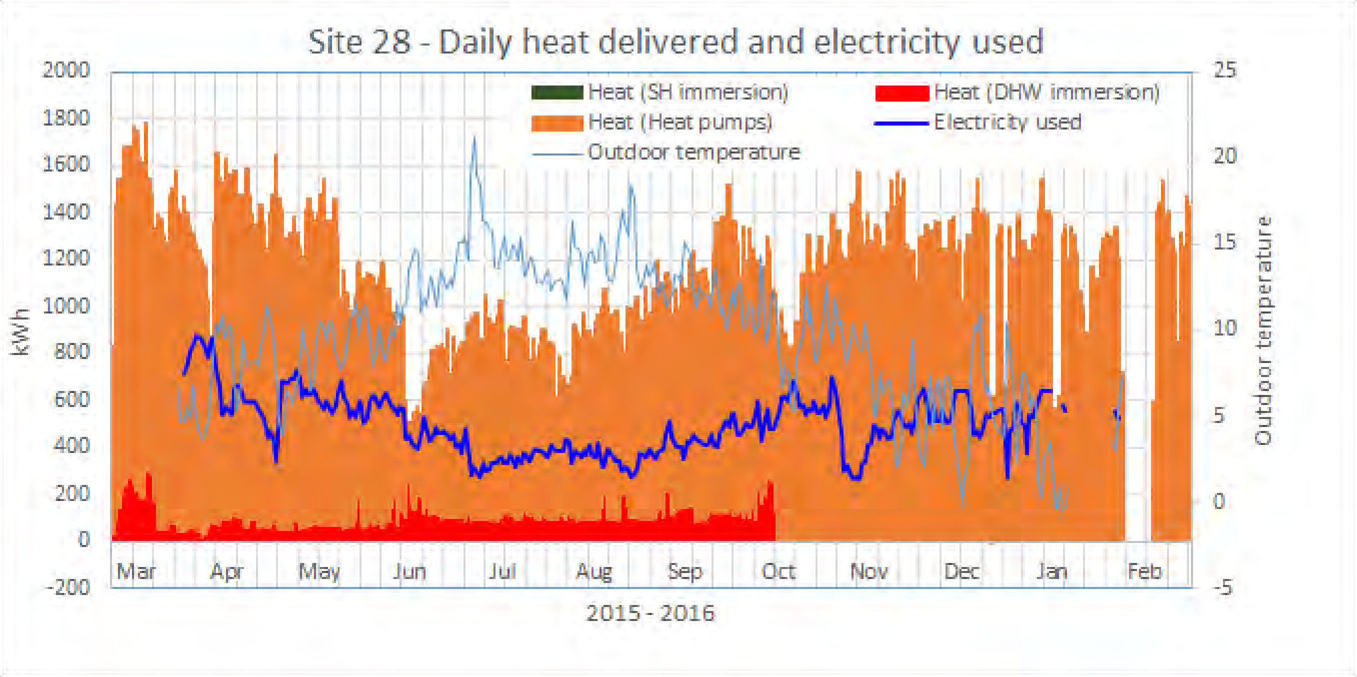

Figure 4 – Daily heat output and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. During the months that the hotel was open (March to October), there was significant use, for several hours every day, of the immersion heaters in the domestic hot water cylinders. This was to boost the heat pump output to domestic hot water, and to increase the temperature in the domestic hot water cylinders for Legionella control, but it would have had a negative influence on system performance.

The brine pump accounted for 4.9% of total electricity use, which is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

The space heating and domestic hot water primary circulating pumps together used 4.2% of electricity, which is also below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance.

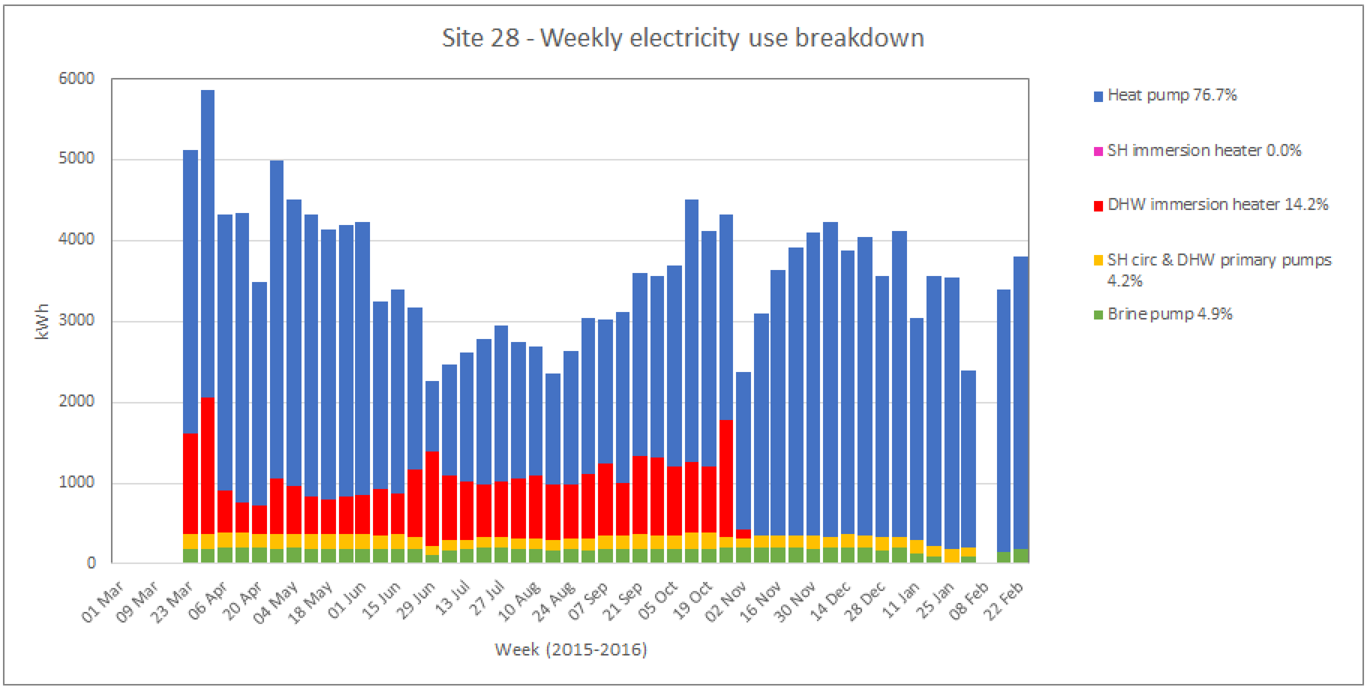

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the typical pattern of operation on 25th March 2015, when the outdoor air temperature was between 1 and 8 °C.

Both heat pumps were in continuous operation, with 3 or 4 compressors in use most of the day. The master heat pump was alternatively providing heat to space heating and to domestic hot water as shown by the pattern of operation of the circulating pumps. The domestic hot water immersion heaters were also being used heavily, presumably to meet the large demand for domestic hot water in the hotel.

The temperature of the brine flow to the heat pumps was between 1 and 2 °C. The output from the heat pumps to space heating was between 45 and 54 °C (the output from each heat pump was at a slightly different temperature). The output from the buffer tank to the heating circuit was at the average of the heat pump output temperatures – indicating no measurable loss of temperature through the 2-pipe buffer tank.

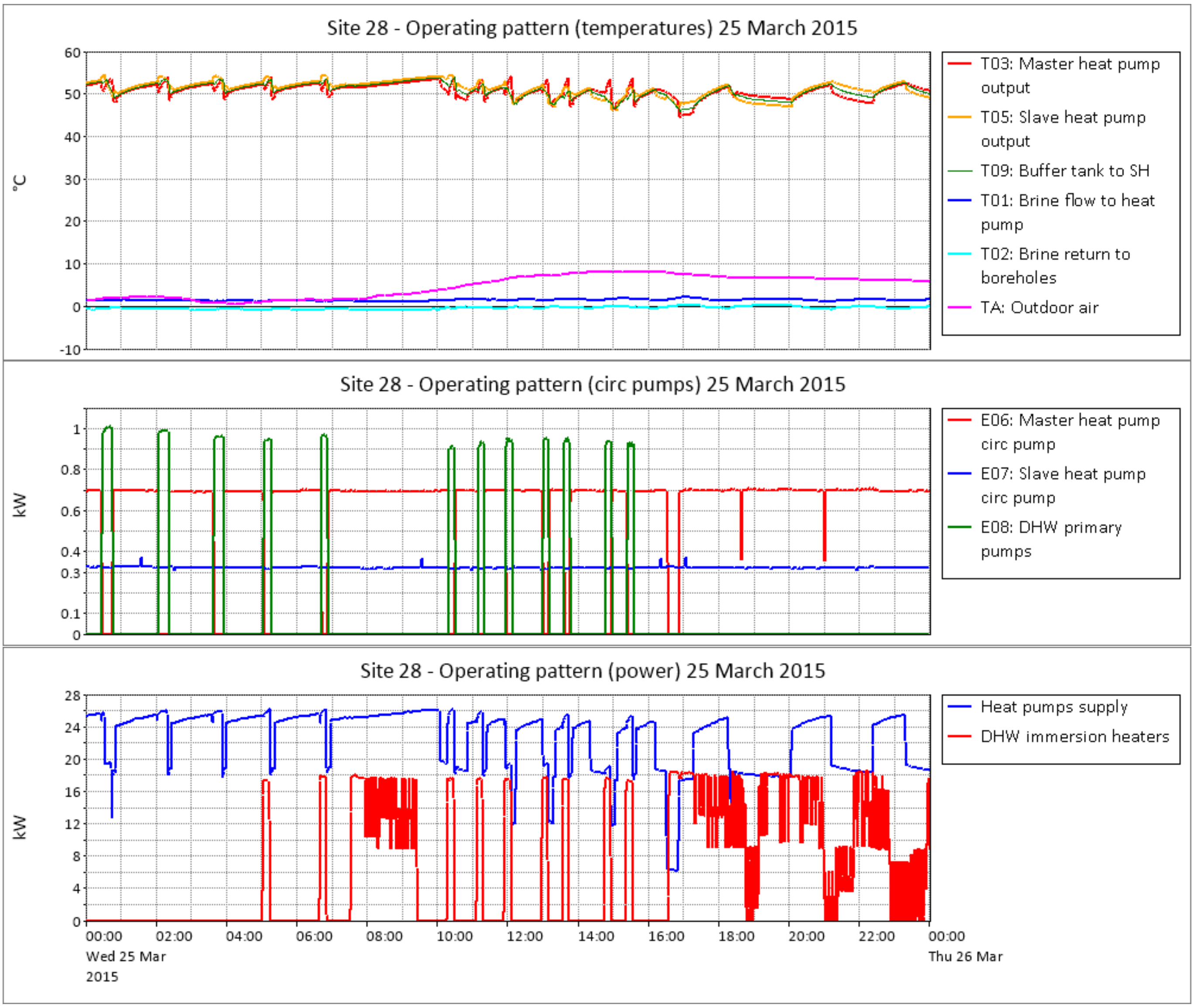

Figure 6 – Operating pattern on 25th March 2015

Figure 7 shows the operating pattern on 3rd July 2015 when the outdoor temperature was between 13 and 24 °C. The heat pumps were used intermittently with 1, 2 or 3 compressors running. The operating pattern of the circulating pumps shows that heat was being provided to space heating and to domestic hot water.

The domestic hot water immersion heaters were also used throughout the day. It is not known why these were used to such an extent when there appeared to be spare heat pump capacity. This suggests an inadequate control strategy.

The brine flow temperature was between 4 and 7 °C. The master heat pump output temperature was between 30 and 55 °C, depending on whether the output was to space heating or domestic hot water. The output from the slave heat pump was between 26 and 42 °C. There was no measurable loss of temperature through the buffer tank.

Figure 7 – Operating pattern on 3rd July 2015

Figure 8 shows the pattern on 7th December 2015 when the hotel was closed. The outdoor temperature was between 2 and 12 °C, and the heat pumps were running to provide space heating. There was no evidence of domestic hot water being heated either by the heat pumps or by immersion heaters.

The brine flow to the heat pumps was between 2 and 3 °C. The output from the heat pumps was between 45 and 55 °C. There was no measurable temperature loss through the buffer tank.

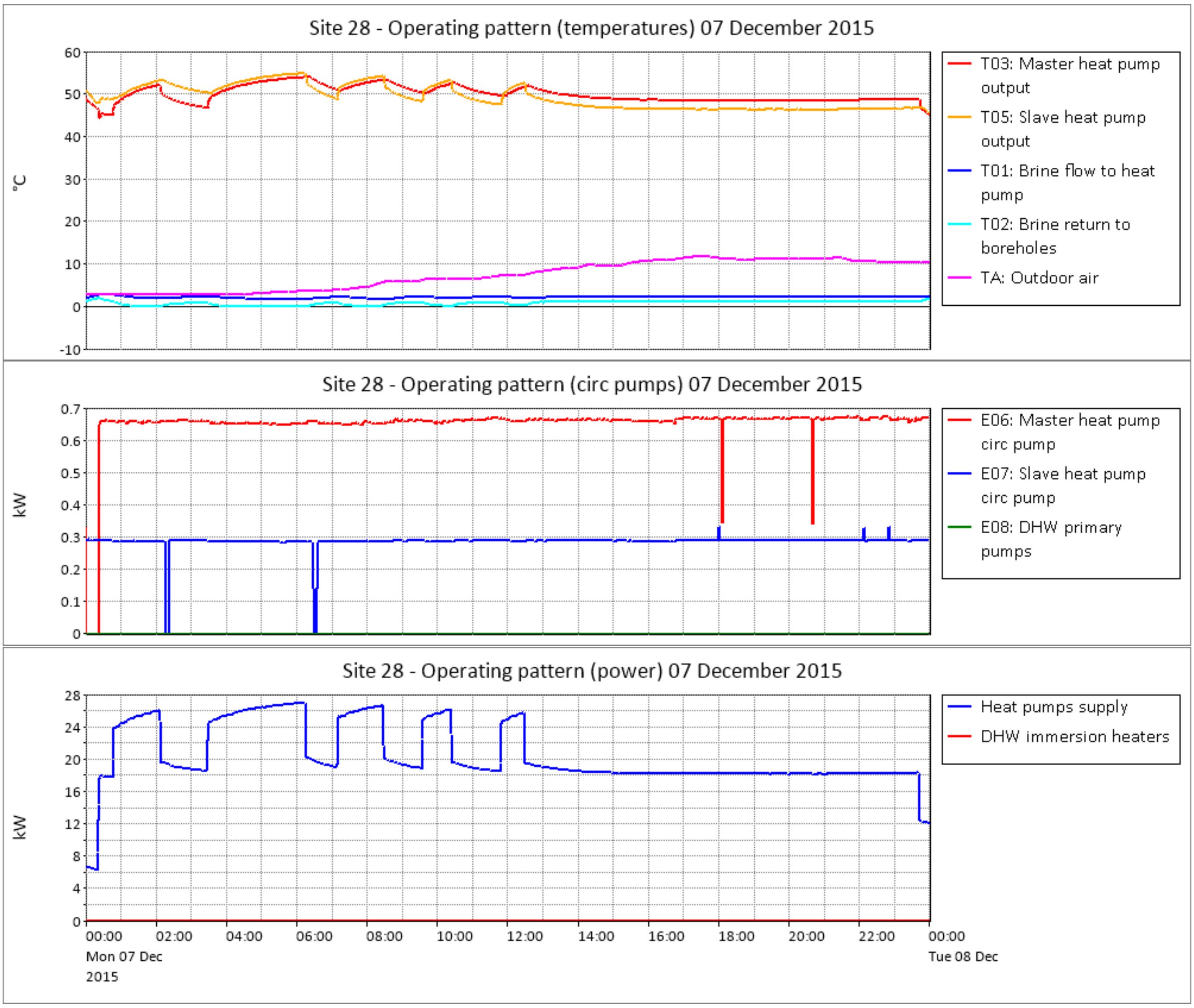

Figure 8 – Operating pattern on 7th December 2015

Source and sink temperatures

Figure 9 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[4]. For clarity, the brine and heat pump output temperatures have been plotted only for times when at least one of the heat pumps was running.

During the months that the hotel was open (March to October), the temperature of the output from the master heat pump to the domestic hot water coils was consistently up to 55 °C or more. The output to space heating was generally at a lower temperature – except during the winter months when the hotel was closed and there was little demand for domestic hot water. The effect of the weather compensation function can be seen, with the temperature of the output to space heating from the slave heat pump reducing as the outdoor air temperature increased.

The temperature of the brine from the boreholes was generally several degrees lower than the outdoor air temperature.

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[4] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes.

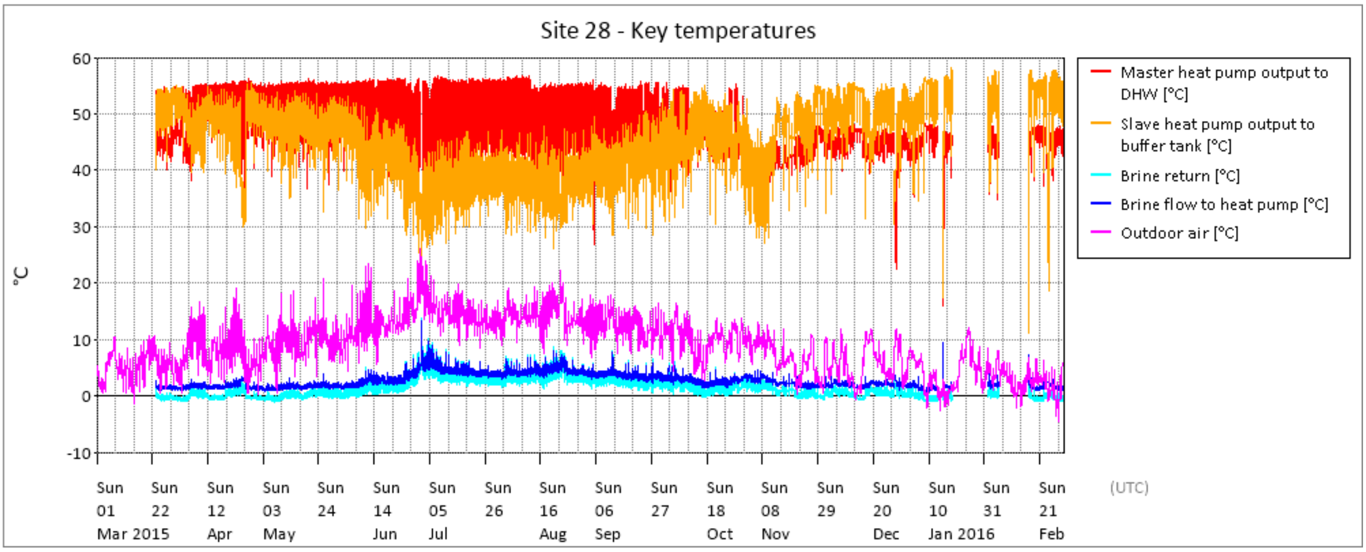

Figure 9 – Key temperatures measured during the period 1st March 2015 – 29th February 2016

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures of all other systems monitored in this project. The temperatures realised on this system (plotted in red) were generally low compared to other systems, but did not drop as much as many other systems during the winter. The low brine temperatures would have had a negative influence on system performance.

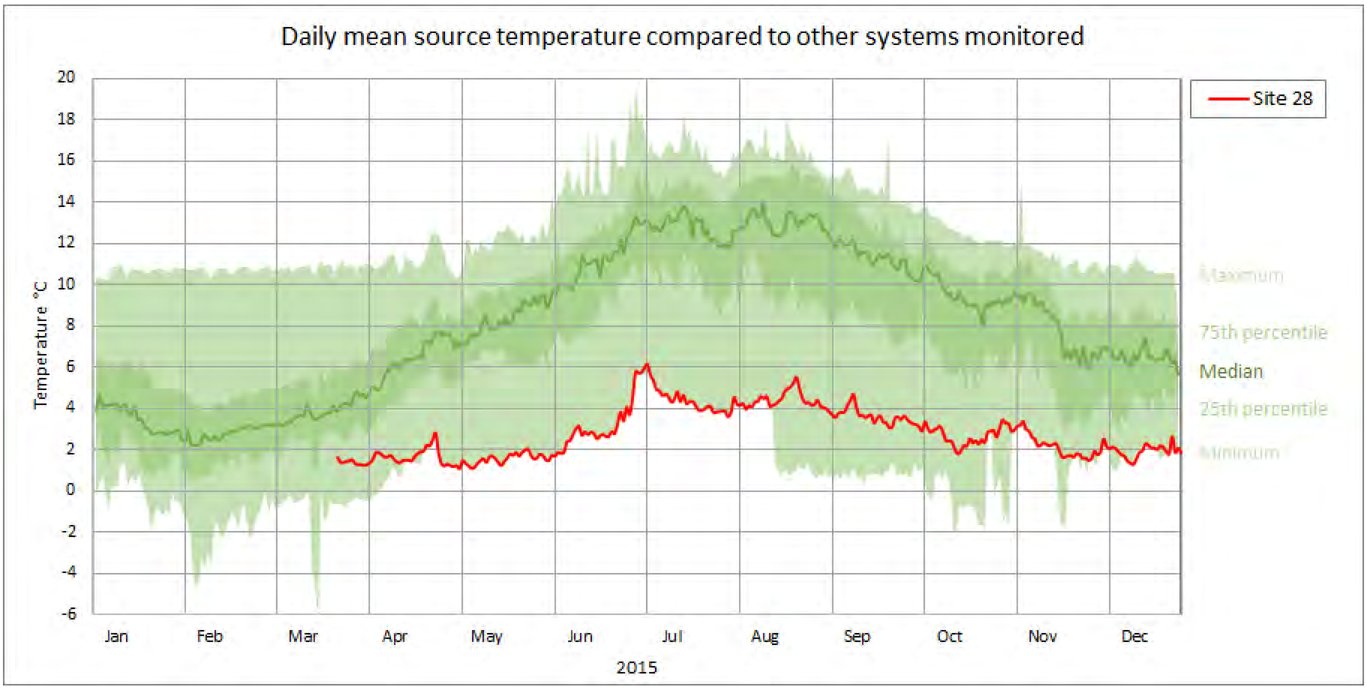

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 28 is shown in red)

Figure 11 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures on this system (plotted in red) were above average during the winter (when most of the heat output is needed) compared to other systems. This would have had a negative influence on the system performance.

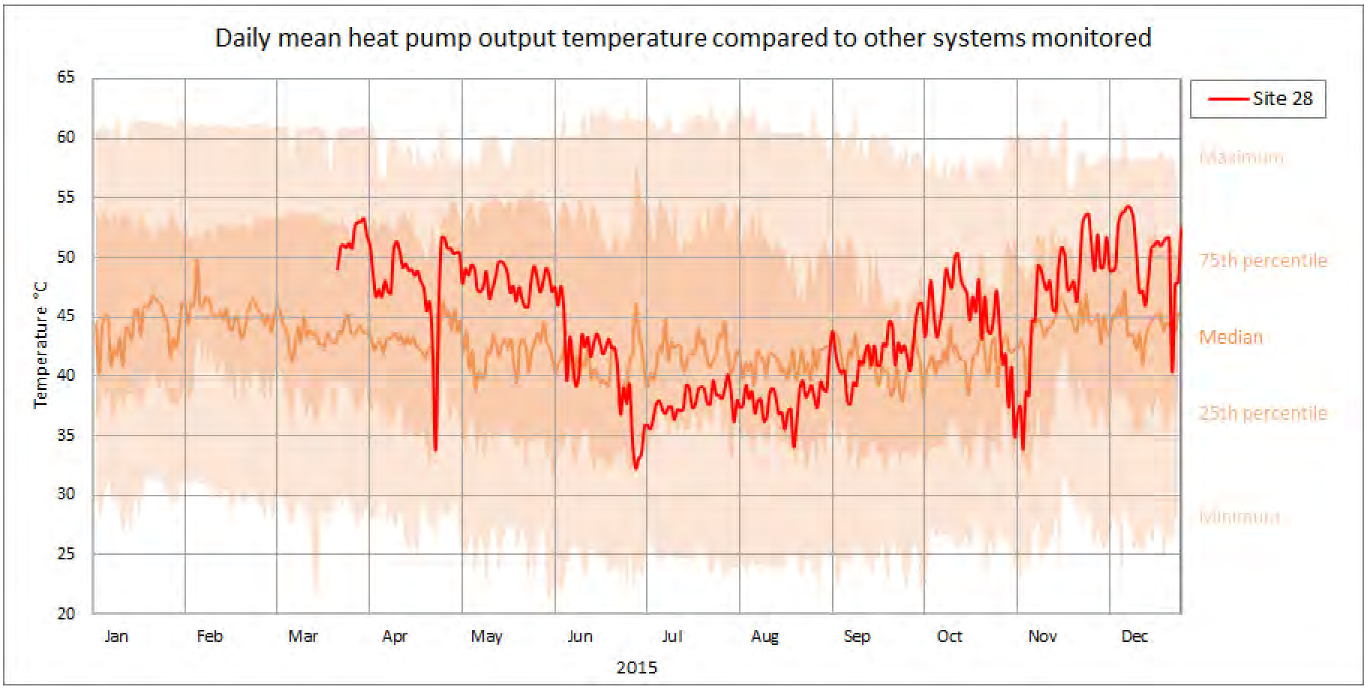

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 28 is shown in red)

Comments

The performance of this system was slightly below average (SPF_{H4} = 2.34), compared to other broadly similar systems monitored that provide space heating and domestic hot water (SPF_{H4} range: 1.54 to 3.13, median value 2.23).

However, it is worth noting that this site is in the most northerly location of all of the systems monitored in this project. This may have some bearing on the performance because of lower ground and outdoor air temperatures. The mean outdoor air temperature at this site during 2015 was 8.8 °C, the third lowest of all sites monitored (range 8.1 °C to 12.5 °C, median 10.3 °C).

Aspects of this system that positively influenced its performance are:

- The electricity used by the brine and heating circulating pumps was lower than average for other systems monitored in this study.
- The temperature of the brine from the ground collectors did not decrease as much during the winter as on many other systems in the monitored sample.
- There was no measurable loss of temperature through the 2-pipe buffer tank.

Aspects of the system that may have negatively influenced its performance include:

- The domestic hot water immersion heaters were used extensively.
- The temperature of the brine from the ground collectors was generally below average compared to other systems monitored.
- The temperature of the output to space heating was higher than average (during the winter) compared to other systems monitored.

- The control strategy did not appear to make best use of the heat pumps for providing domestic hot water. An indication of the potential improvement in performance can be seen in Figure 3 where the SPF_{H4} increased at the start of November when the immersion heaters were switched off (although the space heating temperatures may also have been reduced at the same time).

It would be interesting to know whether the temperature of the brine from the borehole loops is usually lower than the outdoor air temperature. Continued monitoring of these temperatures could be useful in assisting any future decisions with regard to the type of equipment used – e.g. would an air-source heat pump be worth considering?

Bibliography

[1] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[2] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[3] D. Hughes, "Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013," DECC, 2016.

[4] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.," EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 29

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 29 and performance results from 12 consecutive months of monitoring data.

Site 29 is a large house. A single heat pump (thermal capacity 126 kW) provides space heating to radiators and domestic hot water.

The heat source is a river that flows through the grounds of the property, approximately 100 metres from the house. Heat is extracted via a water-to-brine heat exchanger on the river bed. The heat emitters are the radiators that had been used for the previous oil-fired heating system.

The seasonal heating performance factors measured over a year of operation
(1st January 2015 to 31st December 2015) were:

SPF_{H2}	[Heat delivered by the heat pump] -- Electricity used by: [heat pump] + [brine pump]	2.57
SPF_{H4}	[Heat delivered by heat pump] + [heat added by SH circ & DHW primary pumps] + [heat from immersion heaters] – [heat loss from buffer tank] -- Electricity used by: [heat pump] + [brine pump] + [SH circ & DHW primary pumps] + [immersion heaters]	2.37

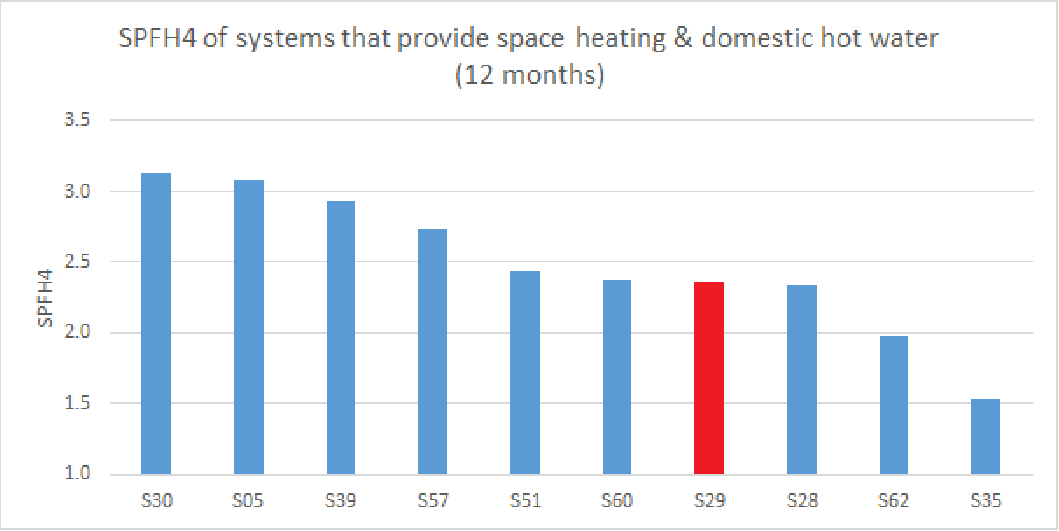

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influenced its performance are:

- Very little electrical auxiliary heat was used (0.05% of total electricity).
- The use of the existing cast-iron radiators as the heat emitters does not seem to have required excessively high temperatures.

Aspects of the system that may have negatively influenced its performance include:

- The electrical energy used by the brine pump was high – 14.7% compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The heat pump output temperature was high (up to 60 °C) during most of the heat pump run cycles, because of the need to provide heat to domestic hot water all day.
- The heating circulating pumps were run continuously during the summer when there was little or no requirement for space heating.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	29
Survey date	22/02/2014
Monitoring installed	06/06/2014
G/WSHP	WSHP
Building type	Large house
Location	Rural
Heat pump capacity kWTH	126
Number of heat pumps	1
Number of compressors	2
Heat source	River. Heat extracted via water-to-brine heat exchanger on river bed.
Heat emitter	Radiators (cast iron)
DHW	Yes
Auxiliary heat	9kW immersion heater in buffer tank. 9kW immersion heater in DHW cylinder.
Source pump	External to heat pump: 4kW
Buffer pump	External to heat pump: 600W
Buffer tank	500 litre 2-pipe in flow
DHW coil pump	External to heat pump: 600W
DHW cylinder	500 litre
Control	Heat pump controller
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	1
Heat meter interface	Pulse (10 kWh/pulse)
Comments	

Table 1 – System details

Site 29 is a large 17th century house, set in extensive grounds in a rural location. The property is sometimes used for private events such as weddings, so the number of people on the site at any time varies considerably.

This application entails extracting heat from a river to provide space heating and domestic hot water in a property that is poorly insulated by current standards and is located in an area with average outdoor temperatures – approximate annual mean 10 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). Radiators originally sized for use with oil-fired heating are used for space heating and the domestic hot water distribution is via a lengthy, pumped circuit. The performance of this system would be expected to be average.

Heat pump and monitoring systems

The water-source heat pump (thermal capacity 126 kW) was installed to replace an old oil-fired heating system.

The heat pump plant is in a room on the ground floor of the house. It provides space heating (SH) and domestic hot water (DHW). Auxiliary heat is provided when needed by immersion heaters in the buffer tank and in the domestic hot water cylinder.

The heat source is the river that flows through the grounds of the property, approximately 100 metres from the house. Brine is circulated from the heat pump through a heat exchanger in the river to extract heat from the river water.

The heat emitters are the cast-iron radiators that had been installed for the previous oil-fired heating. These have not been altered for the heat pump.

The heat pump has two compressors that provide two-step capacity control in a single vapour-compression circuit. The system is controlled by the heat pump controller.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and to domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1].

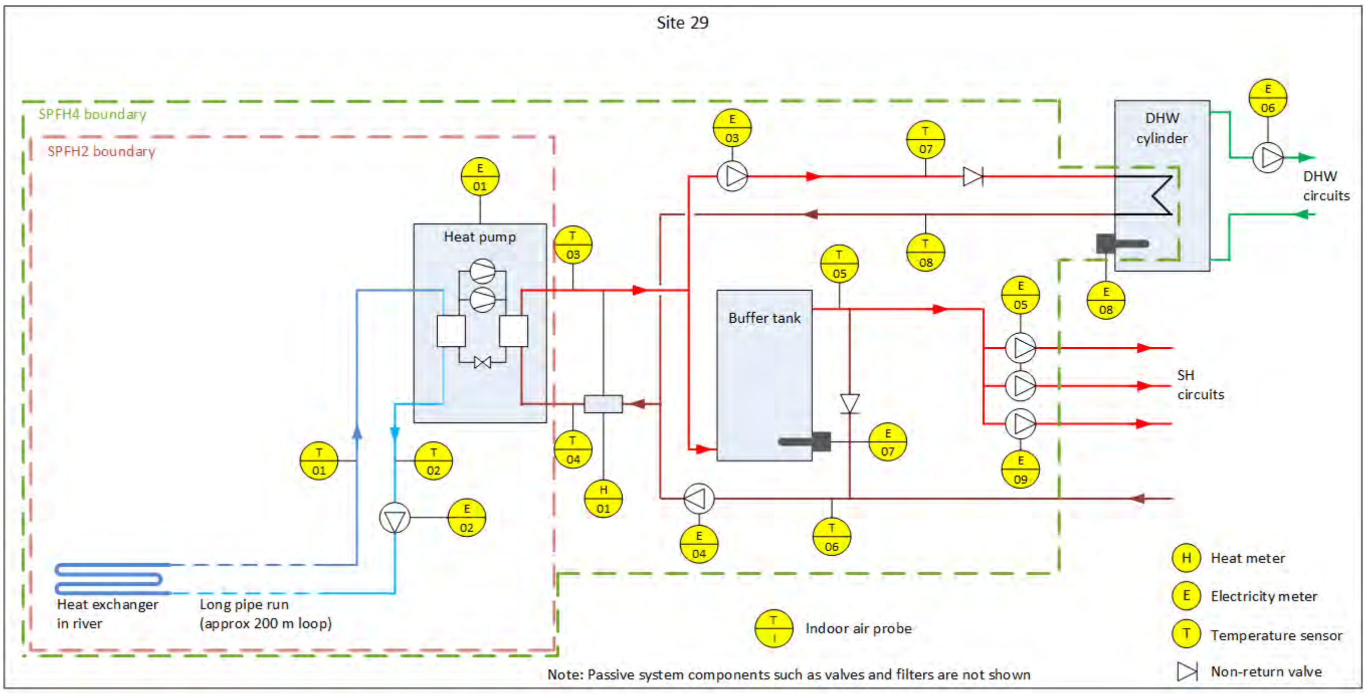

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed at the output of the heat pump. It uses an ultrasonic flow meter installed in the return pipe, with matched temperature sensors installed in pockets in the flow and return pipes. The calculator is battery-powered, and monitoring was via the pulse interface.

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.
- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump]}}{\text{Electricity used by: [heat pump] + [brine pump]}}$$

$$SPF_{H4} = \frac{\begin{array}{c}\text{[Heat output of heat pump] + [heat added by heating circ pumps]} \\ \text{+ [heat added by immersion heaters] – [heat loss from buffer tank]}\end{array}}{\text{Electricity used by: [heat pump] + [brine pump] + [heating circ pumps] + [immersion heaters]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer pump and the heating circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 524 447, which represents 99.8% of the 12-month period.

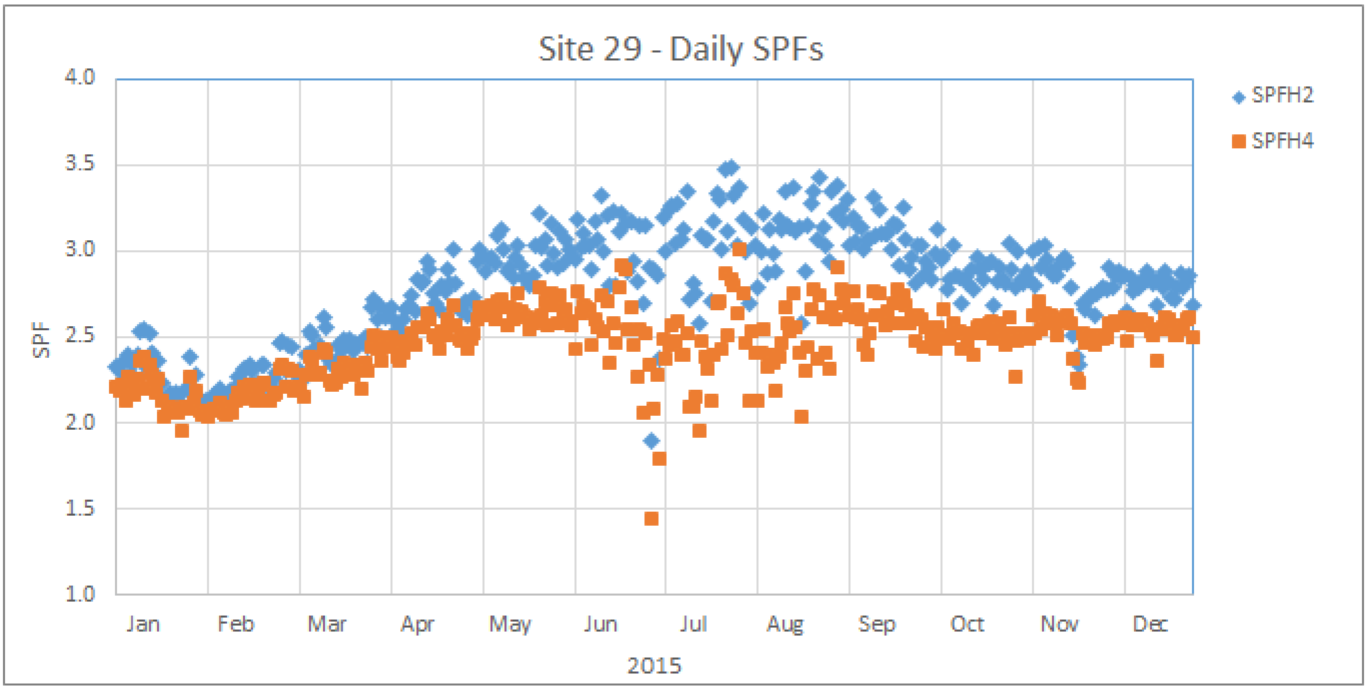
The mean SPFH2 and SPFH4 values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPFH2	2.57
SPFH4	2.37

Table 2 - SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 2.37 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

The daily performance of the system is shown in Figure 3. The SPFH2 and SPFH4 values have been calculated on a daily basis. The general trend was that the SPF values were low during January and February when the outdoor (river and air) temperatures were at their lowest, and rose as the outdoor temperatures increased. The low SPF values during the warm summer months are a consequence of the heat pump operating under very low load conditions. For example, on 1st July when the measured SPFH4 was lowest, only 14 kWh was supplied to space heating and 36 kWh to domestic hot water. The effect on the overall annual performance of these low-load SPF values is not very significant.



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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Figure 4 shows the daily SPFH4 for operation in space heating and in domestic hot water mode. The performance when in domestic hot water mode was lower because the heat pump output temperature was higher in this mode – generally up to 60 °C or more, whereas in space heating mode it was generally between 30 and 45 °C.

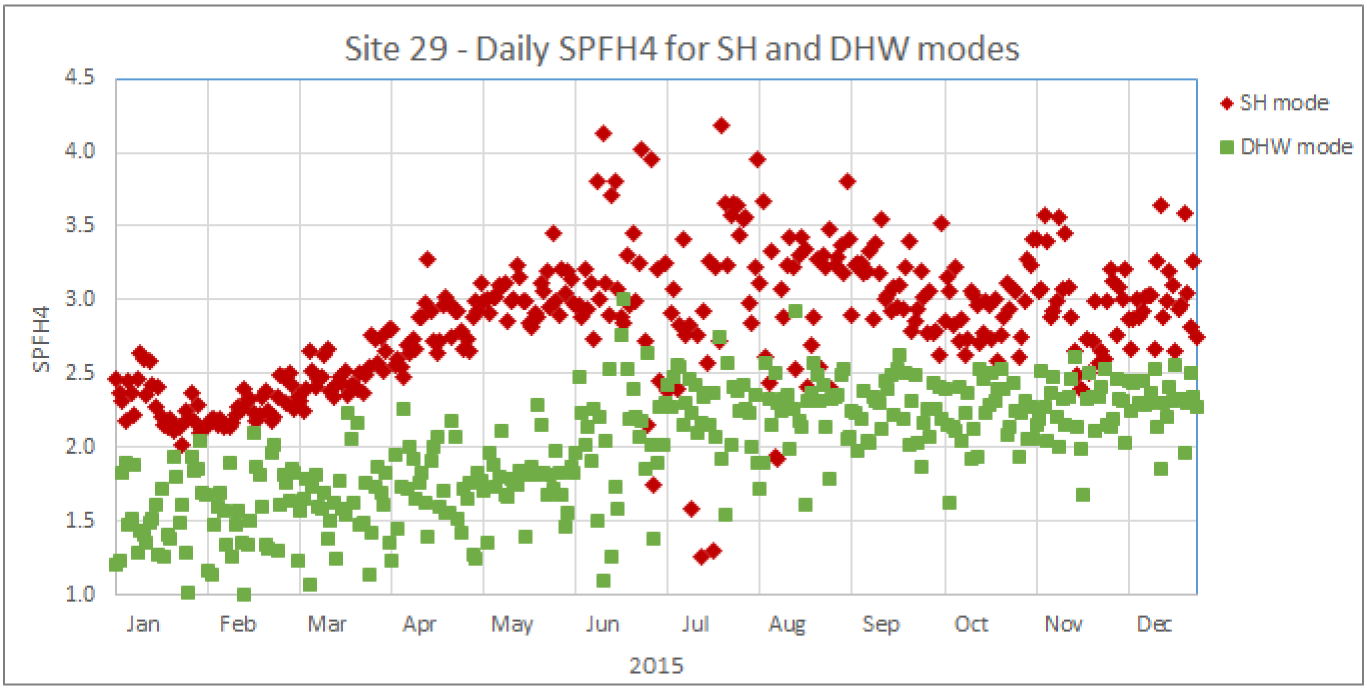

Figure 4 – Daily SPFH4 for space heating and domestic hot water modes

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source is the river water from which heat is being extracted and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the river and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine from the heat pump through the river heat exchanger, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 5 shows the daily heat output to space heating and to domestic hot water. The daily electricity use by the total heat pump system and the mean outdoor temperature[4] are also shown for reference. It can be seen how the heat demand varies with outdoor temperature. There was apparently a demand for space heating every day – even in the middle of summer.

The domestic hot water load increased towards the end of the year. The reason for this is presumed to be the holding of events with large numbers of people present.

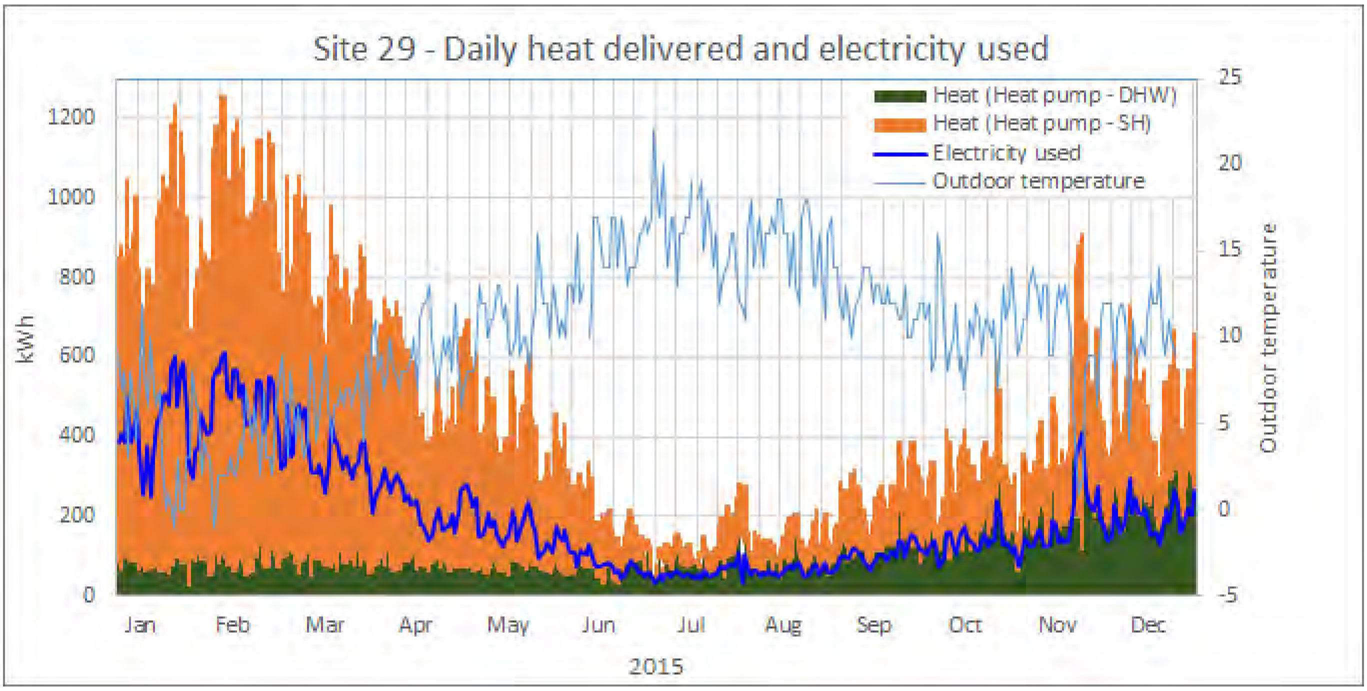

Figure 5 – Daily total heat output and electricity used by the total heat pump system

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[4] The outdoor air temperature was estimated from measurements at other sites in the same part of the country.

Breakdown of heat delivered

Table 3 shows the breakdown of the heat delivered to space heating and to domestic hot water during the period from 1st January to 31st December 2015.

	%
Heat delivered to space heating	76%
Heat delivered to domestic hot water	24%

Table 3 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 6 shows the weekly breakdown of electricity use.

The brine pump accounted for a 14.7% of the electricity used. This is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%) and can probably be explained by the long pipe run to the heat exchanger in the river and the consequently large pump needed (4 kW). This high electricity usage would have had a negative influence on the system performance.

The heating circulating pumps and the domestic hot water primary pump together used 9.3% of total electricity, slightly above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a small negative influence on the system performance.

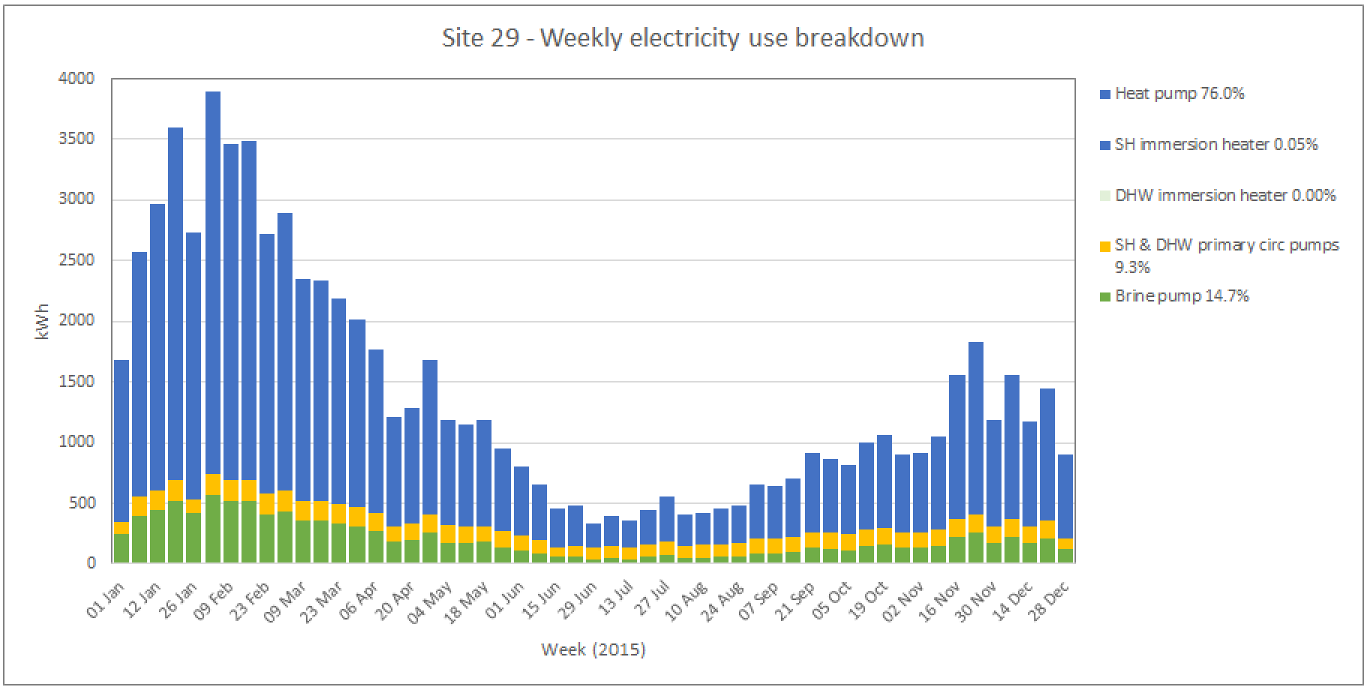

Figure 6 – Weekly electricity use breakdown

Possible reduction of brine pumping power when running on 1 compressor

Analysis of the electrical power measurements shows that the heat pump operated with only one compressor for approximately 80% of the total operating time during the monitoring period. However, the brine pump always operated at full power.

The temperature drop of the brine flow through the evaporator was between 3.0 and 3.3 °C when operating with two compressors, and between 1.5 and 2.0 °C when running with one compressor. It appears therefore that it may be possible to operate the brine pump at reduced speed[5] when running with one compressor. This would reduce the required pumping power by approximately 80% for 80% of the time the heat pump operates, giving a significant annual electricity saving of approximately 7000 kWh with a value of £1030[6]. The annual SPF_{H4} would be improved by approximately 10% to 2.61.

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 7 shows the typical pattern of winter operation on 12th January 2015, when the outdoor air temperature was between 7 and 11 °C. The temperature of the heat pump output to the domestic hot water coil can be seen to rise to 60 °C every time the heat pump was run between 05:00 and 23:00. It is not known why this should be required: a possible explanation is that the domestic hot water circulation pump runs at regular intervals throughout the day, and the heat losses from the domestic hot water distribution pipes give rise to a significant demand for heat into the domestic hot water cylinder. The total heat supplied to the domestic hot water cylinder during the 24-hour period was approximately 70 kWh (from analysis of the detailed temperature and heat meter readings).

It may alternatively be that the 60 °C output temperature is intended for Legionella control in the domestic hot water cylinder, although this is not known.

The temperature of the hot water circulated through the space heating system varied during the day between 27 and 40 °C. This range of temperature was good (low), considering that the heat emitters are cast-iron radiators originally installed for oil-fired heating which would have operated at a higher temperature.

There was no measurable temperature loss through the 2-pipe buffer tank.

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[5] This would require installation of a variable-speed inverter drive.

[6] Assuming an electricity unit cost of 14.7 p/kWh [5].

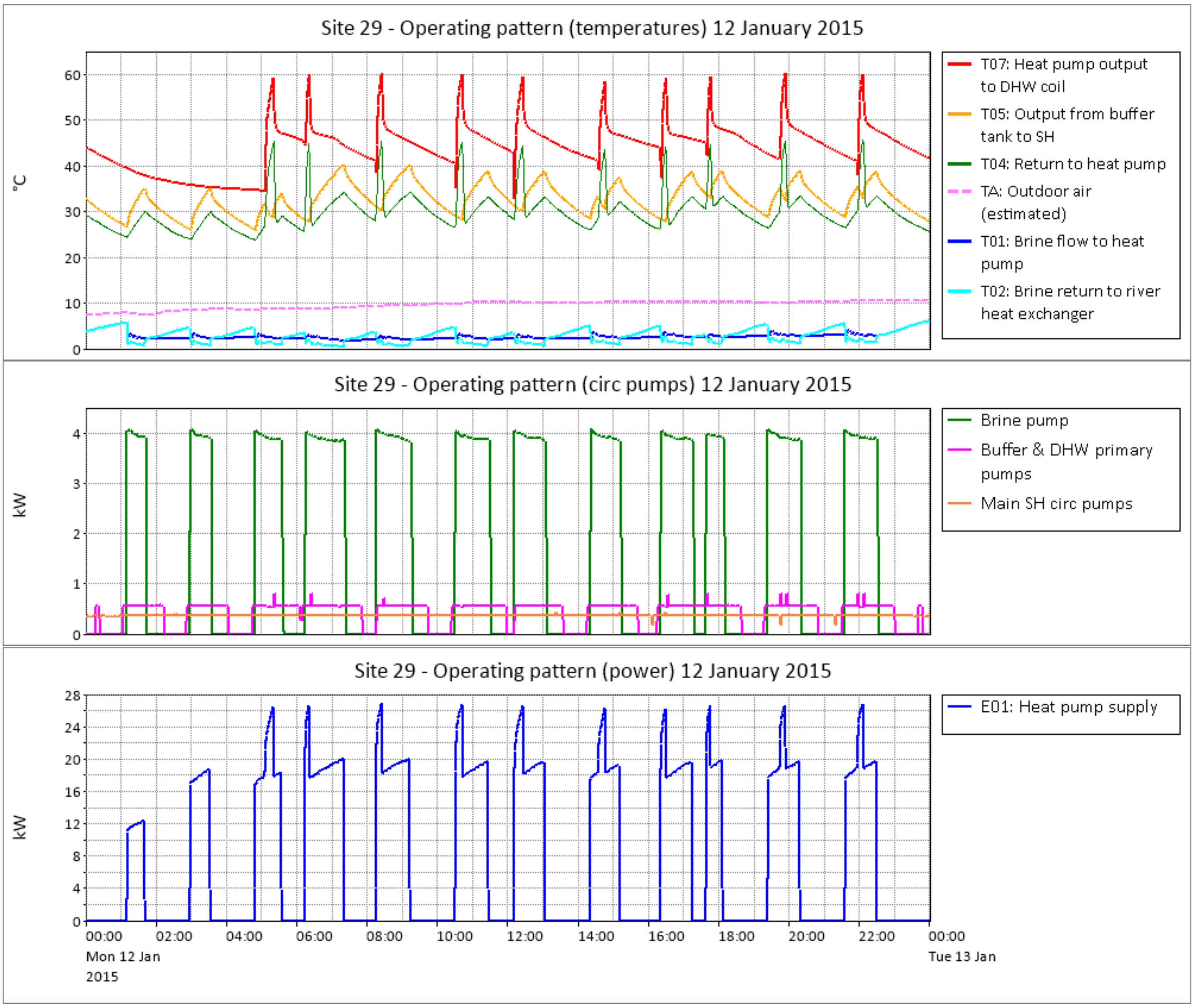

Figure 7 – Operating pattern on 12th January 2015

Figure 8 shows the behaviour on 14th July 2015 when the outdoor temperature was between 15 and 21 °C. The heat pump operated for ten short runs of between 7 and 17 minutes, with the output mainly to domestic hot water, at a maximum temperature of 61 °C.

The temperature of the brine flow to the heat pump was 14 °C.

The heating circulating pumps were running all day, although the temperature of the output to space heating was only between 21 and 29 °C. It seems unlikely that there was any significant demand for heat, so there should have been no need to run the heating circulating pumps all day.

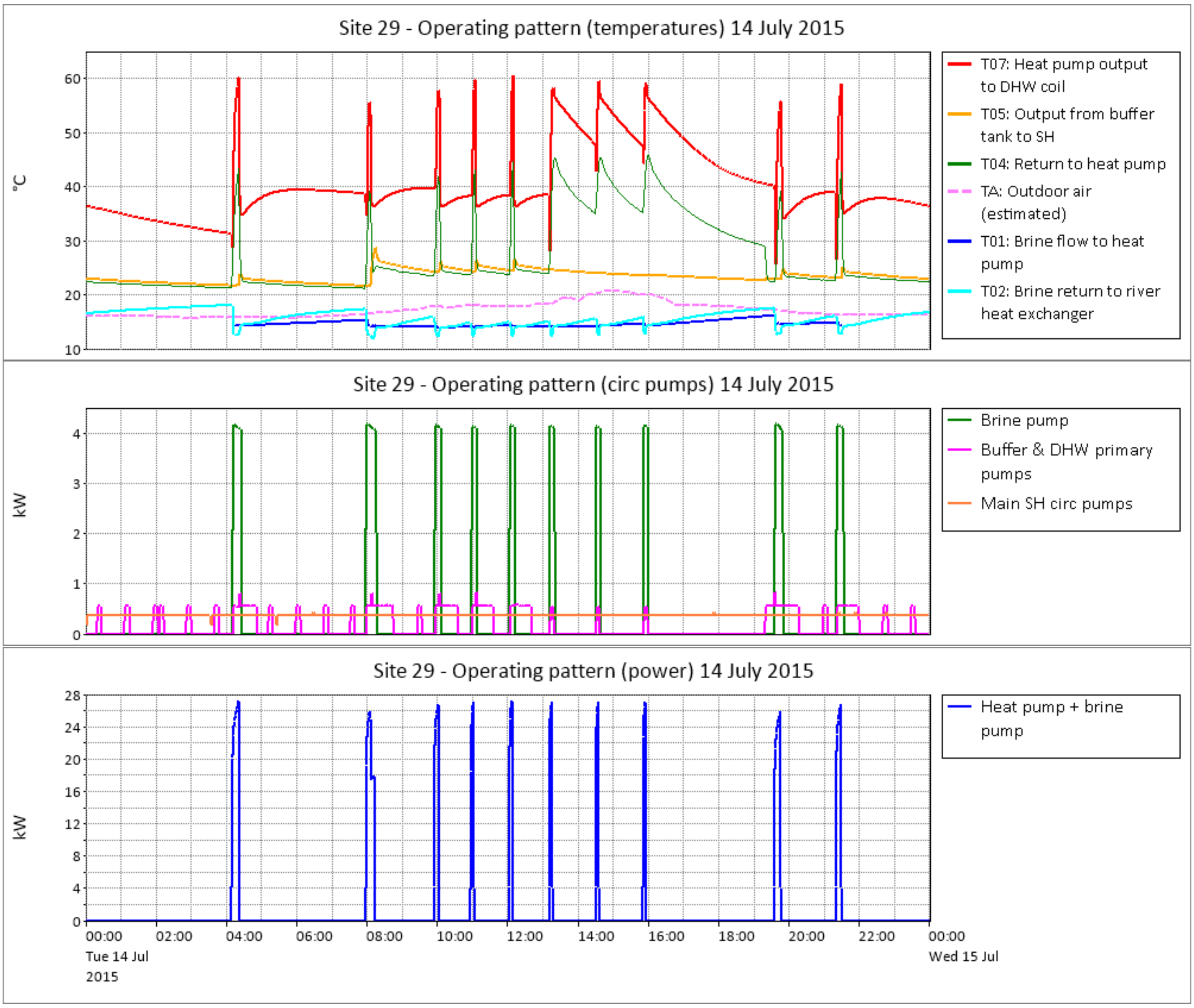

Figure 8 – Operating pattern on 14th July 2015

Source and sink temperatures

Figure 9 shows the principal temperatures of the brine and the outputs from the heat pump, plotted over the year. For clarity, the brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The temperature of the heat pump output to the domestic hot water was between 58 and 62 °C throughout the year.

The temperature of the output to space heating was between 24 and 49 °C, varying through about 10 °C as the heat pump cycled on and off. The effect of the weather compensation function can be seen, with the daily mean temperature of the flow to the heating system ranging from 22 °C in the summer time to 44 °C in the winter.

The brine flow temperature ranged from just below 0 °C in January to 16 °C in July.

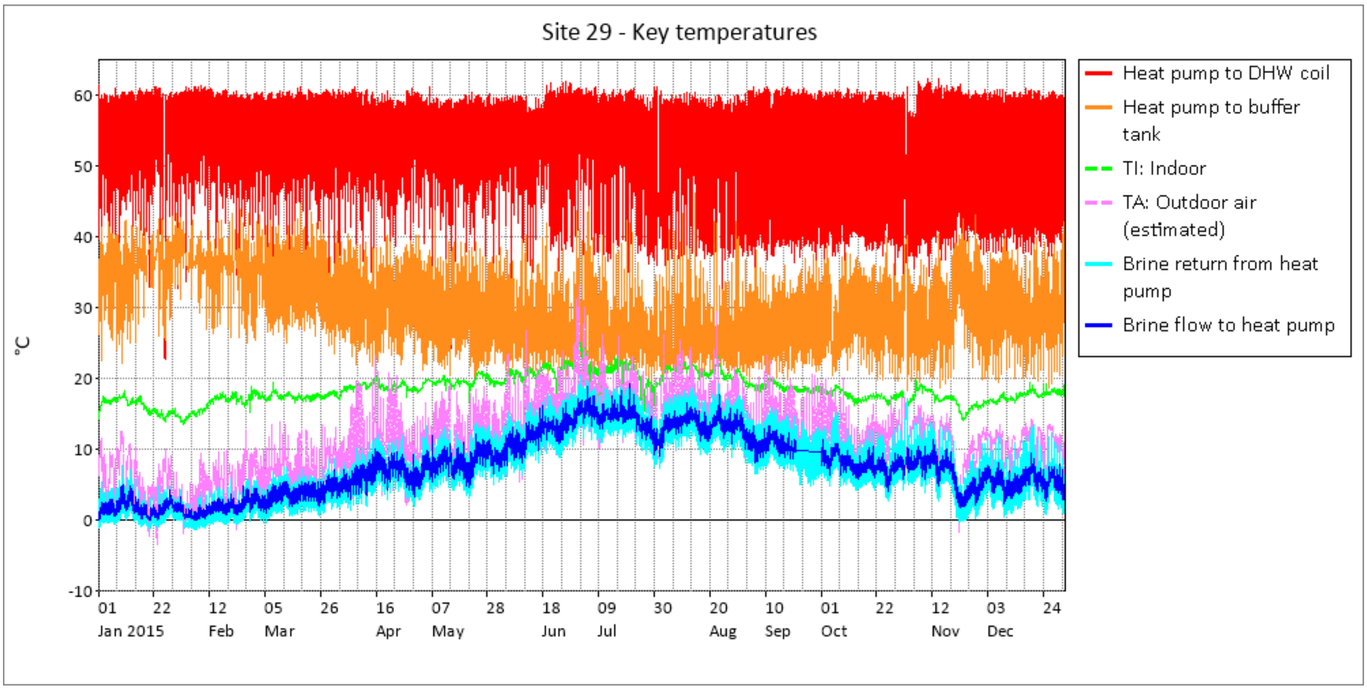

Figure 9 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were average compared to those measured on other systems monitored.

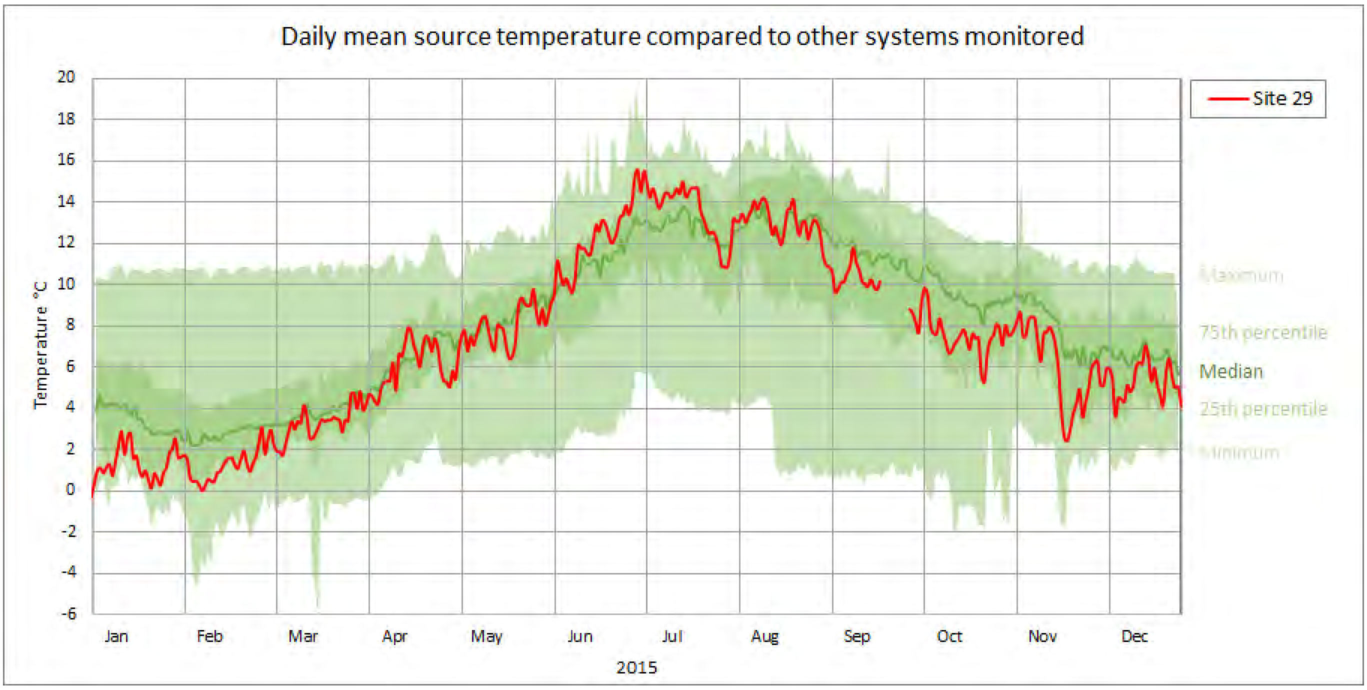

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 29 is shown in red)

Figure 11 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures on this system (plotted in red) were average compared to the values observed on other installations.

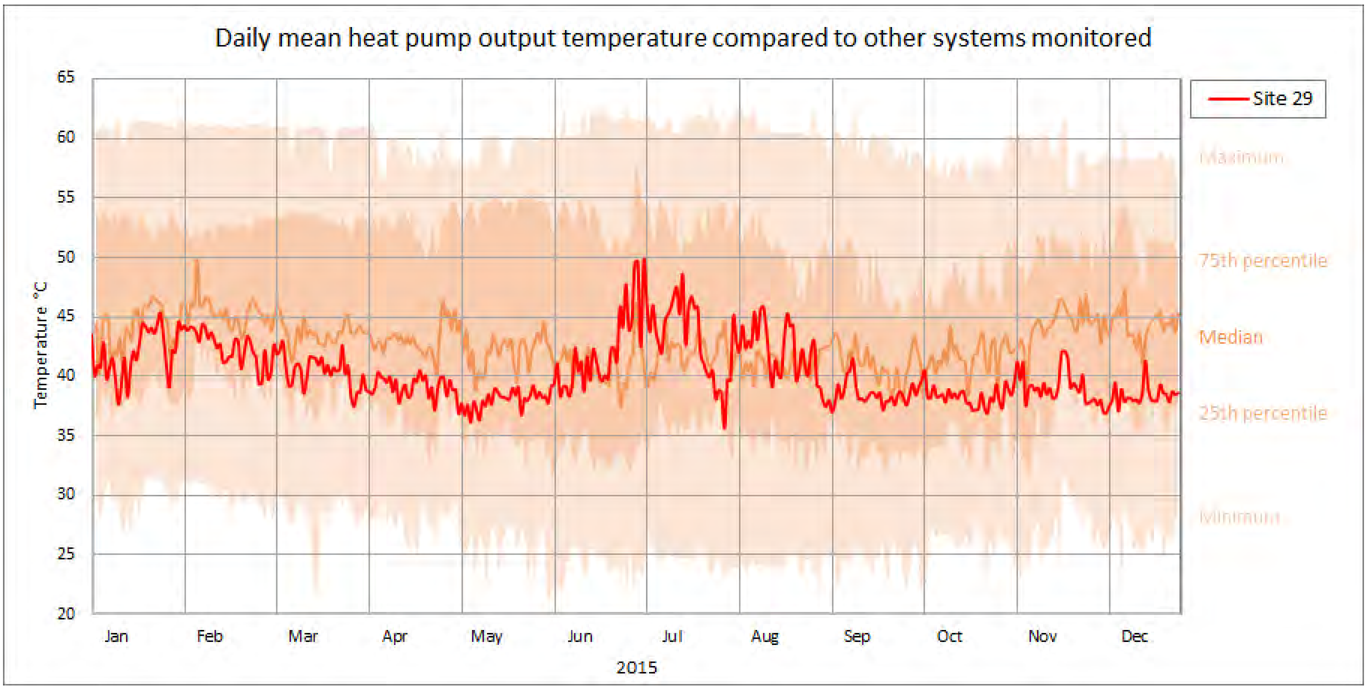

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 29 is shown in red)

Comments

The performance of this system (SPFH4 = 2.37) was average, compared to other systems providing both space heating and domestic hot water that were monitored in this project (SPFH4 range: 1.54 to 3.13, median value 2.23).

Aspects of this system that positively influenced its performance are:

- Very little electrical auxiliary heat was used (0.05% of total electricity).
- The use of the existing cast-iron radiators as the heat emitters does not seem to have required excessively high temperatures: the space heating flow temperature was very rarely above 50 °C, and was more generally in the range 25 – 44 °C during winter, spring and autumn.
- There was no measurable loss of temperature through the 2-pipe buffer tank.

Aspects of the system that may have negatively influenced its performance include:

- The electrical energy used by the brine pump was high – 14.7% compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). It would be worth considering installing a variable-speed drive to reduce the speed of the brine pump when running on only one compressor. The estimated electricity saving would be 7000 kWh per annum with a value[7] of £1030, and the SPFH4 would be improved by around 10%.
- The apparent need to provide heat to the domestic hot water system several times a day causes the heat pump output temperature to be high (up to 60 °C) during a high proportion of the heat pump run cycles. It would be worth considering installing point-of-use electric hot water heaters at places with low use and far from the heat pump. This could avoid continuously circulating hot water throughout the premises and should reduce the demand for domestic hot water from the heat pump system. The heat pump could then operate with lower output temperatures for longer times, with a consequent improvement in overall performance.

- The electricity used by the space heating and domestic hot water primary circulating pumps was slightly above average compared to other systems monitored – 9.3% of total electricity compared to other systems monitored (range 2.9 – 20.5%, median 8.8%).

- The heating circulating pumps were run continuously during the summer when there was little or no requirement for space heating. The electricity used by these pumps during July and August was 619 kWh. At least half of this was probably wasted, representing an excess cost[7] of £45. The control strategy should be amended so that the pumps run only when there is a need for heating.

Alternative means of Legionella control (e.g. ultraviolet lamps) are available and would be worth considering on this site to reduce electricity use by the heat pump, by allowing the heat pump to run with the lower output temperatures needed for space-heating only operation – thereby improving overall performance.

Bibliography

[1] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[2] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[3] D. Hughes, "Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013," DECC, 2016.

[4] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.," EN 14511-3.

[5] "Quarterly Energy Statistics (https://www.gov.uk/government/collections/quarterly-energy-prices)," DECC.

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[7] Assuming an electricity unit cost of 14.7 p/kWh [5].

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 30

Prepared by GRAHAM Energy Management
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January 2018

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Dr David Hughes asserts his moral right under the Copyright, Designs and Patents Act 1988 to be identified as the author of this work.

This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 30 and performance results from 12 consecutive months of monitoring data.

Site 30 is a public hall built in 2011.

A ground-source heat pump extracts heat from horizontal ground loops and provides heat to underfloor heating throughout the building and to domestic hot water.

The seasonal heating performance factors measured over a year of operation
(1st January 2015 to 31st December 2015) were:

SPF$_{H2}$	[Heat delivered by the heat pump (excluding auxiliary heater & buffer pump)] -- [Electricity used by the heat pump (excluding aux heater & buffer pump) + brine pump]	3.89
SPF$_{H4}$	[Heat delivered by the heat pump (including auxiliary heat)] + [Heat added by SH circ pumps] – [Buffer tank heat loss during warm weather] -- Electricity used by: [heat pump (incl aux heater & internal pumps)] + [SH circ pumps]	3.13

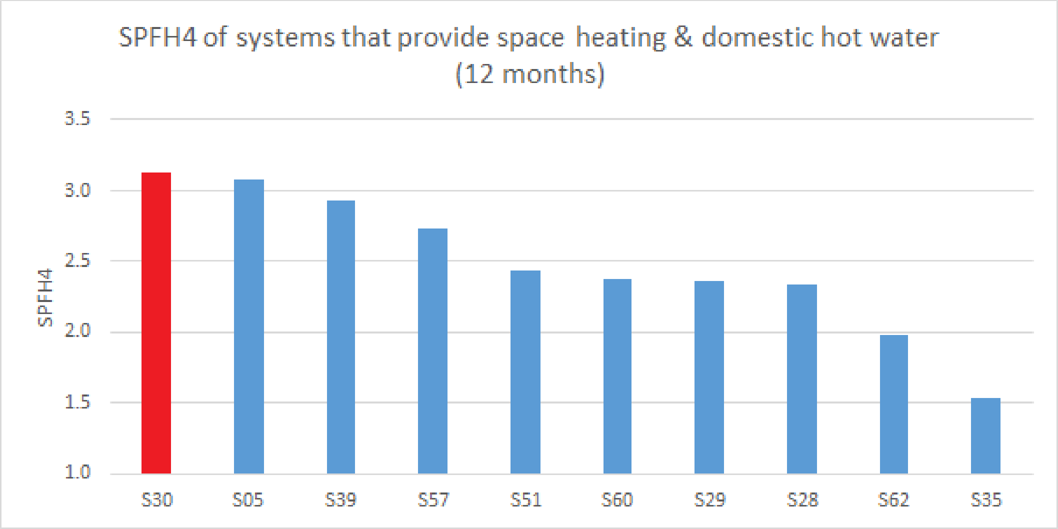

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influenced its performance are:

- The temperature of the output to the underfloor heating was below average compared to other systems monitored (second lowest of all systems).
- The electricity used by the brine pump was 4.1% of the electricity used by the total heat pump system. This was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

Aspects of the system that may have negatively influenced its performance include:

- The heating circulating pumps appeared to be run more than necessary, especially during the summer months.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	30
Survey date	18/02/2014
Monitoring installed	09/07/2014
G/WSHP	GSHP
Building type	Public hall
Location	Rural
Heat pump capacity kW_{TH}	14
Number of heat pumps	1
Number of compressors	1
Heat source	Horizontal ground loops. Approx. 200 m
Heat emitters	Underfloor heating pipes
DHW	Yes
Auxiliary heat	9kW immersion heater in heat pump
Source pump	Internal to heat pump: 390 W
Buffer pump	Internal to heat pump: 165 W
SH circulating pumps	External to heat pump: 1 x 71 W; 1 x 50 W
Buffer tank	180 litre 4-pipe
DHW cylinder	100 litre
Control	Room thermostats + manual pump switching + heat pump controller
Weather compensation	Yes
Heat meter type	Vortex
No. of heat meters	1
Heat meter interface	Pulse (1 kWh/pulse)
Comments	Ground floor and upper floor heating are switched on as required (i.e. the circulating pumps are switched manually).

Table 1 – System details

This site is a public hall, built in 2011.

This application entails extracting heat from the ground to provide space heating and domestic hot water in a modern well-insulated building that is in a location with average outdoor temperatures – annual mean 10.3 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3°C). The performance of the system would be expected to be good.

Heat pump and monitoring systems

The ground-source heat pump (thermal capacity 14 kW) was installed as original equipment at the time of construction of the building and provides both space heating (SH) and domestic hot water (DHW).

Space heating is provided via underfloor heating coils throughout the building. There are two separately-controlled heating zones on the ground floor and one on the first floor. Room thermostats are used to control the temperature in each zone.

Auxiliary heat is provided by a 9 kW immersion heater inside the heat pump. This is used mainly to raise the domestic hot water temperature above 60 °C approximately once a week for Legionella control.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and to domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1]. The outdoor air and ground temperatures are also monitored.

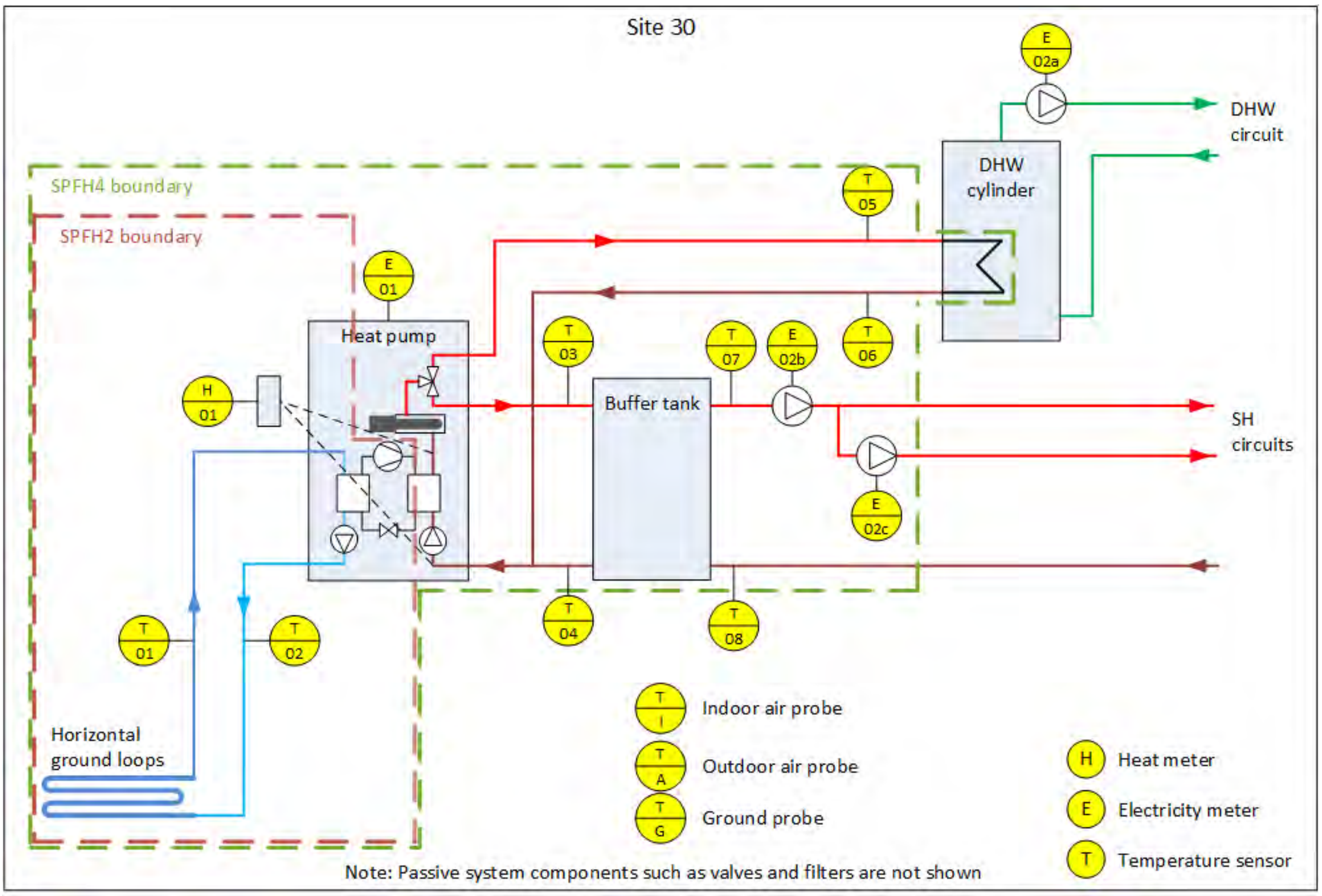

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed inside the heat pump. It uses a vortex flow meter installed in the return pipe, with matched temperature sensors installed in pockets in the flow and return pipes, in positions that exclude the heat added by the immersion heater. The calculator is mains-powered. Monitoring was via the pulse interface.

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump, excluding the internal buffer pump and immersion heater.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump] – [heat added by buffer pump]}}{\text{Electricity used by: [heat pump] – [buffer pump] – [immersion heater] + [brine pump]}}$$

- This calculation required the electrical energy used by the buffer pump and the immersion heater inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running. The immersion heater power was determined by digital filtering using the instantaneous power and power factor readings from the electricity meter[3].

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

[3] See Appendix H of the Interim Report [3] for details of the calculation methodology.

- The heat added by the buffer pump was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pump.

$$SPF_{H4} = \frac{\text{[Heat output of heat pump (including immersion heater and buffer pump)]} + \text{[heat added by SH circ pumps]} - \text{[heat loss from buffer tank when outdoor temperature > 15°C]}}{\text{Electricity used by: [heat pump (including immersion heater and buffer pump)]} + \text{[brine pump]} + \text{[heating circulating pumps]}}$$

- The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pumps.

- The buffer tank is located inside the heated envelope. The heat loss from it was deducted from the total heat output during times when the outdoor air temperature was above 15 °C (i.e. when there was output to space heating that was probably not needed).

- The heat output to domestic hot water was calculated by determining for each 1-minute interval whether the heat pump was providing heat to domestic hot water or to space heating, by analysis of the flow and return temperatures T_{03}, T_{04}, T_{05} and T_{06}.

The number of 1-minute intervals selected as valid for analysis was 524 472, which represents 99.8% of the 12-month period.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	3.89
SPF_{H4}	3.13

Table 2 - SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 3.13 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. These figures represent the combined space heating + domestic hot water performance. The daily performance figures were lower during the summer months. This is because during warmer weather the heat pump ran mainly for heating domestic hot water, which is a less efficient process – as explained below. The total heat output under these conditions was low, so the effect on the overall annual performance was quite small.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

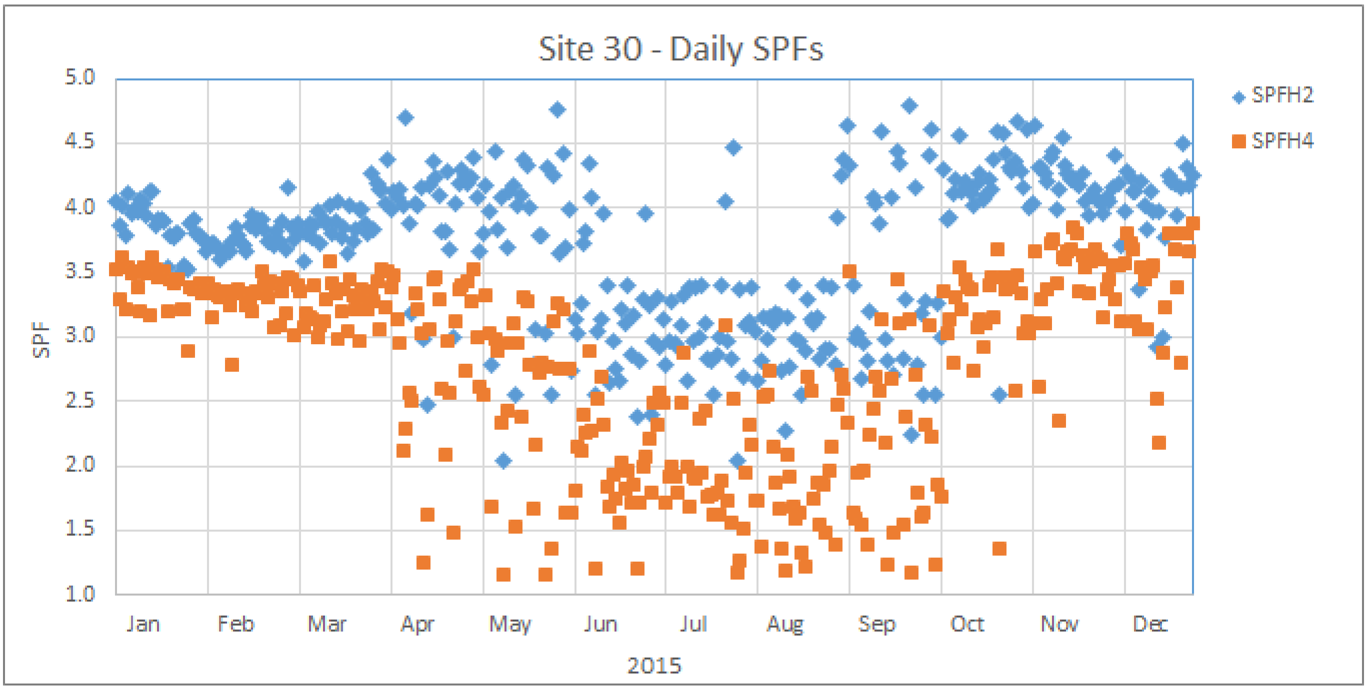

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Figure 4 shows the estimated[5] daily SPFH4 values for the system in space heating and in domestic hot water mode. The performance in domestic hot water mode was lower because of the higher output temperature required and the (approximately weekly) use of the immersion heater to raise the domestic hot water temperature for Legionella control.

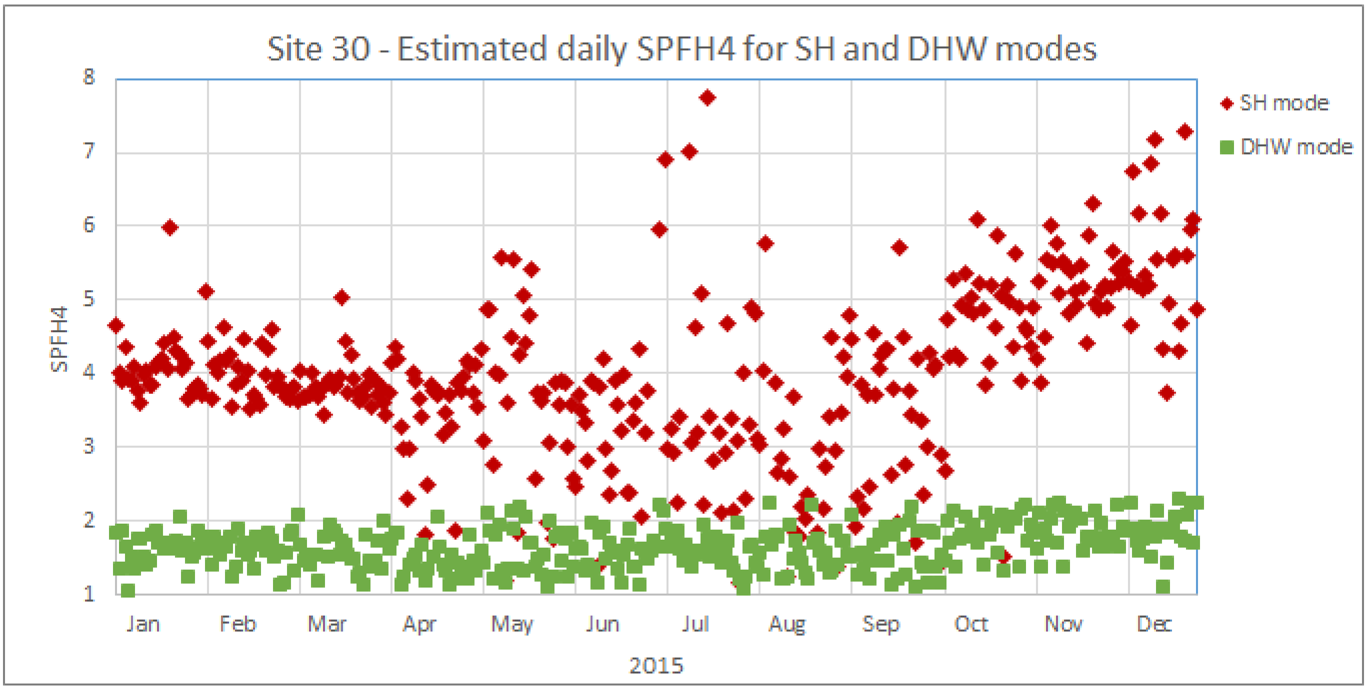

Figure 4 – Estimated daily SPFH4 for SH and DHW modes

Figure 5 shows the estimated SPFH4 data for domestic hot water mode in more detail. The days when the immersion heater was used for Legionella control are indicated by the red points. The SPFH4 was generally lower

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[5] The values presented are to illustrate the behaviour of the system and have been estimated as noted above.

when the immersion heater was used, because the heat from the immersion heater is provided at an output-to-input ratio of 1:1.

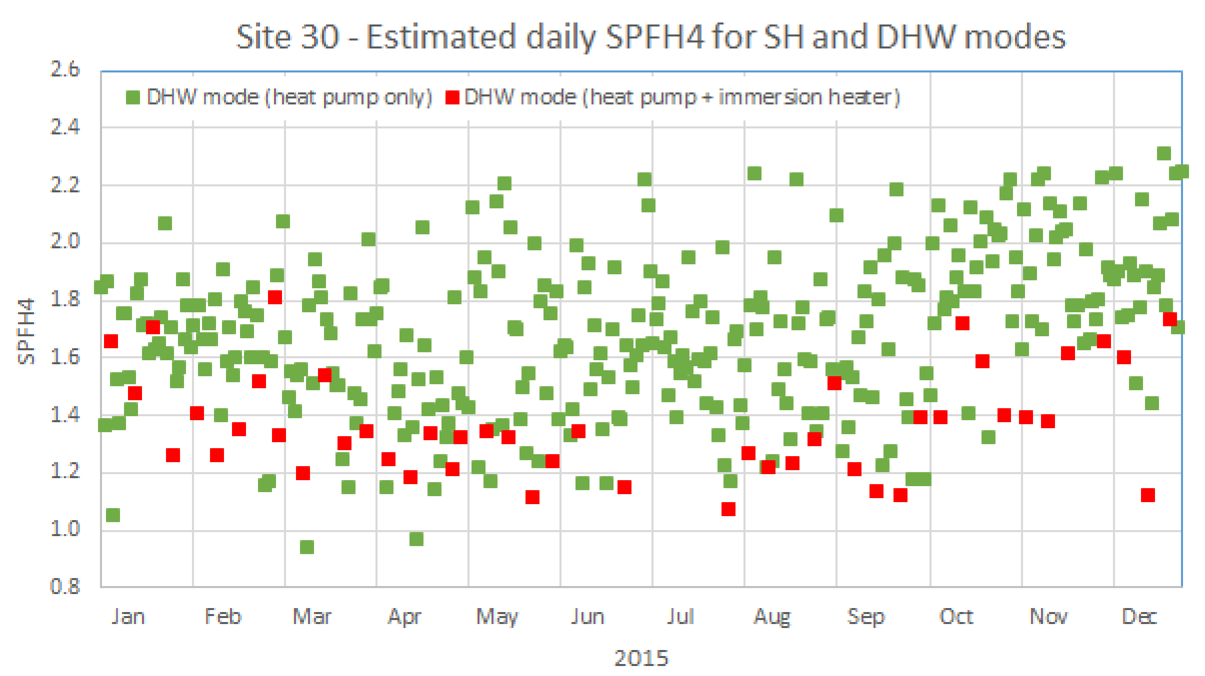

Figure 5 – Estimated daily SPFH4 for DHW mode, showing days when the immersion heater was in use

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 6 shows the daily heat output to space heating and to domestic hot water. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The total heat output was highest during the colder weather in January and February. The higher domestic hot water demand during the cold weather was probably due to greater use of showers for winter sports activities. The periodic use of the immersion heater for Legionella control can be seen on the graph.

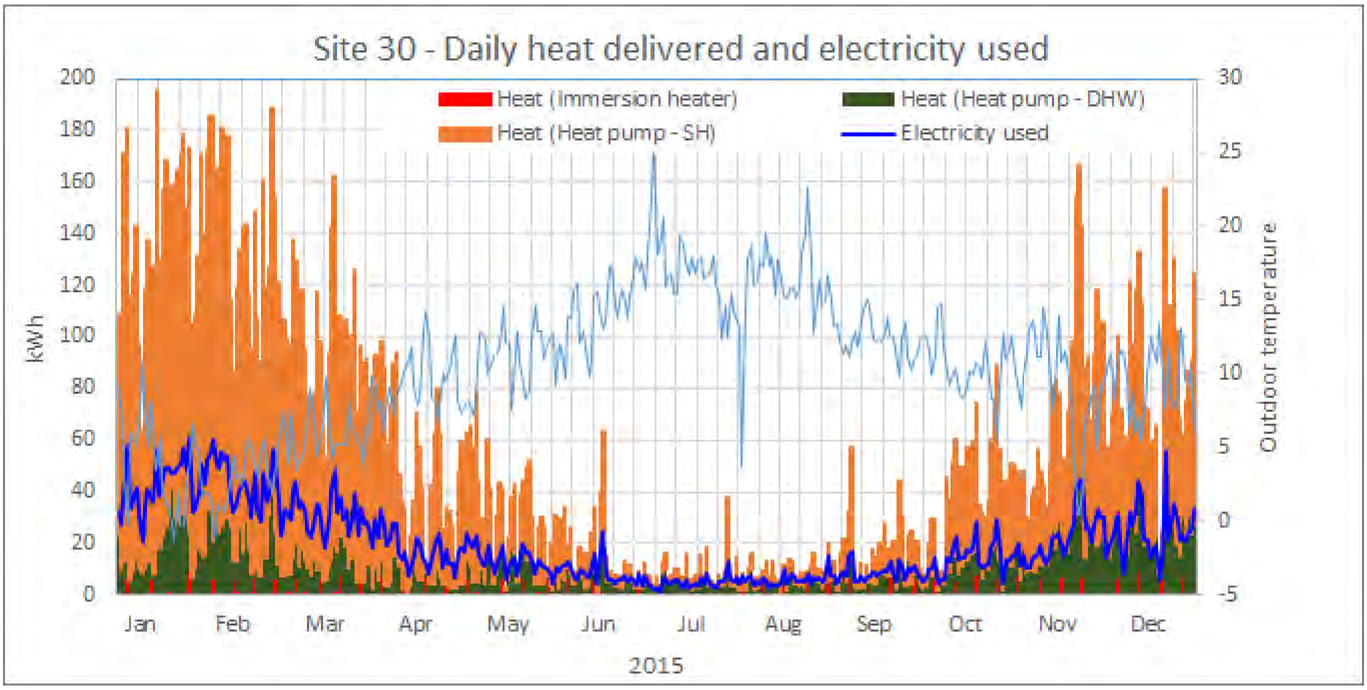

Figure 6 – Daily heat output and electricity use by the total heat pump system

Breakdown of heat delivered

Table 3 shows the estimated breakdown of the heat delivered to space heating and to domestic hot water during the period from 1st January to 31st December 2015.

	%
Heat delivered to space heating	79.1%
Heat to domestic hot water (from heat pump)	19.2%
Heat to domestic hot water (from immersion heater)	1.7%

Table 3 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 7 shows the weekly breakdown of electricity use. The electricity used by the brine pump, buffer pump and immersion heater (which are all internal heat pump components) have been estimated by analysis of the detailed data from the multi-function electricity monitor.

The brine pump accounted for 4.1% of the electricity use of the total heat pump system, which is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

It can be seen that the electricity used by the buffer pump and the heating circulating pumps was approximately constant throughout the year, and accounted for 20.5% of the total electricity. This was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%) and would have had a negative influence on the system performance.

During some weeks in the summer, when there was little or no requirement for space heat (as shown in Figure 6) the space heating circulating pump used over 50% of the total electricity. The overall performance could have been slightly better if this pump had only been run when needed[6].

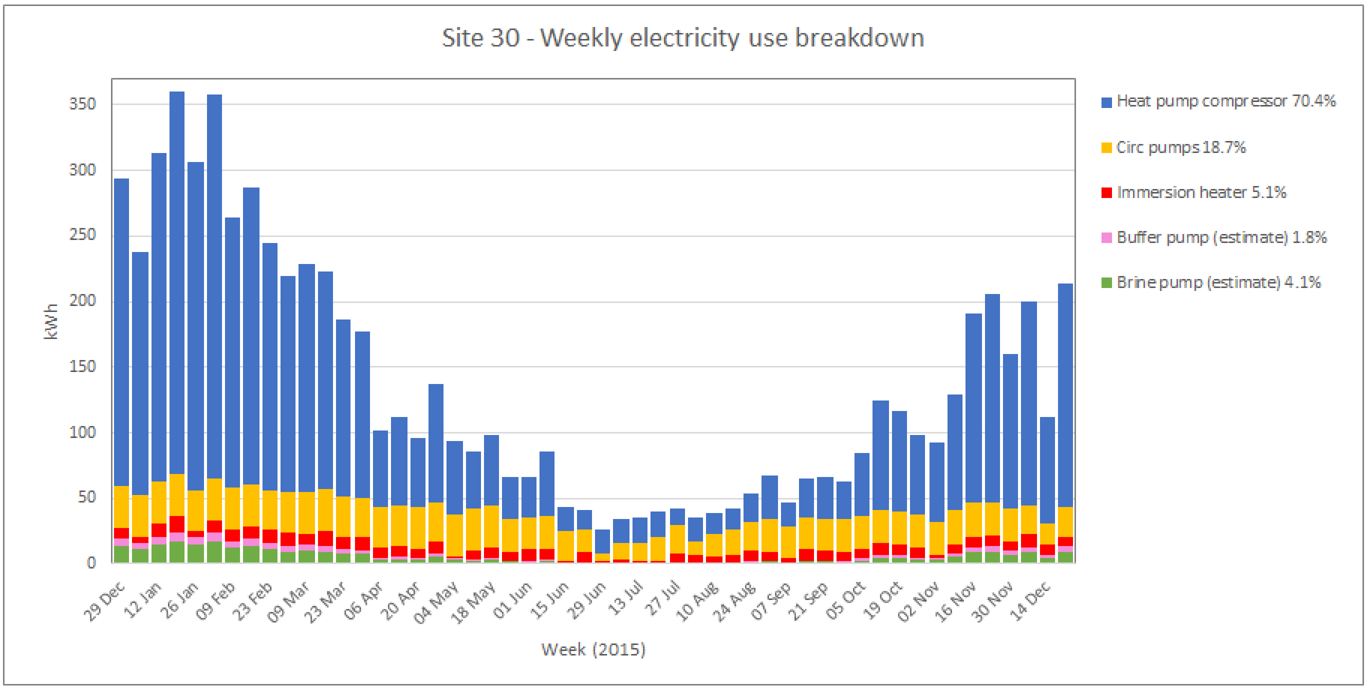

Figure 7 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump, immersion heater and circulating pumps. The heat pump operating cycles are indicated by the electrical power graph.

The temperatures of the heat pump output and of the brine are shown highlighted for times when the heat pump was operating.

Figure 8 shows the operating pattern over a 24-hour period on 4th – 5th January 2015 when the outdoor temperature was between 0 and 8 °C. The most notable feature is the use of the immersion heater just before

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[6] If the electricity used by the heating circulating pump had been reduced by 50% between May and September, a saving of approximately 300 kWh of electricity would have been made, and the overall SPFH4 would have improved by 1%.

midnight to raise the temperature of the output to the domestic hot water cylinder heating coil to 68 °C. This was done approximately once a week, presumably for reasons of Legionella control. At other times (e.g. at 14:00 on the graph), when the heat pump vapour compression system was used for heating domestic hot water, the maximum output temperature was 57 °C.

The temperature of the heat pump output to the buffer tank was between 28 and 36 °C. The temperature of the output from the buffer tank to the underfloor heating circuits was generally within 1 °C of the heat pump output, indicating a low loss of temperature through the buffer tank.

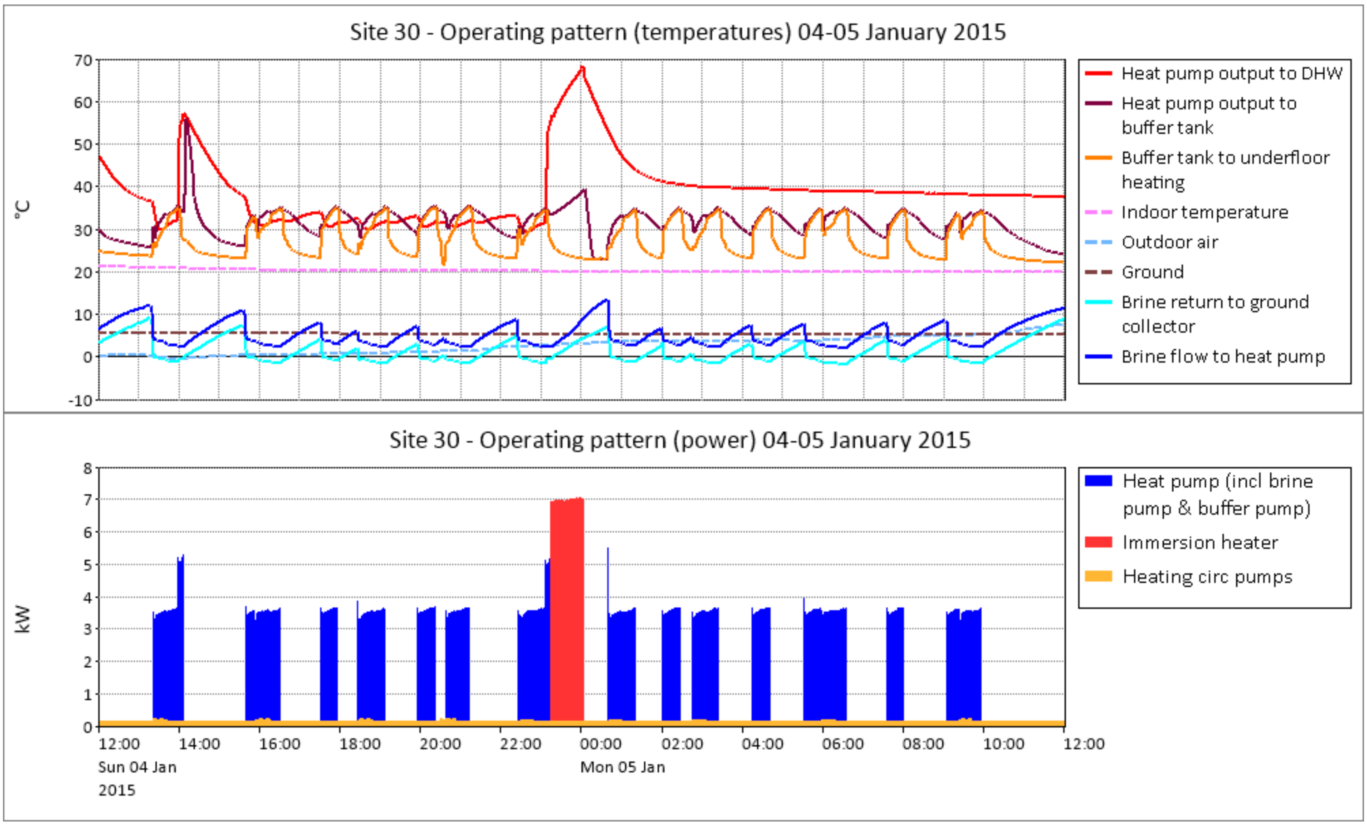

Figure 8 – Operating pattern on 4th – 5th January 2015

Figure 9 shows the operating pattern during a 24-hour period on 6th – 7th July 2015 when the outdoor temperature was between 14 and 22 °C. The immersion heater was not used during most of July, and, on this day, the heat pump was used only to heat the domestic hot water, with the temperature of the output to domestic hot water rising to 60 °C. The heat pump ran four times for short periods of between 6 and 8 minutes – just within the minima recommended by previous research [2]. Reference to Figure 5 shows that the daily SPF_{H4} in domestic hot water mode did not deteriorate during the summer months.

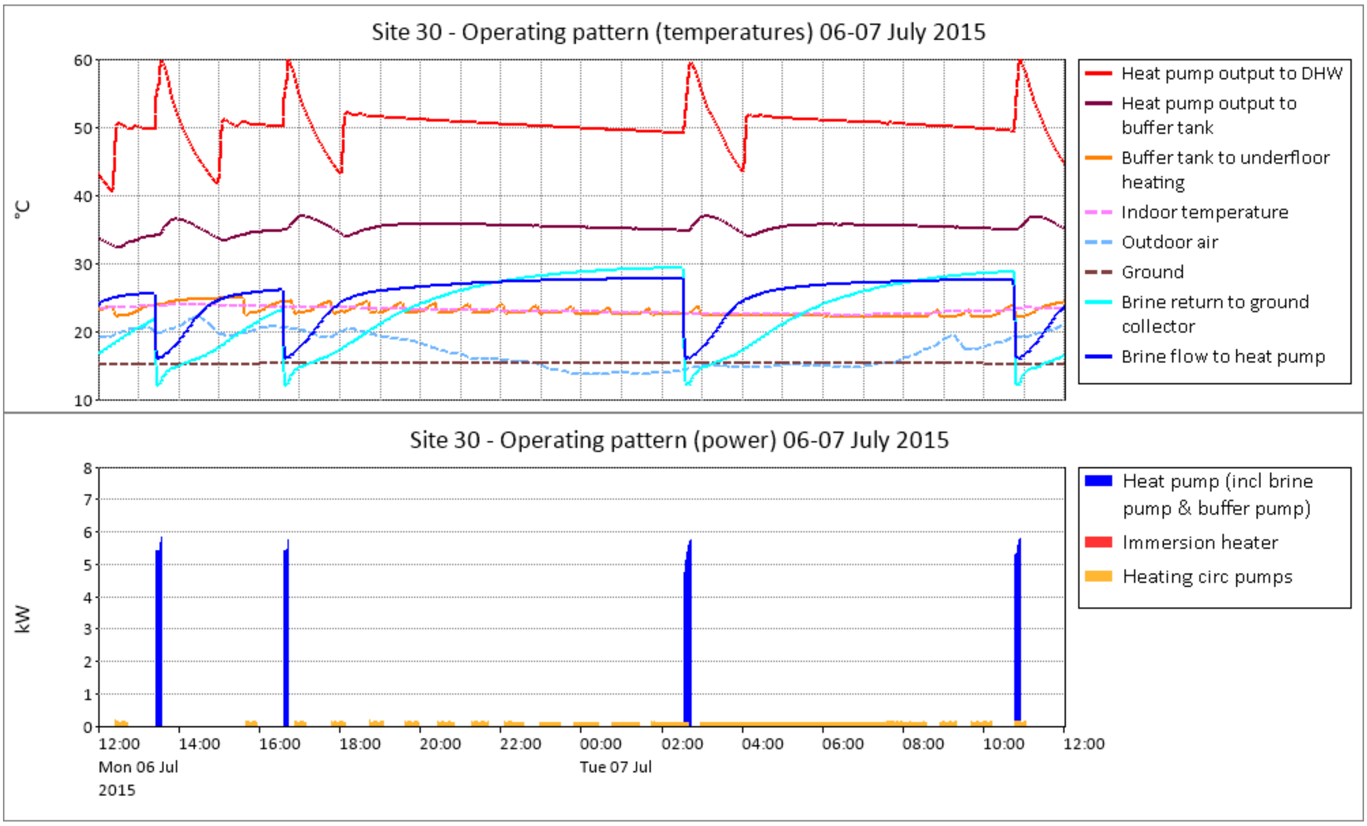

Figure 9 – Operating pattern on 6th – 7th July 2015

Source and sink temperatures

Figure 10 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[7]. For clarity, the brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The red line shows the temperature of the output to the domestic hot water cylinder – generally below 60 °C, but rising approximately once a week (except during July) to 68 °C for Legionella control. The output to the underfloor heating was at a maximum of 38 °C during the coldest day in January when the outdoor air temperature was -7 °C. During warmer weather in May, the flow to the underfloor heating was down to 21 °C.

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[7] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

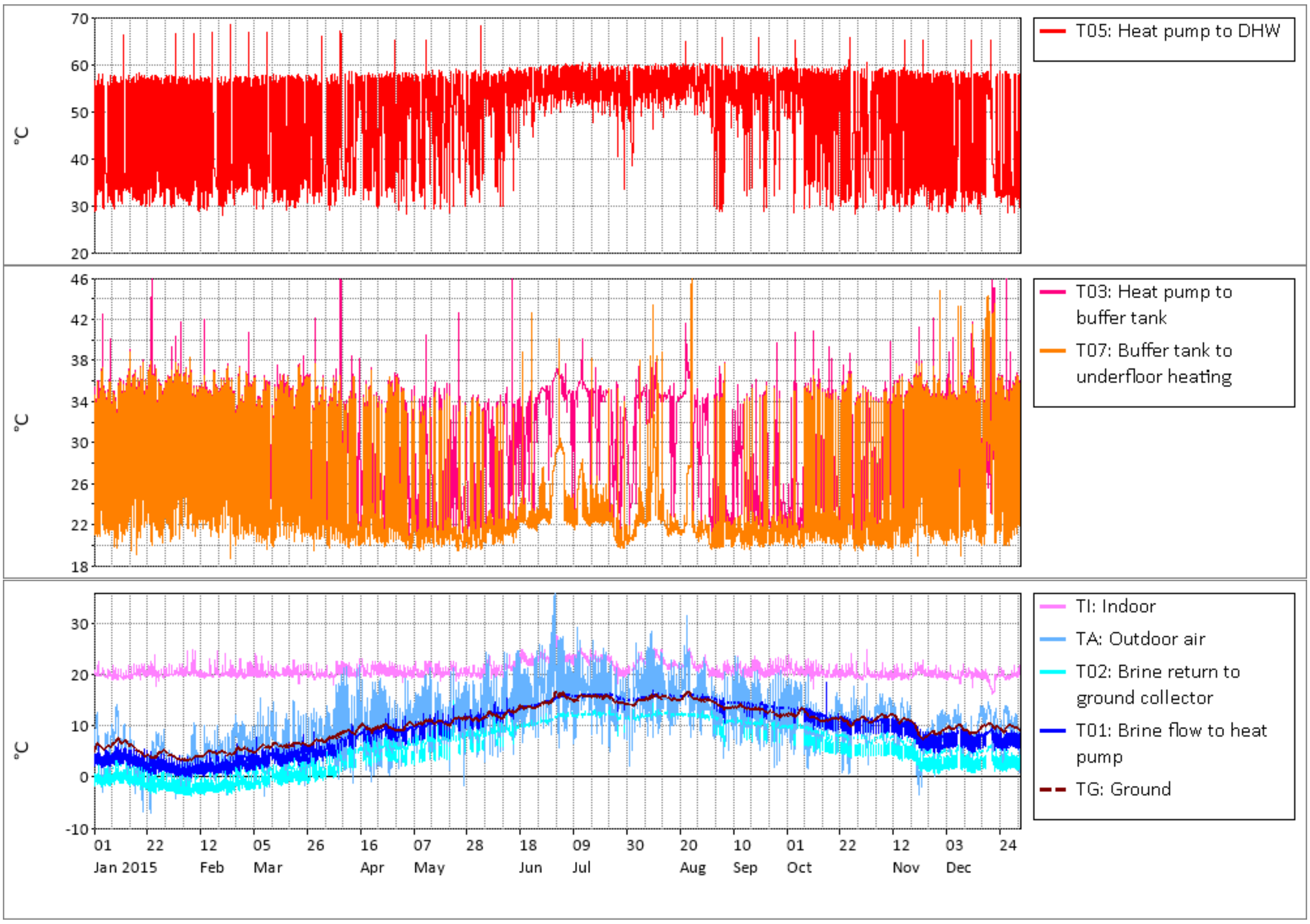

Figure 10 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 11 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were slightly below average between January and March, and average or above at other times, compared to other systems monitored in this project. This would have had a positive influence on the system performance.

The brine temperature generally followed the average outdoor air temperature which appears to have been higher at the end of the year that at the beginning.

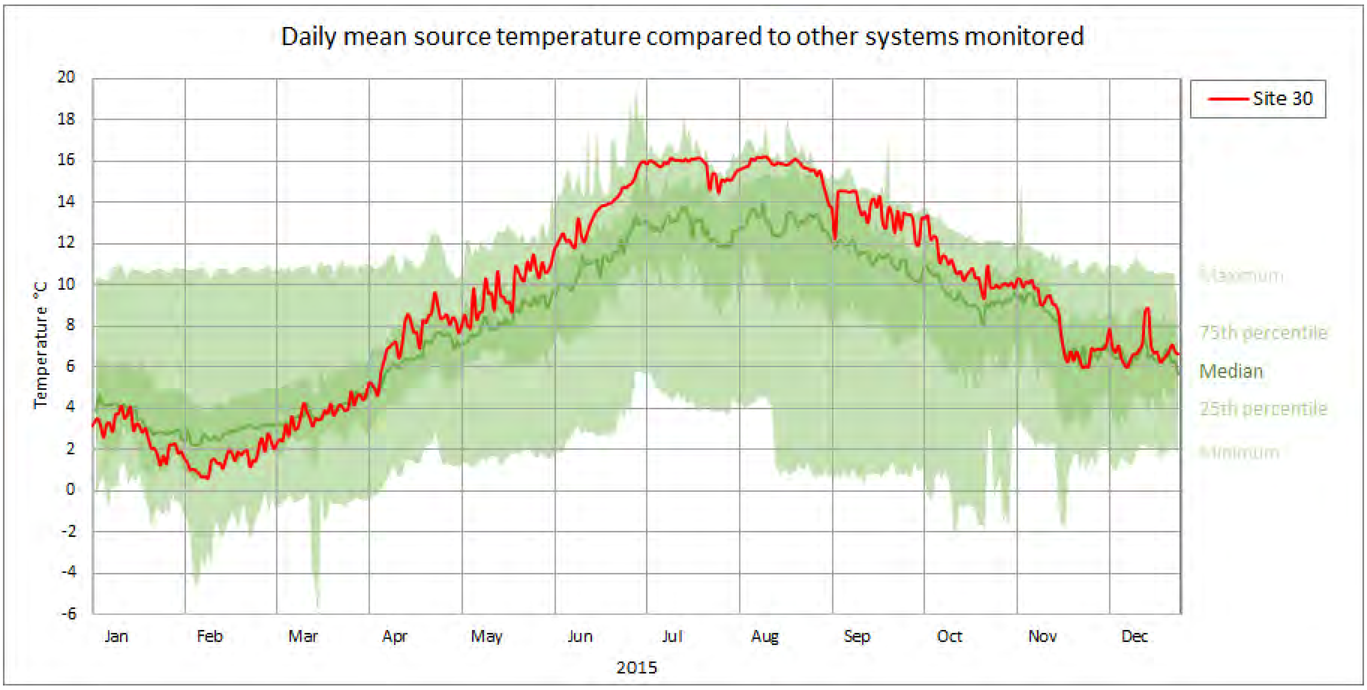

Figure 11 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 30 is shown in red)

Ground collector effectiveness

Figure 12 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The temperature difference on this system was the median value of all systems, which indicates average collector performance.

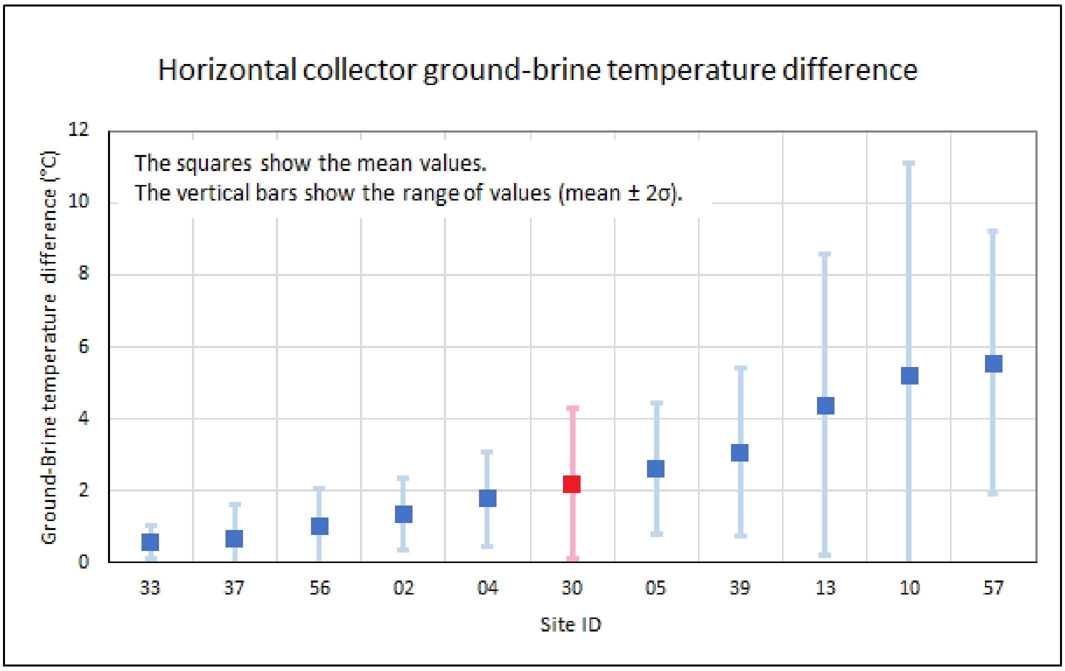

Figure 12 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 30 is shown in red)

Figure 13 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures on this system (plotted in red) were the second lowest of all installations. This would have had a positive influence on the system performance.

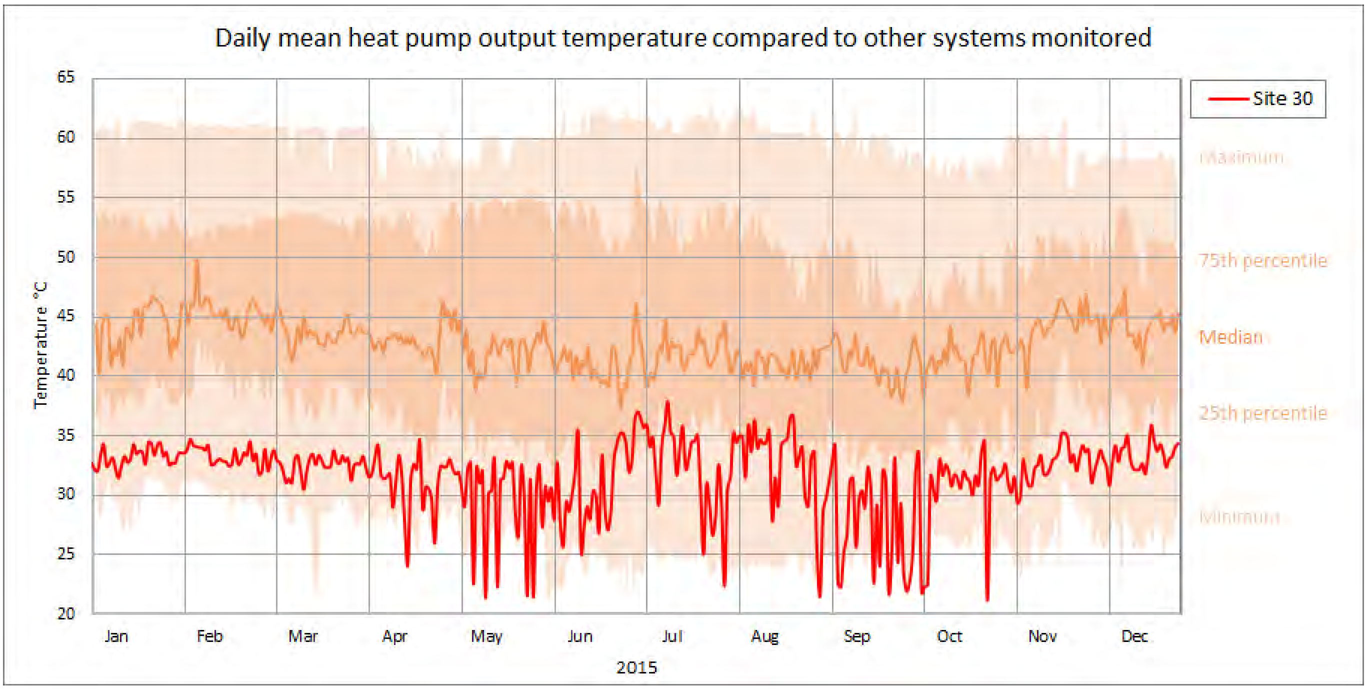

Figure 13 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 30 is shown in red)

Figure 14 shows how the output temperature of this system compares to other heat pump systems that use underfloor heating. The temperatures on this system (plotted in red) were low (below the 25th percentile), which would have had a positive influence on system performance.

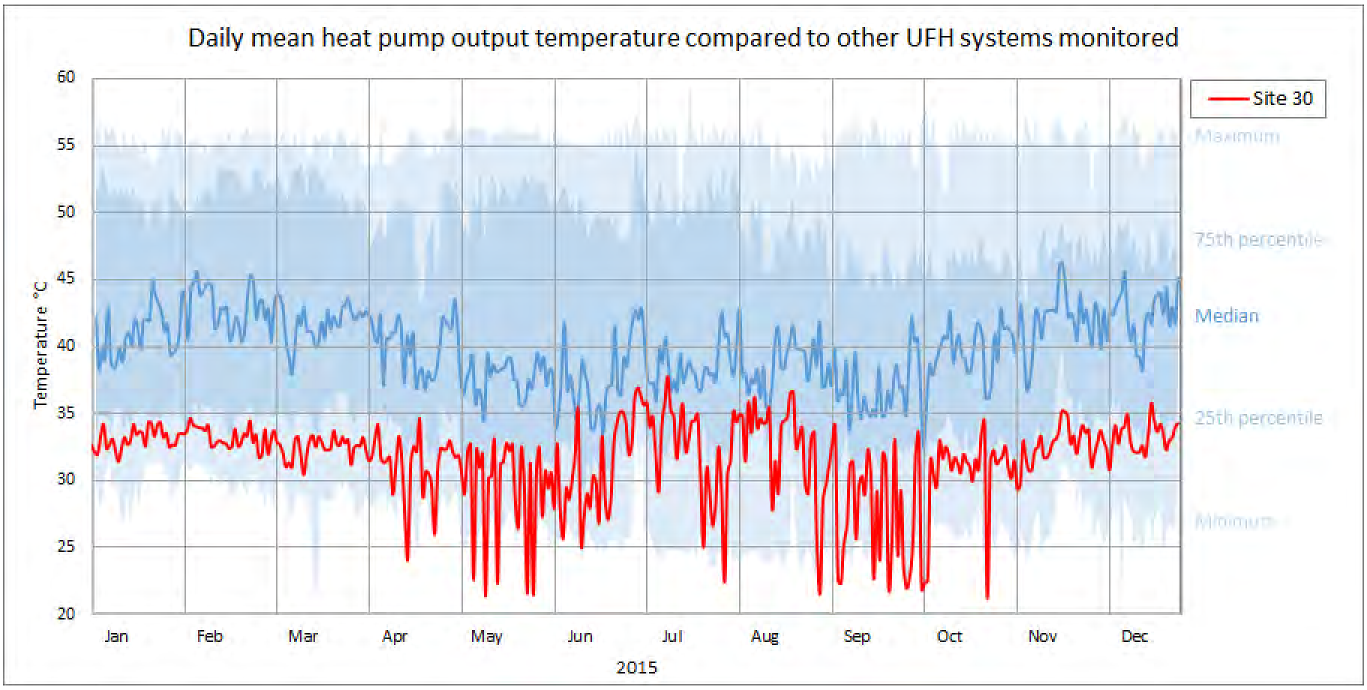

Figure 14 – Daily mean heat pump output temperature (to space heating) compared to those of other systems using underfloor heating monitored in this project (site 30 is shown in red)

Comments

This system had the best performance (SPF_{H4} = 3.13) of all systems providing both space heating and domestic hot water that were monitored in this project (SPF_{H4} range: 1.54 to 3.13, median value 2.41).

Aspects of this system that positively influenced its performance are:

- The temperature of the output to the underfloor heating was below average compared to other systems monitored (second lowest of all systems).
- The brine pump used 4.1% of the electricity used by the total heat pump system, which was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The loss of temperature through the 4-pipe buffer tank was low – generally less than 1°C.

Aspects of the system that may have negatively influenced its performance include:

- The heating circulating pumps appeared to be run more than necessary, especially during the summer months.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 33

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 33 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 33 is a small healthcare practice in a rural location. A ground-source heat pump provides heat to underfloor heating and to domestic hot water from a desuperheater. The heat source is horizontal ground loops installed in a field adjacent to the building.

Aspects of this system that positively influenced its performance are:

- The source temperature was above average compared to other systems.
- The temperature of the output to the space heating system was the lowest of all systems monitored.
- The use of a desuperheater to provide domestic hot water allows the heat pump to operate with low temperatures for the main output to space heating.
- No auxiliary heat was used.

Aspects of the system that may have negatively influenced its performance include:

- The heating circulating pump was run continuously throughout the year, using an estimated 19% of the total electricity. It is not known whether this is required for correct operation of the heat pump, but if the circulating pump could be switched off at times when there is no demand for space heating, a worthwhile improvement in system performance could be realised.

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[1] The heat meter installed on this system measures only the output to space heating. A significant proportion of the output is provided to domestic hot water. As this cannot be reliably estimated, it is not possible to present performance values for this system.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
Desuperheater	A heat exchanger that removes heat from superheated gas discharged from a compressor. This provides a small amount of heat at a temperature which is higher than that of the main condensation process.
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**33**
Survey date	13/03/2014
Monitoring installed	09/07/2014
G/WSHP	GSHP
Building type	Healthcare practice
Location	Rural
Heat pump capacity kWTH	10
Number of heat pumps	1
Number of compressors	1
Heat source	Horizontal ground loops: 500m
Heat emitters	Underfloor heating pipes
DHW	Yes – provided by desuperheater
Auxiliary heat	6 kW immersion heater in heat pump
Source pump	Internal to heat pump: 100 W
SH circulating pump	Internal to heat pump : 100 W
Buffer tank	Internal to heat pump: 420 litres
DHW cylinder	None (DHW is provided via a coil inside the buffer tank)
Control	Heat pump controller + room thermostats
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	1
Heat meter interface	Pulse (1 kWh/pulse)
Comments	The DHW output is not metered

Table 1 – System details

The site is a small healthcare practice. The building is in a rural location and was built in 2012. The ground-source heat pump was installed as original equipment.

This application entails extracting heat from the ground to provide space heating and domestic hot water to a modern well-insulated building in a location with an average outdoor temperature – annual mean 10.5 °C (the range for all systems monitored was 8.1 – 12.5 °C, median 10.3°C). The performance of the system would be expected to be good.

Heat pump and monitoring systems

The ground-source heat pump (thermal capacity 10 kW) provides space heating (SH) and domestic hot water (DHW).

The heat source is 500 metres of horizontal pipe buried at a depth of approximately 1.2 metres, in a field adjacent to the building.

The heat emitter is underfloor heating pipes.

The heat pump has an internal buffer tank that is arranged as two interconnected compartments, one above the other. This provides stratification of the hot water produced by the heat pump, with the upper compartment being heated to a higher temperature than the lower one by using the heat available from the desuperheater, as described below. Domestic hot water is provided via a heat exchanger coil inside the buffer tank. Cold mains water drawn through this coil is heated at the time of use.

A 6 kW immersion heater in the internal buffer tank can provide auxiliary heat if required. This heater was not used during the monitoring period.

Desuperheater for domestic hot water

The heat pump provides DHW by means of a desuperheater. This is a small heat exchanger in the heat pump which removes heat from the superheated vapour discharged by the compressor before it passes to the condenser. This technique allows a small amount of heat to be delivered at a high temperature while the main condensation process (where most of the heat is delivered) can operate at the lower temperature needed for space heating, thereby helping to improve overall performance.

It was not possible to meter the heat delivered to DHW. Reference to the thermodynamic properties of the refrigerant used in the heat pump (R407C) indicates that a maximum of approximately 8% of the total heat output could be delivered through the desuperheater. If no DHW were ever used, this superheat would be included in the output to space heating. However, it is also possible that more than 8%[2] of the total heat output of the heat pump was used for DHW, especially as the site is a healthcare practice where relatively large amounts of hot water would be needed for cleaning and hand washing.

System schematic

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures (“T”) were monitored at key points in the system using surface-mounted probes[3]. The outdoor air and ground temperatures were also monitored.

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[2] Heat to DHW is not necessarily all provided by the superheat.

[3] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

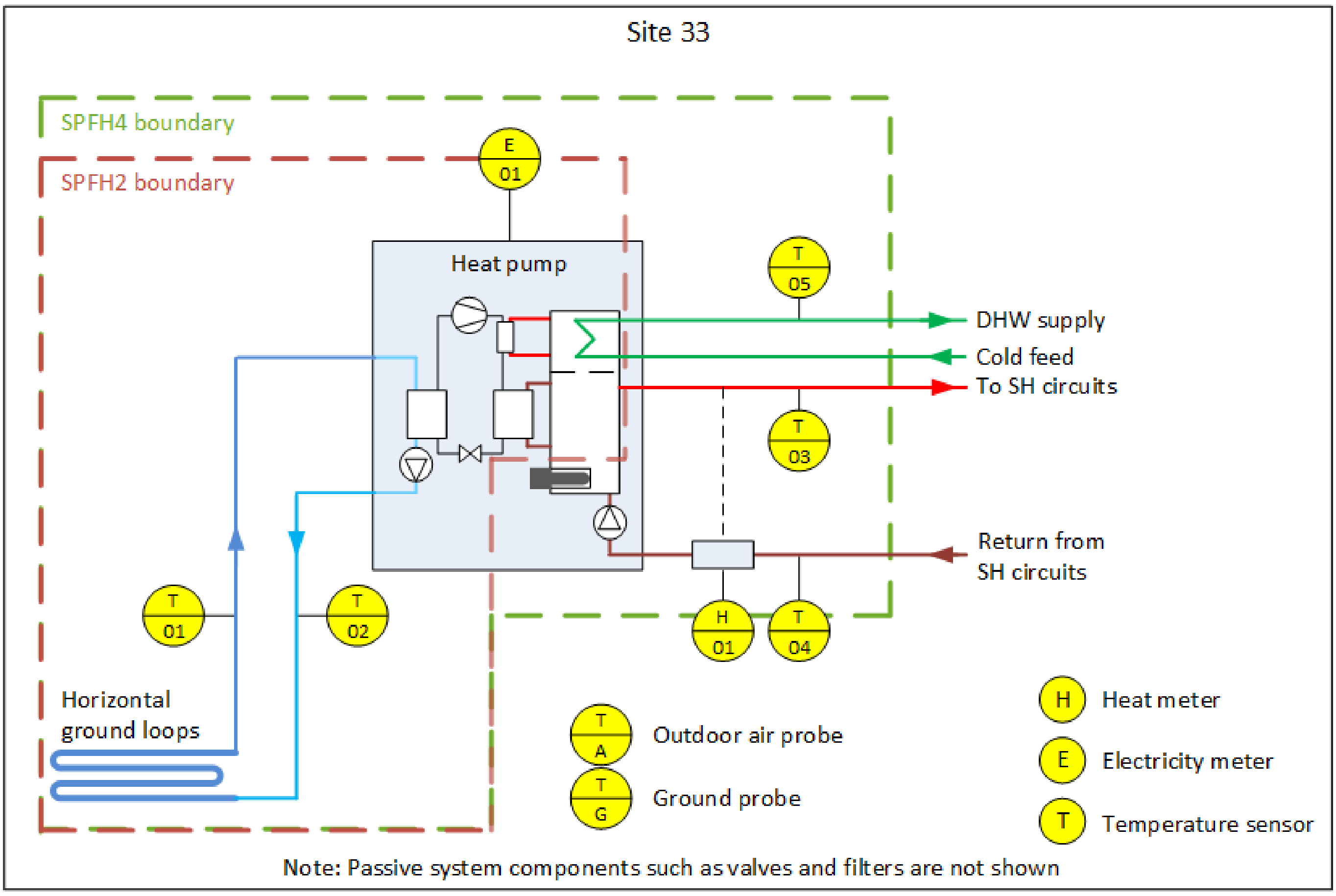

Figure 1 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the space heating circuit. It uses an ultrasonic flow meter installed in the return pipe, with matched temperature sensors installed in pockets in the flow and return pipes. The calculator is battery-powered. Monitoring was via the pulse interface.

Estimate of heat delivered to DHW

The heat meter does not measure the heat provided to DHW. An approximate estimate can be made from the hot-water draw-offs determined from the temperature data – by inspecting the value and rate of change of T05, as illustrated in Figure 2.

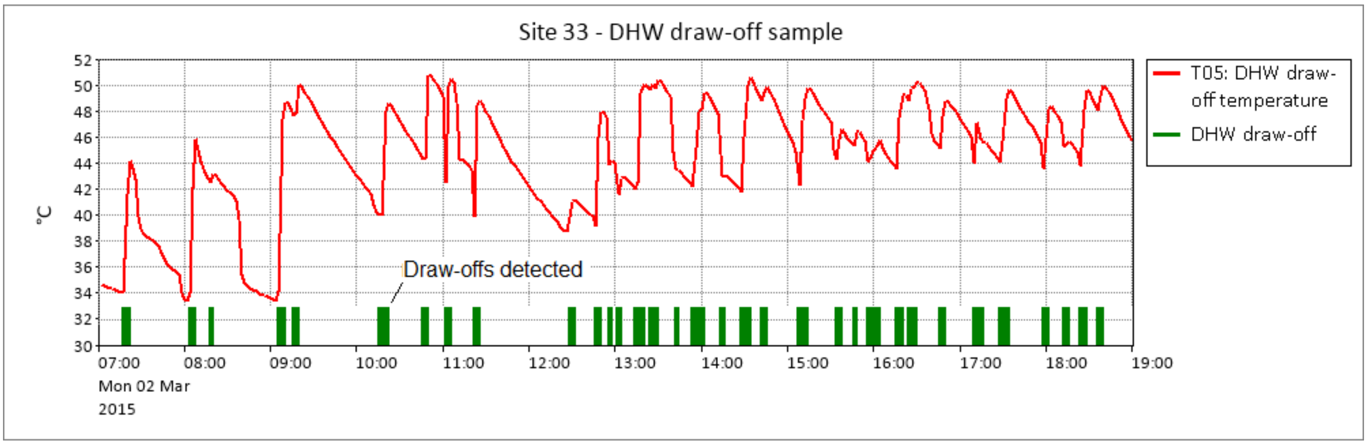

Figure 2 – Sample of DHW draw-off detection using the T05 temperature data

The temperature readings were recorded every 2 minutes, which is probably longer than many draw-offs, so this technique is unlikely to be very accurate. It does however provide an indication that the heat provided to DHW is at least 20% of the total heat output and possibly considerably more.

The uncertainty of this estimate is too high to allow the overall SPF values to be calculated with acceptable accuracy.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump including the internal brine pump but excluding the internal heating circulating pump and the immersion heater.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[4] procedures tailored to suit this heat pump system.

Indicative SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.
- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

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[4] Structured Query Language: a programming language used for managing data held in a relational database management system.

$$SPF_{H2} = \frac{\text{[Heat measured by heat meter] + [heat loss from buffer tank] + [heat output to DHW]} \atop \text{– [heat added by heating circ pump] – [heat added by immersion heater]}}{\text{Electricity used by: [heat pump incl. brine pump] – [buffer pump] – [immersion heater]}}$$

- This calculation required the electrical energy used by the heating circulating pump and the immersion heater inside the heat pump to be subtracted from the heat pump electricity meter readings. The circulating pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running. The immersion heater power was determined by digital filtering using the instantaneous power and power factor readings from the electricity meter.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured temperatures of the outputs to SH and to DHW at each calculation interval to determine the temperature in the tank and an assumed temperature inside the heat pump casing of 20 °C.

- The heat added by the heating circulating pump was estimated as 30% (the assumed pump efficiency[5]) of the electrical energy supplied to the pump.

$$SPF_{H4} = \frac{\text{[Heat output of heat pump to SH \& DHW]}}{\text{Electricity used by: [heat pump including internal pumps and immersion heater]}}$$

The number of 1-minute intervals selected as valid for analysis was 524 353, which represents 99.8% of the 12-month period.

SPF results presented as relative values

Because of the heat metering issues noted above, the performance factors SPF_{H2} and SPF_{H4} are therefore presented in this case study as “relative” values, whereby each value is shown as an amount above or below a nominal performance.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} behaviour[6] of the system. The lower values during the summer months are due to the heat pump providing mainly domestic hot water (which is not metered), or very small amounts of space heating. The run times during this period were short, but the heating circulating pump was always running, and the overall system efficiency was low. However, as the total heat delivered during the summer was low, the effect of these low SPF values on the overall annual performance is quite small.

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[5] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[6] The actual values are not shown. The relative values are plotted to give an indication of the behaviour

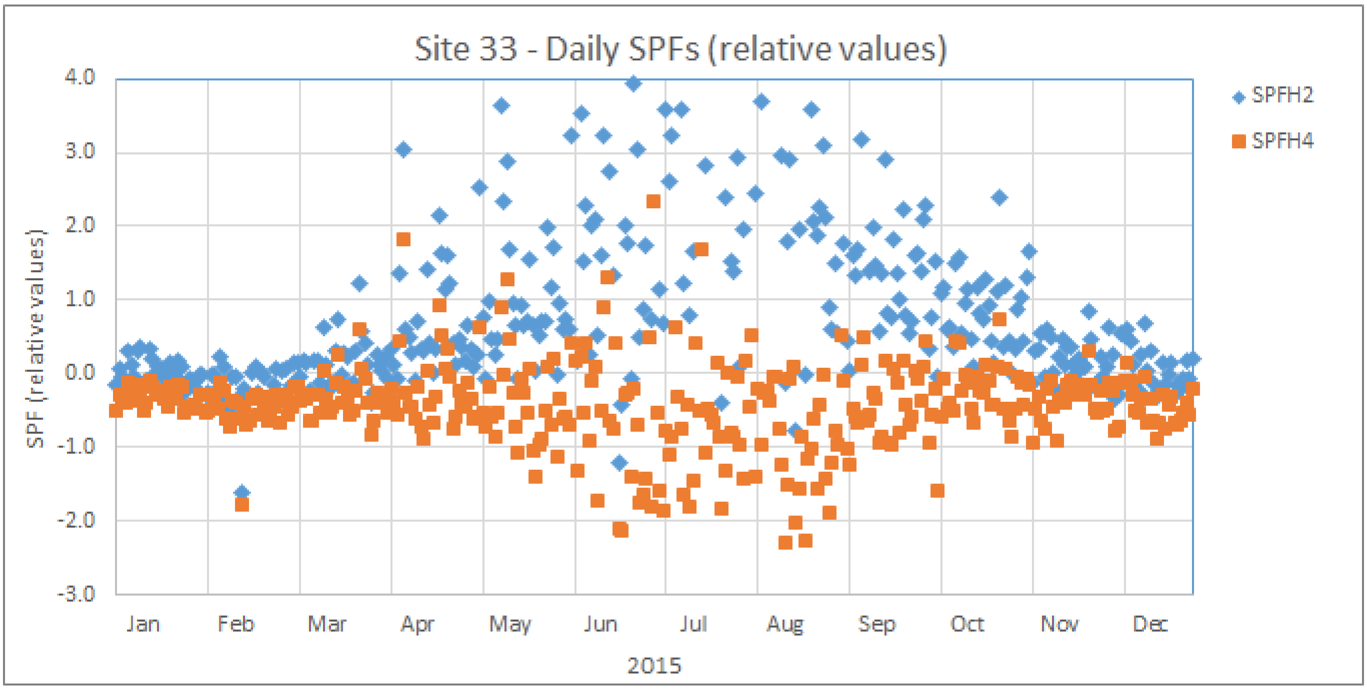

Figure 3 – Seasonal performance factors SPF$_{H2}$ and SPF$_{H4}$ calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the heat output from the heat pump. The heat to space heating was measured by the heat meter; the heat to domestic hot water was estimated as described above. Note that the kWh values have been removed from the graph because of the uncertainty of measurement of the heat provided to DHW.

The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The heat output during the summer months was low, but not zero even on the warmest days.

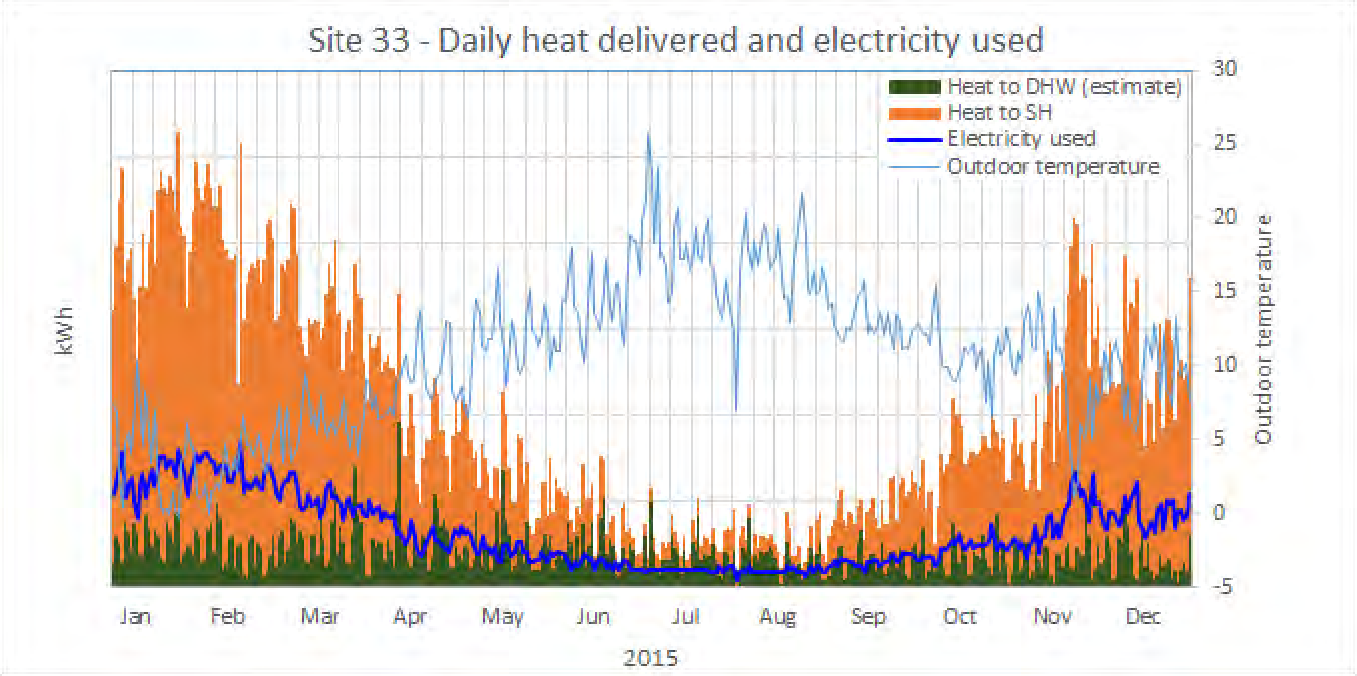

Figure 4 – Daily heat delivered and electricity use by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The data for the brine pump and the space heating circulation pump have been estimated from the pump ratings. The space heating circulation pump ran continuously all year, whereas the brine pump ran only while the heat pump compressor was running.

The brine pump accounted for 2.3% of the total electricity which is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

The heating circulating pump used 18.6% of total electricity, which is well above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a negative influence on the system performance.

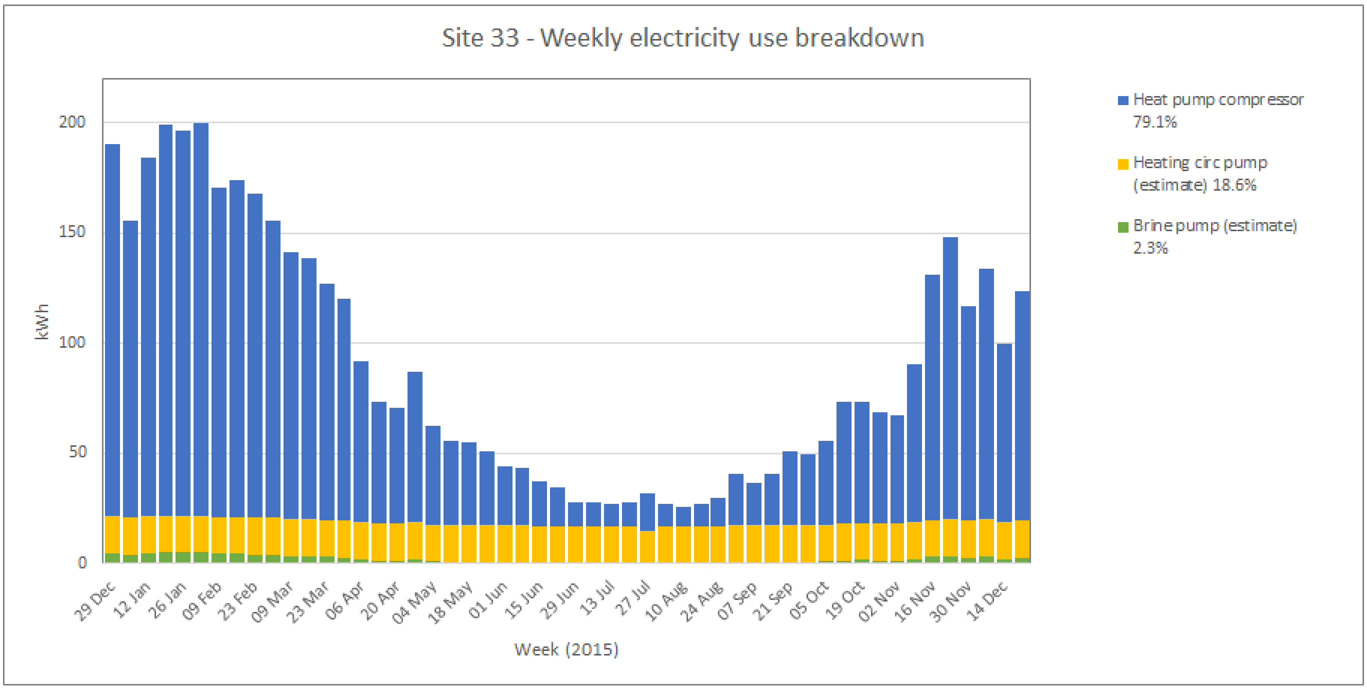

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated the heat pump supply power graph.

Figure 6 shows the operating pattern during a cold day on 20th January 2015.

The outdoor air temperature was between -5 and +5 °C, the ground temperature (at a depth of 1 metre, remote from the ground loops) was 6 °C and the brine flow to the heat pump (while it was running) was 5.5 °C.

The output to space heating was between 31 and 32 °C, and the output to domestic hot water (while hot water was being drawn off) was at a maximum of 51 °C.

The heat pump cycled approximately twice every hour, and ran for 12 - 14 minutes each time. This was well within the limits for short cycling recommended from previous research [2].

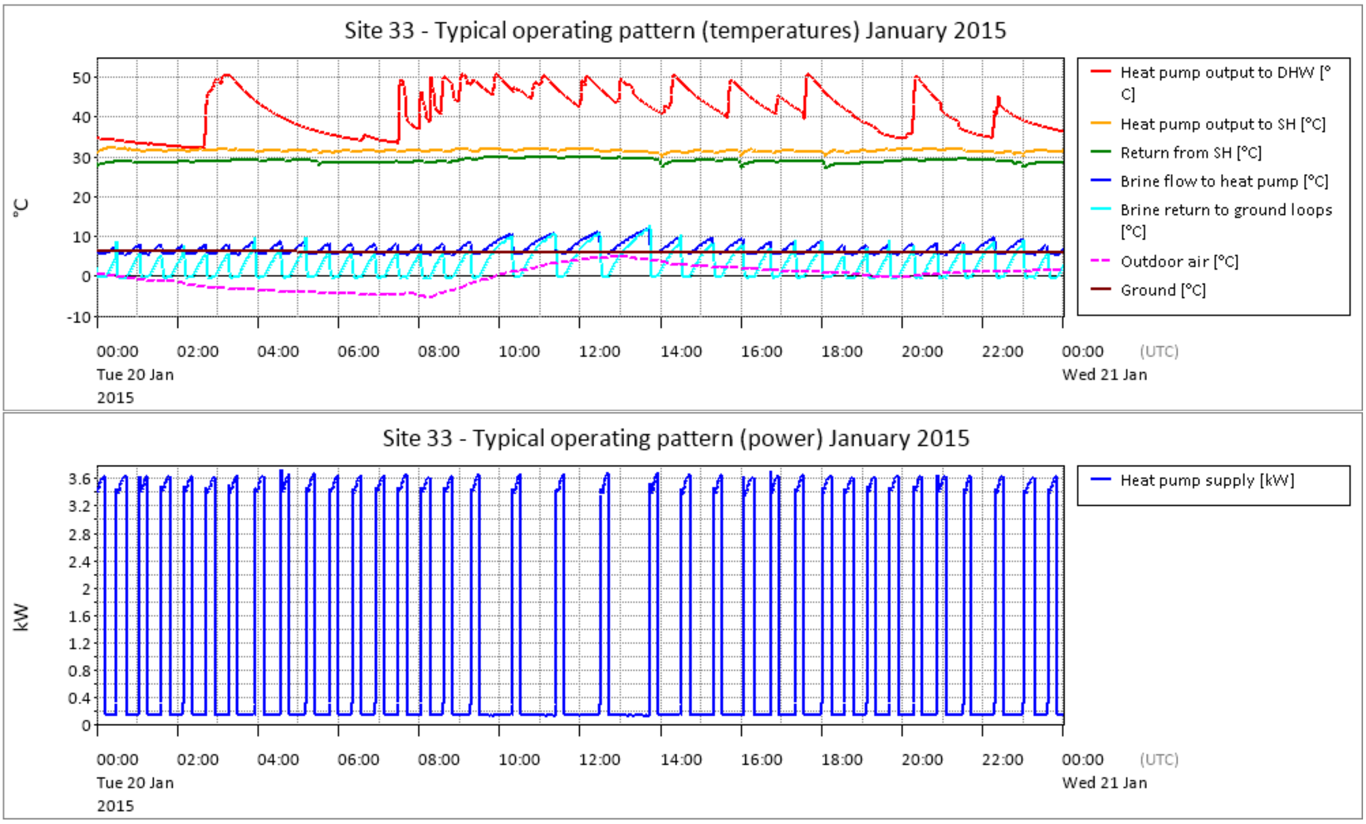

Figure 6 – Operating pattern on 20th January 2015

Figure 7 shows the operating pattern for a warm day on 20th July 2015, when the outdoor air temperature was between 7 and 28 °C. The ground temperature was 15.5 °C, and the brine flow to the heat pump while it was running was between 15.5 and 15.8 °C. The output to domestic hot water was up to 54 °C.

The heat pump ran once only during the day, for 21 minutes – apparently to replenish the temperature in the domestic hot water tank in the heat pump. There was also some heat output to space heating: the heat meter recorded 4 kWh during the day (four 1 kWh pulses were recorded several hours apart). The temperature of the flow to the underfloor heating pipes was fairly steady all day at around 25 °C.

The heating circulating pump was running continuously. This would have caused any heat rejected to the internal buffer tank to be circulated to the underfloor heating pipes. The pump would also have added a small amount of heat: it is a nominal 100 W pump, so allowing for 30% of this power being added as heat to the water, it would have added around 0.7 kWh.

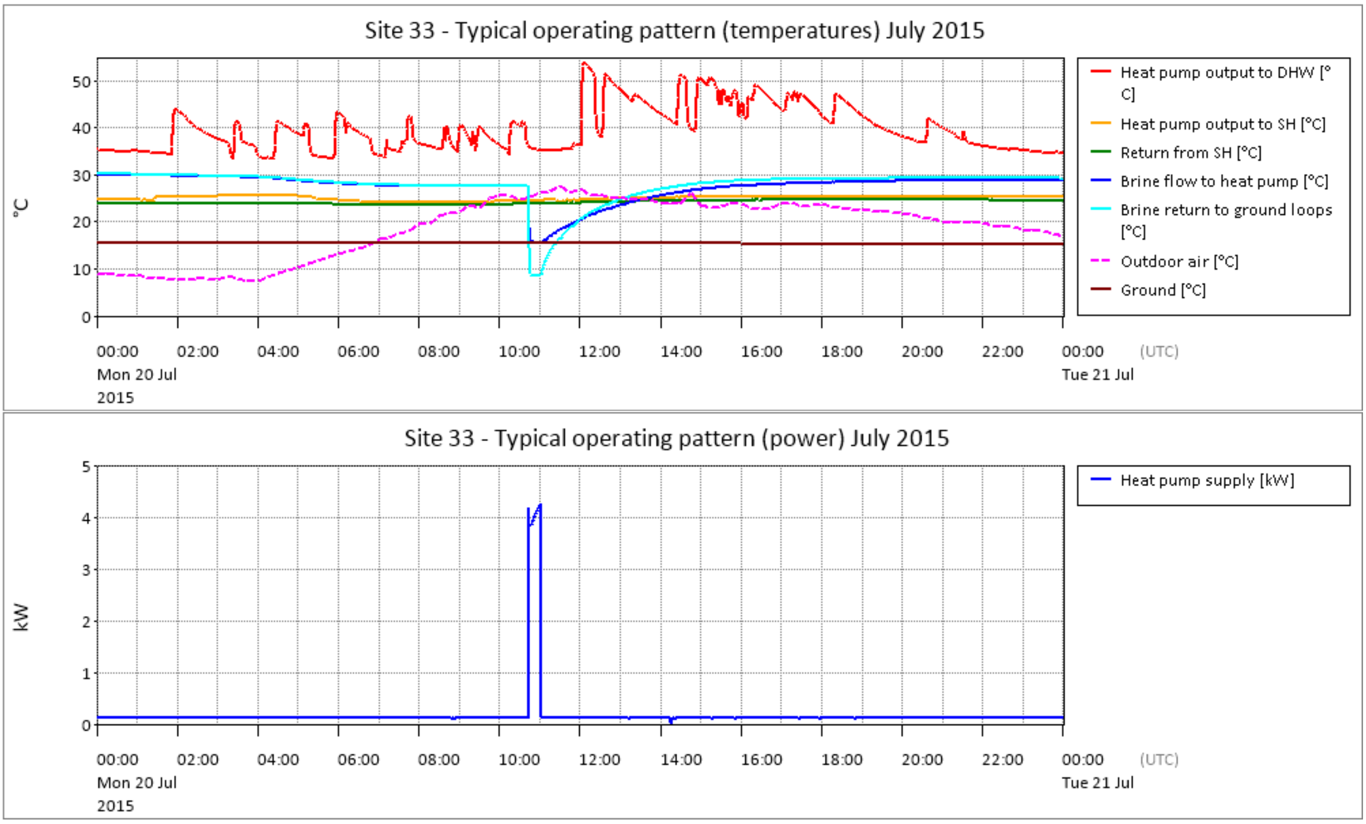

Figure 7 – Operating pattern on 20th July 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[7]. For clarity, the brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The temperature of the output to the underfloor heating reached a maximum of 32 °C during the coldest weather in January, February and November. The effect of the weather compensation function can be seen, with reduced output temperatures during warmer weather.

The domestic hot water output temperature was rarely above 50 °C, but it is noticeable that the domestic hot water temperature did not affect the temperature of the space heating output. This is presumably a consequence of the higher temperature needed for domestic hot water being provided by the desuperheater. This should have a positive influence on the system performance.

The temperature of the brine flow to the heat pump was never more than 1.5 °C below the ground temperature[8]. This suggests good ground collector design.

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[7] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

[8] The ground temperature was measured 1 metre below the surface at a location remote from the collector loops.

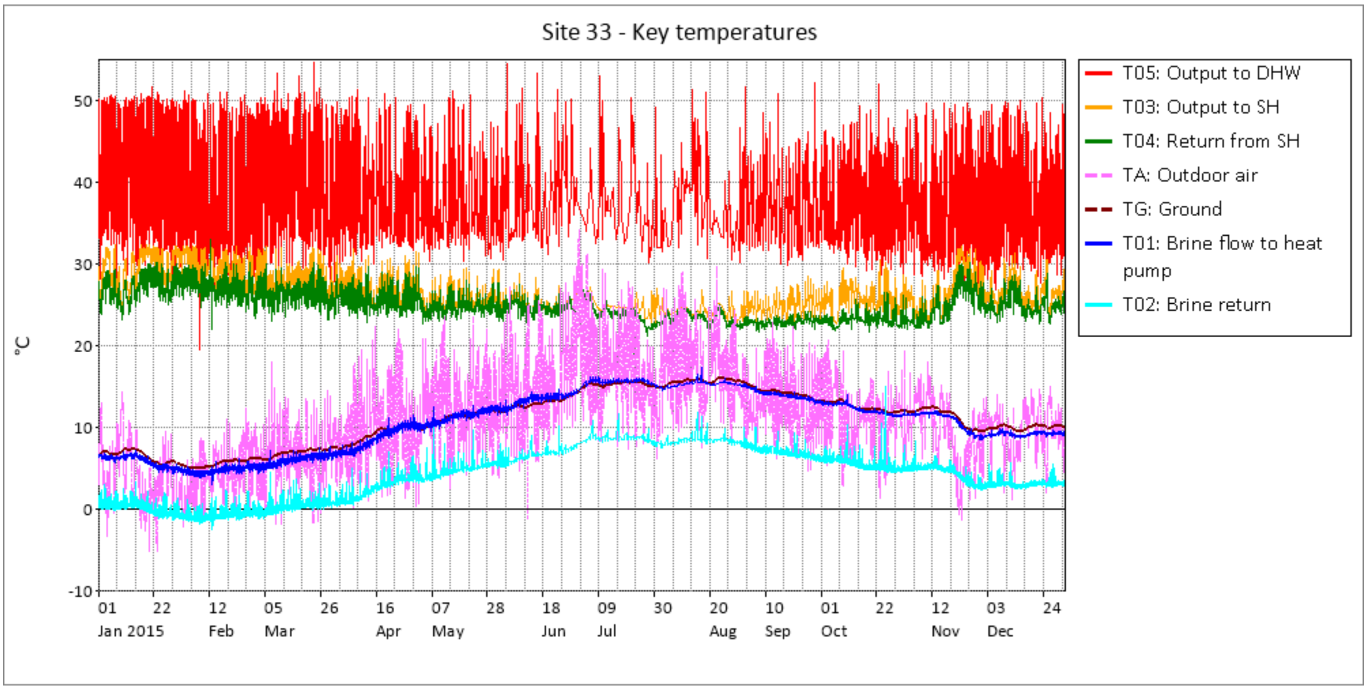

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) are above average, which would have had a positive influence on the system performance.

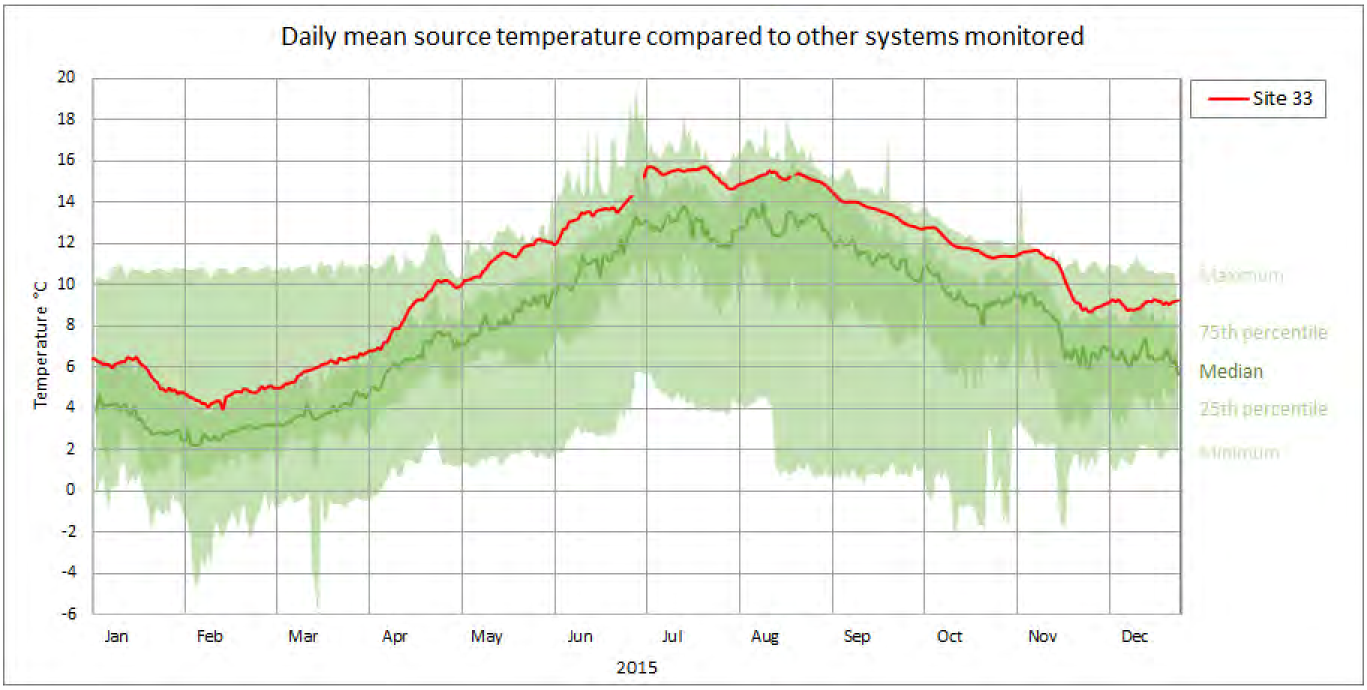

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 33 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The low temperature difference on this system indicates good collector performance.

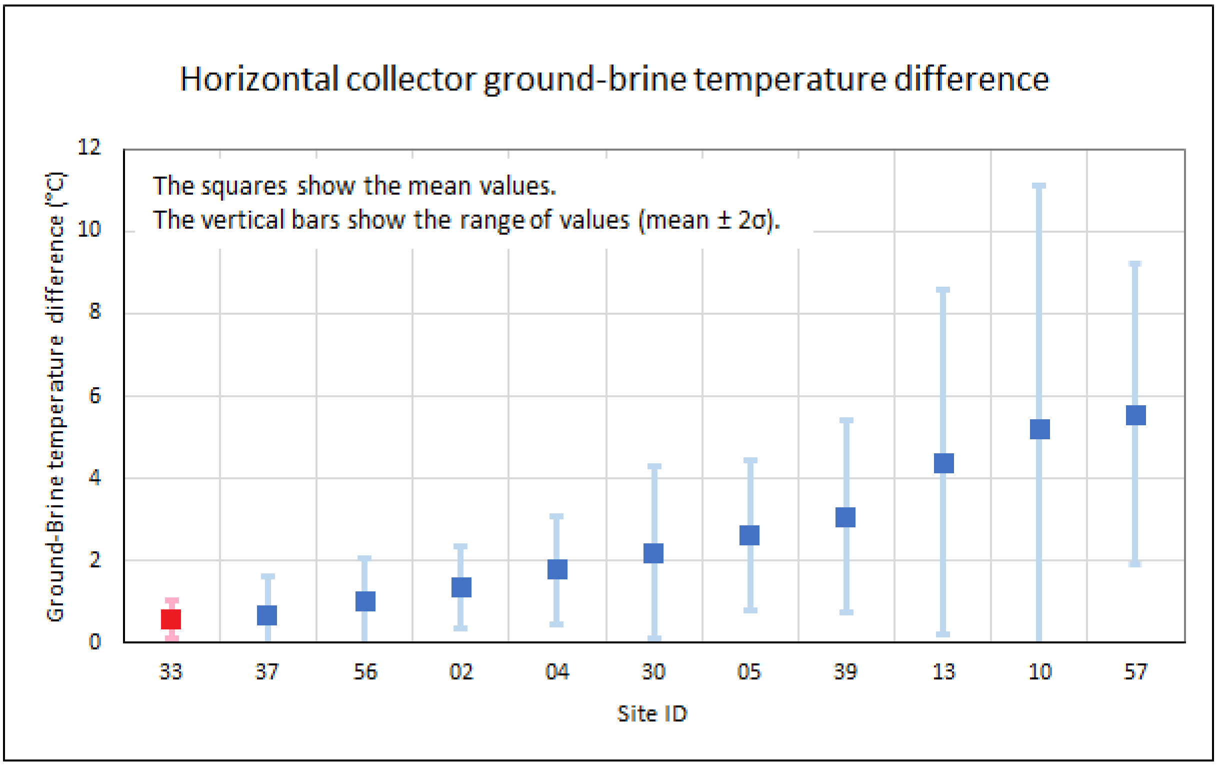

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 33 is shown in red)

Figure 11 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures were the lowest of all installations. This would have had a positive influence on the system performance.

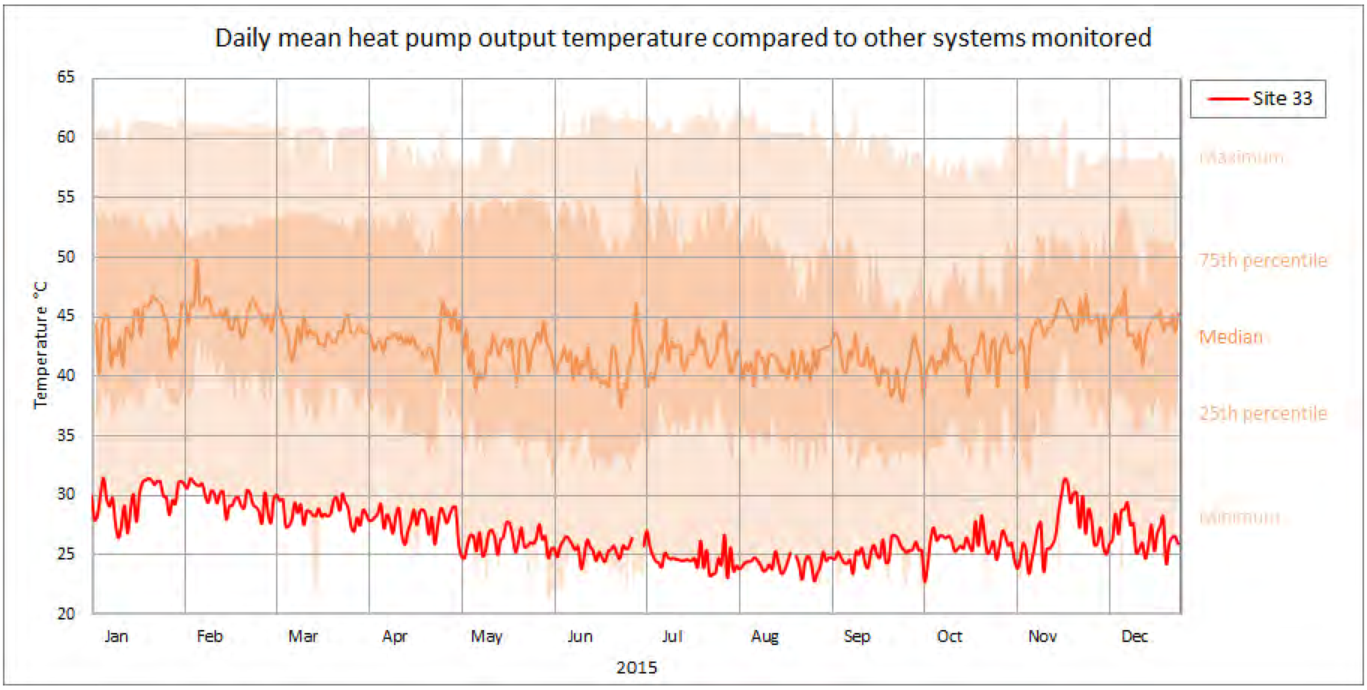

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 33 is shown in red)

Figure 12 shows how the output temperature of this system compares to other heat pump systems that use underfloor heating. The output temperatures on this system (plotted in red) were the lowest of all systems monitored. This would have had a positive influence on system performance.

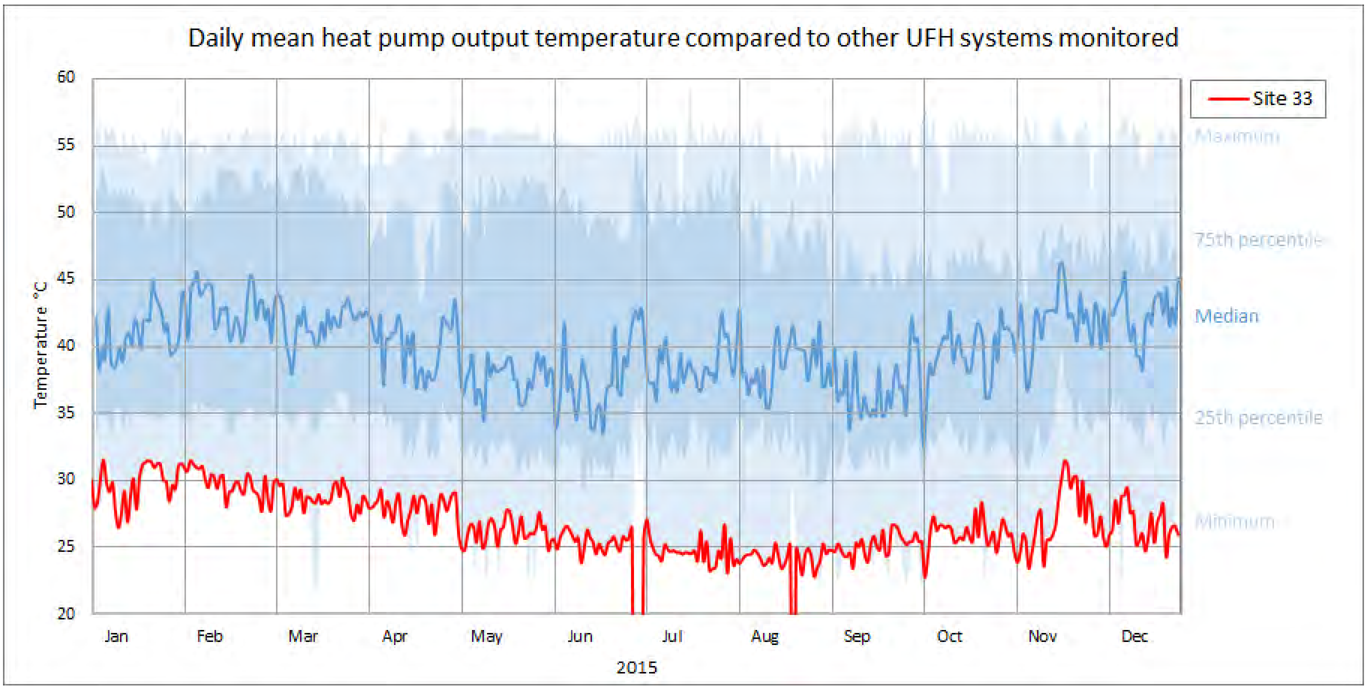

Figure 12 – Daily mean heat pump output temperature (to space heating) compared to those of other systems that use underfloor heating monitored in this project (site 33 is shown in red)

Comments

The performance of this system could not be determined with reliable accuracy because the heat output to domestic hot water was not metered.

Aspects of this system that positively influenced its performance are:

- The source temperature was above average compared to other systems.
- The temperature of the output to the space heating system was the lowest of all systems monitored.
- The use of a desuperheater to provide domestic hot water allows the heat pump to operate with low temperatures for the main output to space heating.
- No auxiliary heat was used.

Aspects of the system that may have negatively influenced its performance include:

- The heating circulating pump was run continuously throughout the year, using an estimated 19% of the total electricity. It is not known whether this is required for correct operation of the heat pump, but if the circulating pump could be switched off at times when there is no demand for space heating, a worthwhile improvement in system performance could be realised.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 34

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 34 and performance results from 12 consecutive months of monitoring data.

Site 34 is a healthcare clinic.

A ground-source reversible heat pump (heating capacity 64 kWTH) extracts heat from boreholes in open ground adjacent to the building and provides heat to an underfloor heating system throughout the 4-storey building. The heat pump is also used for cooling in warm weather.

The seasonal heating performance factors measured over a year of operation
(1st January to 31st December 2015) were:

SPFH2	[Total heat delivered by the heat pump] -- [Electricity used by the heat pump + brine pump]	2.45
SPFH4	[Total heat delivered by the heat pump] -- [Electricity used by heat pump + brine pump + buffer pump + heating circulation pumps]	2.23

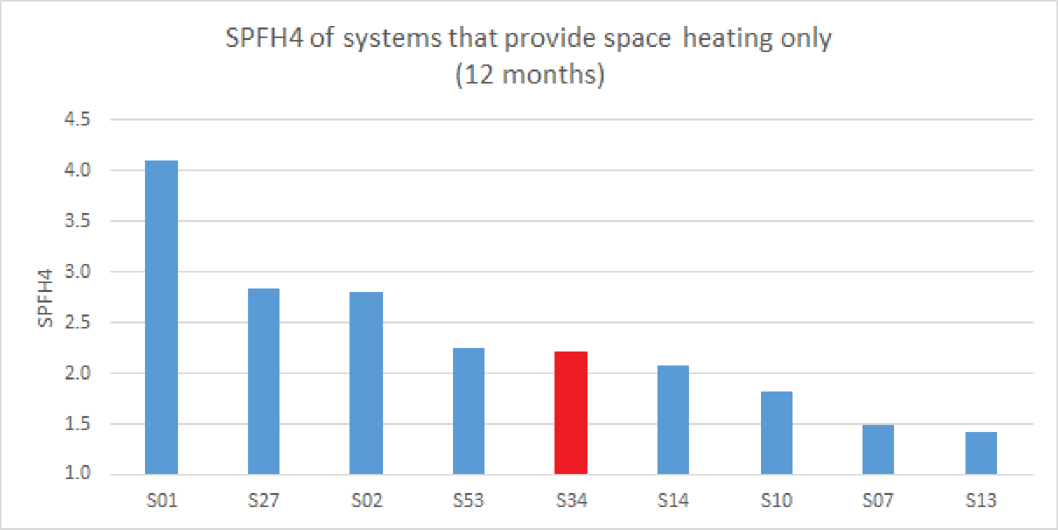

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

Aspects of this system that positively influence its performance are:

- The brine temperature from the boreholes was always above 2 °C, and above average throughout the year, compared to other systems monitored in this project.
- Weather compensation was used from March onwards to reduce the output temperature when the outdoor temperature was higher.

Aspects of the system that may have negatively influenced its performance include:

- The brine pump used 16.6% of the total electricity used by the heat pump system, which was high compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

- The buffer pump and heating circulating pumps used 9.5% of the total electricity, which was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).
- Weather compensation was not used before March, resulting in the heat pump output temperature being higher than necessary.
- Heating and cooling modes were both used during some days in the summer. This should be unnecessary and may have been due to incorrect control settings.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	34
Survey date	14/03/2014
Monitoring installed	14/07/2014
G/WSHP	GSHP
Building type	Healthcare clinic
Location	Urban
Heat pump capacity kWTH	64
Number of heat pumps	1
Number of compressors	2
Heat source	Vertical boreholes
Heat emitters	Underfloor heating pipes
DHW	No
Auxiliary heat	Gas-fired boilers
Source pump	External to heat pump: 1 pump of 3 kW
Buffer pump	External to heat pump: 1 pump of 610 W max
SH circulating pumps	1 pumpset: 2 pumps of 900 W max (duty/standby, variable speed) 1 pumpset: 2 pumps of 450 W max (duty/standby, variable speed)
Buffer tank	1500 litre 2-pipe in flow
DHW cylinder	N/A
Control	BMS + heat pump controller
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	1
Heat meter interface	Pulse (10 kWh/pulse)
Comments	The heat pump is reversible and is used to provide cooling during warm weather. In cooling mode, heat is rejected to the boreholes.

Table 1 – System details

Site 34 is healthcare clinic in a 4-storey building, constructed in 2011. It was designed to be heated and cooled by a heat pump, using underfloor pipes throughout the building.

This application entails extracting heat from the ground to provide space heating and alternately rejecting heat to the same ground to provide cooling in a modern well-insulated building, located in an area with above-average outdoor temperatures – annual mean 11.7 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The heating-mode seasonal performance of the system would be expected to be good.

Heat pump and monitoring systems

A dual-compressor reversible heat pump (thermal heating capacity 64 kW) is installed in a ground floor plant room, to provide both space heating (SH) and cooling during warm weather.

In heating mode, heat is extracted via a brine loop from vertical boreholes[1] in open ground adjacent to the building.

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[1] The number and depth of the boreholes is unknown.

Domestic hot water (DHW) is provided by the gas-fired boilers installed in an upper-floor plant room. Hot water from these boilers can be fed to the underfloor heating circuits if required, to boost the output from the heat pump.

A 1500-litre 2-pipe buffer tank is installed in the flow from the heat pump to the underfloor heating.

Cooling mode

The heat pump is used in cooling mode during warm weather, with heat being rejected to the boreholes.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2]. The outdoor air and ground temperatures are also monitored.

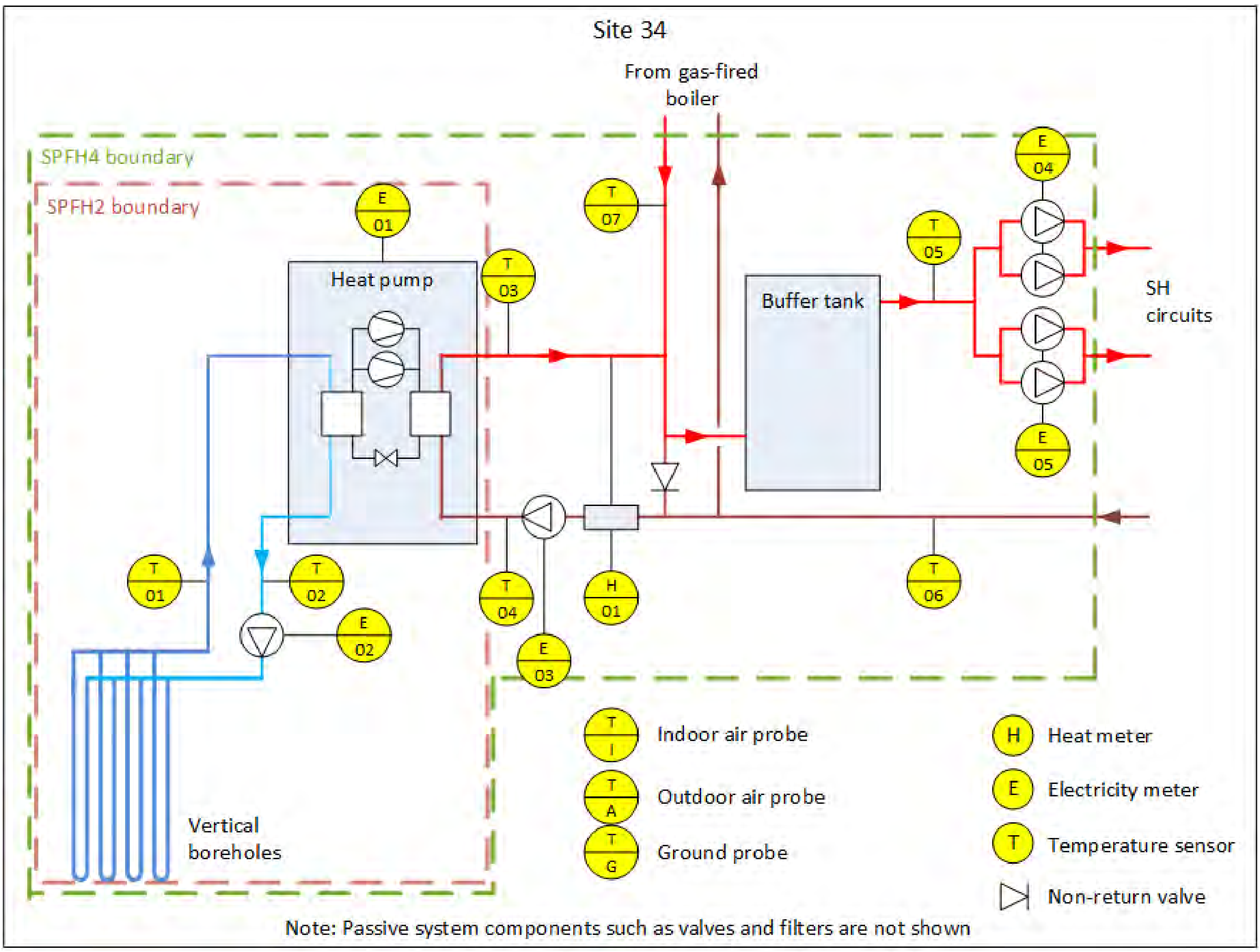

Figure 2 – System schematic showing the monitoring instrumentation installed

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[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses an ultrasonic flow meter installed in the return pipe, with matched temperature sensors installed in pockets in the flow and return pipes. The calculator is battery-powered. Monitoring was via the pulse output.

The heat meter only records heat generated in heating mode.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat measured by heat meter] – [heat added by buffer pump]}}{\text{Electricity used by: [heat pump] + [brine pump]}}$$

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer pump was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pump.

$$SPF_{H4} = \frac{[\text{Heat measured by heat meter}] - [\text{heat loss from buffer tank}] + [\text{heat added by SH circulating pumps}]}{\text{Electricity used by: } [\text{heat pump}] + [\text{brine pump}] + [\text{buffer pump}] + [\text{SH circulating pumps}]}$$

- The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 491 245, which represents 93.5% of the 12-month period. Some of the intervals excluded were for times when the heat pump was operating in cooling mode.

The mean SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPF_{H2}	2.45
SPF_{H4}	2.23

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 2.23 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system in heating mode. Data for all intervals when the system was in cooling mode have been excluded. The higher SPF values after September were due to lower heat pump output temperatures. This appears to have been due to a combination of weather compensation and altered control settings.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

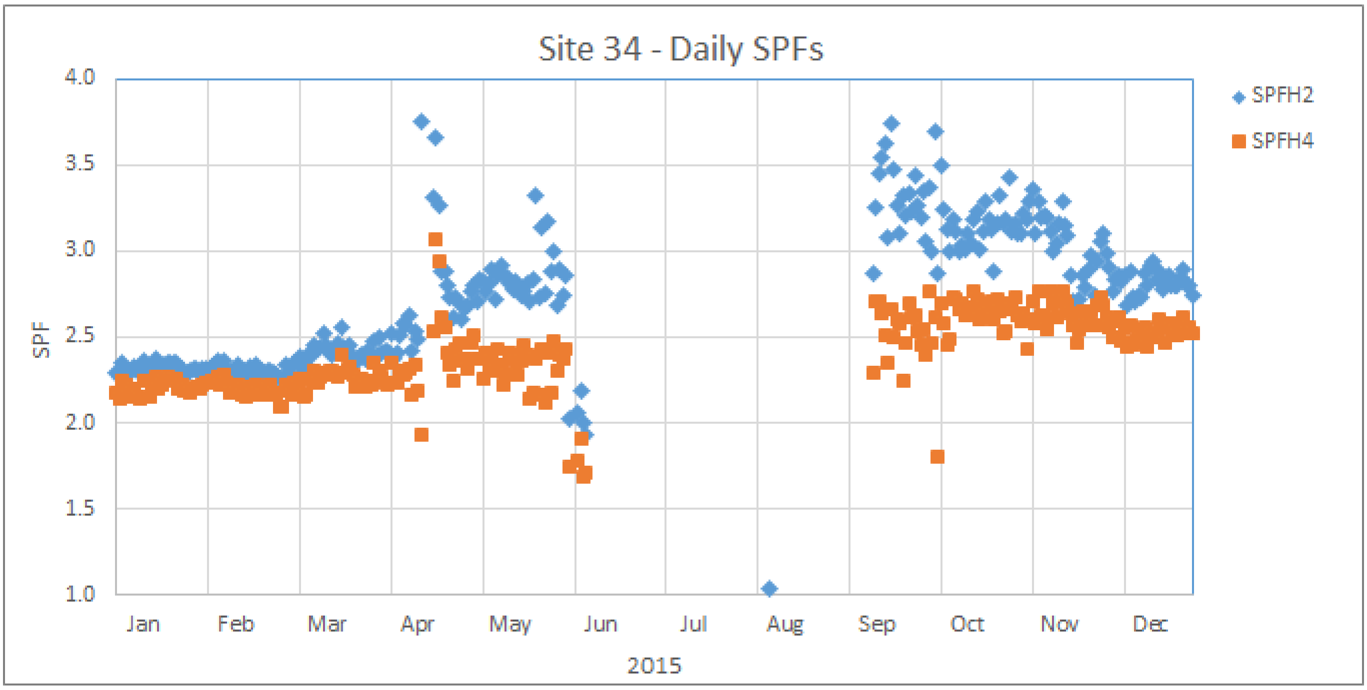

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collectors, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity use by the total heat pump system (excluding cooling mode operation) and the outdoor air temperature are shown for reference. There was very little heat output during the summer months, when the system was operated mainly in cooling mode.

There was no addition of auxiliary heat from the gas boilers at any time during the period monitored.

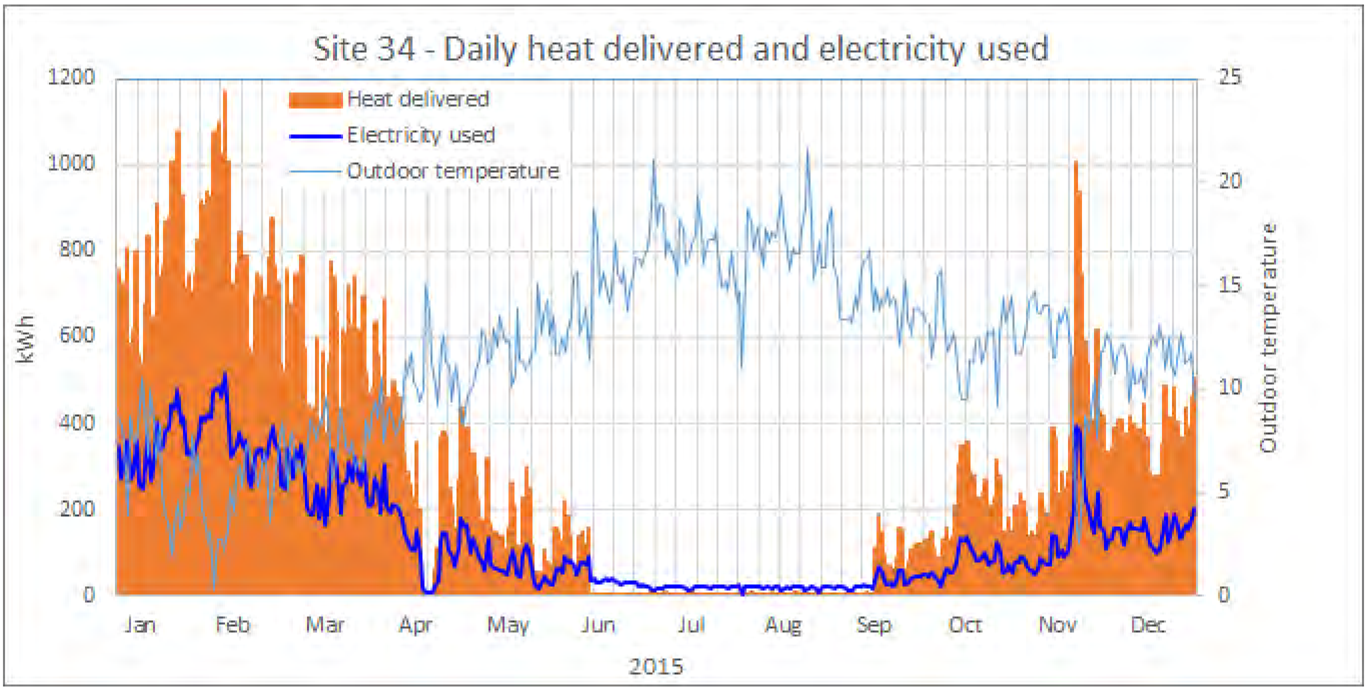

Figure 4 – Daily heat delivered and electricity used by the total heat pump system (excluding cooling mode operation)

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. Data for cooling mode operation has been excluded.

The brine pump used 16.6% of the total electricity, which is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance.

The buffer pump and heating circulating pumps used 9.5% of the electricity, which is above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a negative influence on the system performance.

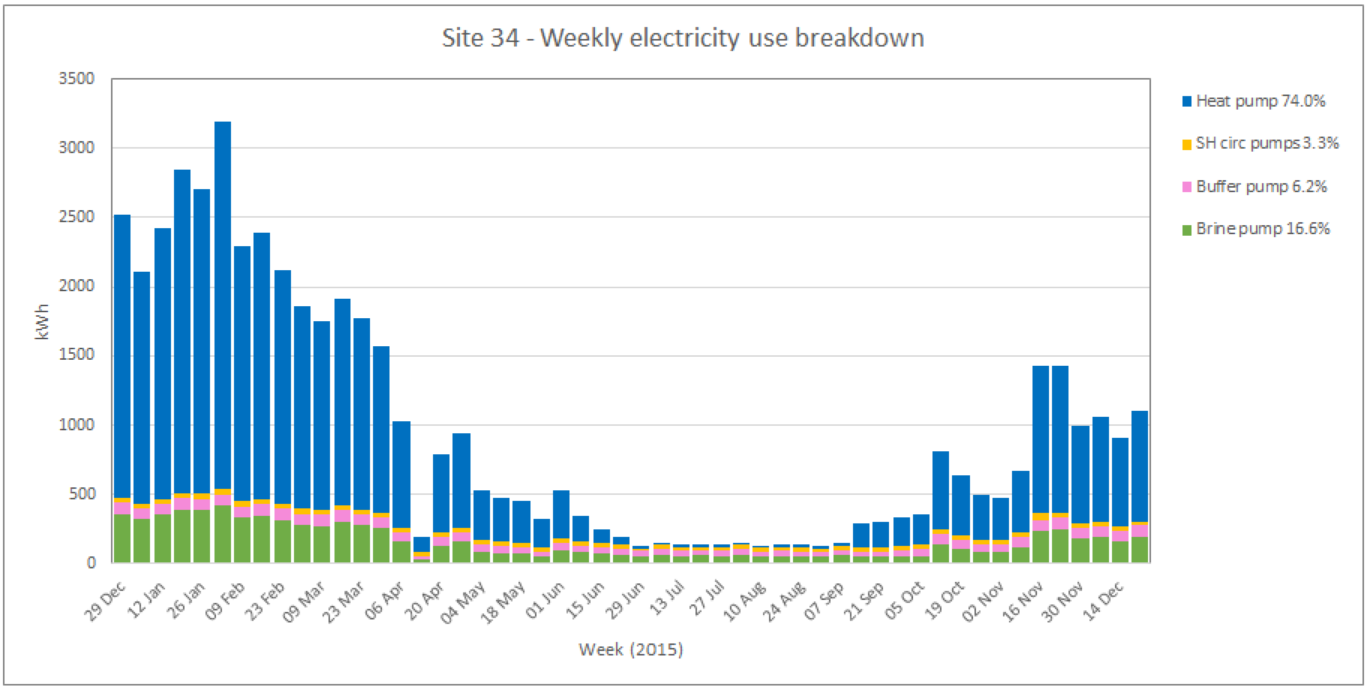

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated the heat pump supply power graph.

Figure 6 shows the operating pattern during a cold day on 23rd January 2015, when the outdoor temperature was between -2 and +8 °C.

Both heat pump compressors were in use until 10:30, by which time the outdoor temperature had risen to 4 °C and the space heating load had reduced sufficiently so that one compressor was sufficient for the rest of the day.

The brine pump and the buffer pump both ran continuously all day. The space heating circulating pump ran from 04:00 to 19:15.

The temperature of the brine flow to the heat pump was fairly constant throughout the day, between 3 and 7 °C while the heat pump was running. The ground temperature (measured 1 metre below the surface, remote from the boreholes) was 5 °C.

The temperature of the output from the heat pump output was between 38 and 52 °C, and there was no measurable loss of temperature through the 2-pipe buffer tank.

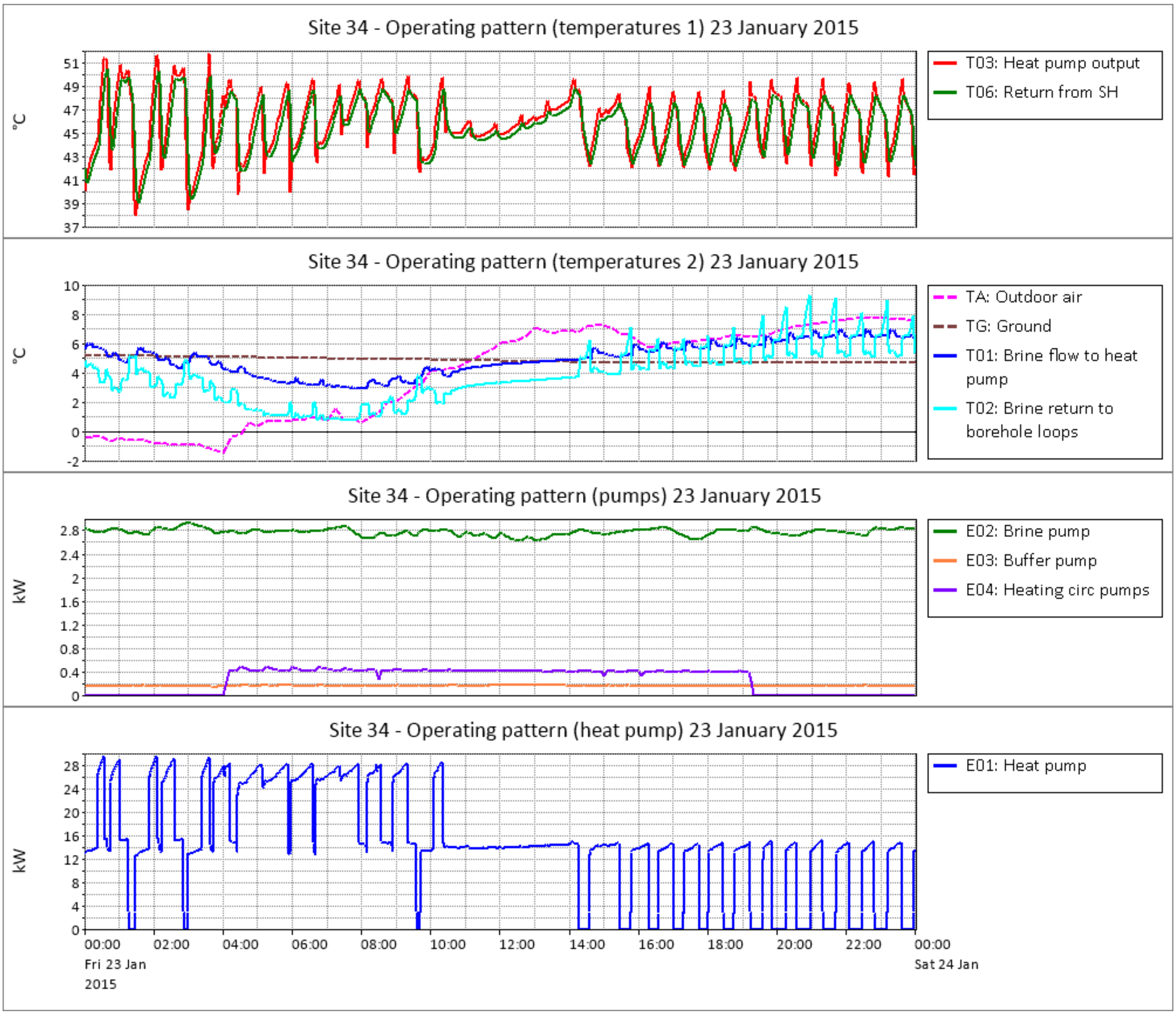

Figure 6 – Operating pattern on 23rd January 2015

Figure 7 shows the operating pattern on 3rd June 2015, when the outdoor temperature was between 12 and 17 °C. The heat pump was reversed into cooling mode between 08:00 and 16:00, as can be seen from the heat pump output temperatures. The heat pump was then off until the end of the day. It is not known why both heating and cooling were used on the same day. This may have been due to an incorrect control strategy or setting.

The brine flow temperature during heating mode was between 9 and 10 °C. In cooling mode, when the system was rejecting heat to the ground, the brine temperature rose to 15 °C. However, when the heat pump reverted to heating mode at 16:30, the brine temperature quickly dropped back to 10.5 °C. The ground temperature was 12.7 °C.

The spikes in the heat pump power graph at 08:30 and 16:50 were probably due the changeover from heating to cooling and back to heating causing large, rapid changes in fluid temperatures in the heat pump.

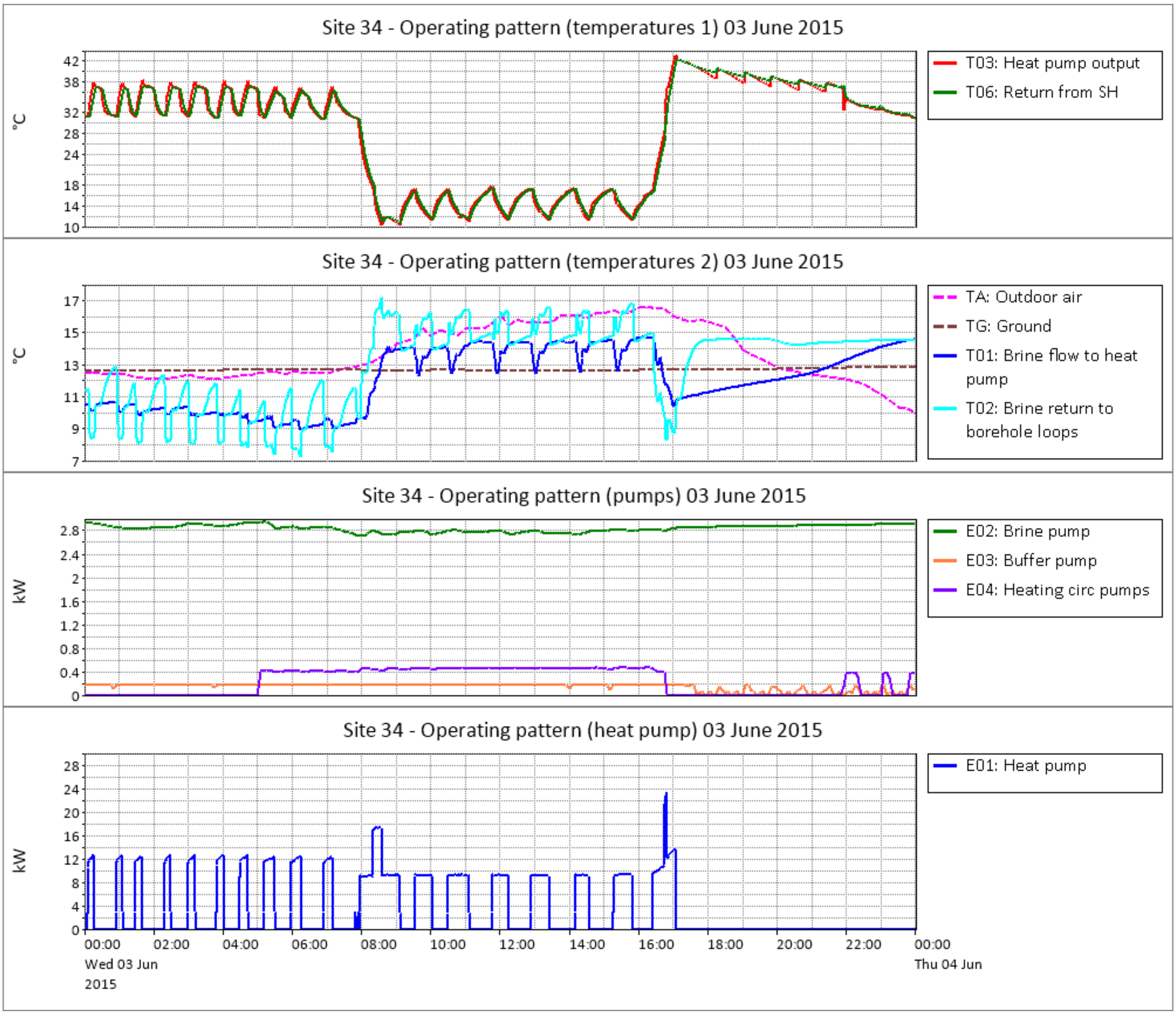

Figure 7 – Operating pattern on 3rd June 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[5]. For clarity, the brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The reversal of the heat pump to cooling mode can be seen during warm weather in April and the summer months. The operation of the weather compensation function can also be clearly seen, with the temperature of the output to space heating reducing as the outdoor temperature rises.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

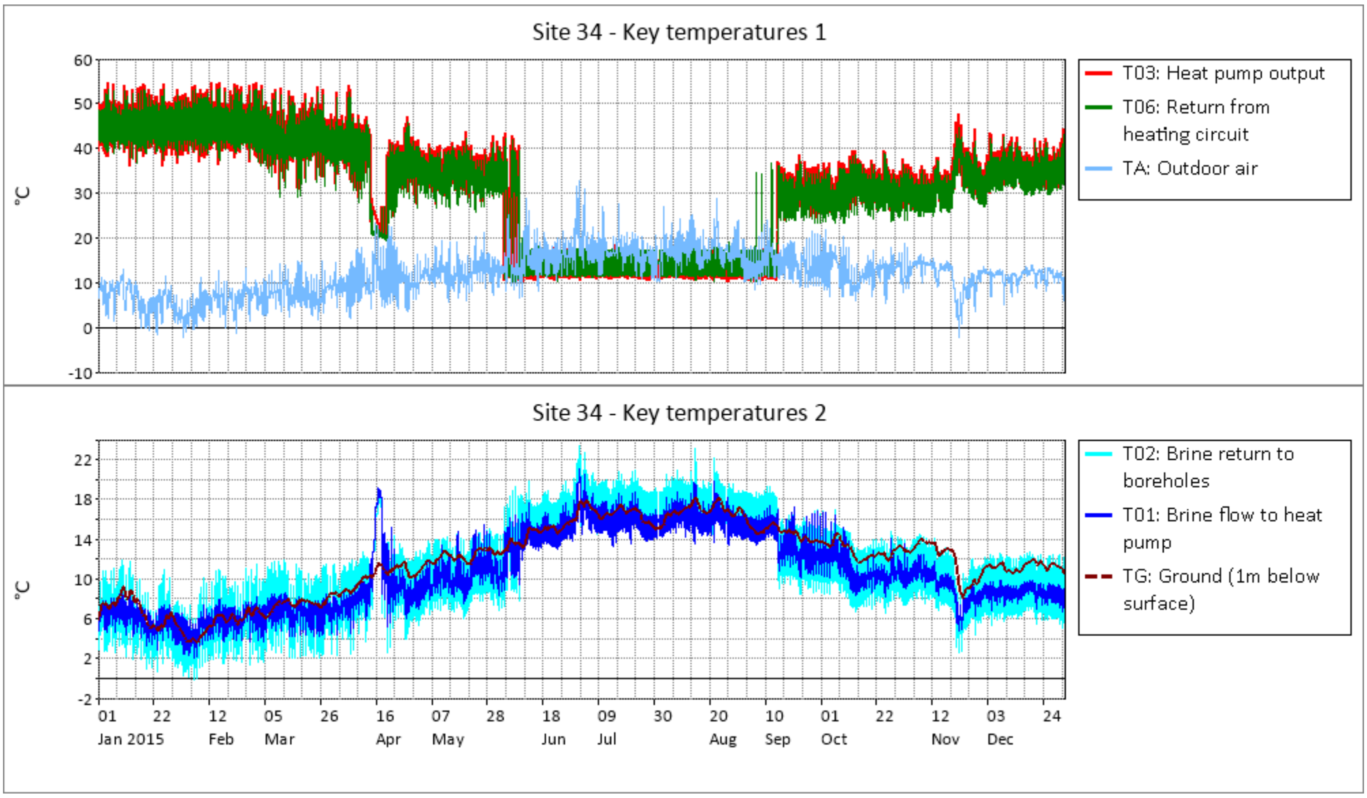

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. Days when the system was operating in cooling mode have been excluded. The temperatures realised on this system (plotted in red) are well above average. This would have had a positive influence of the performance.

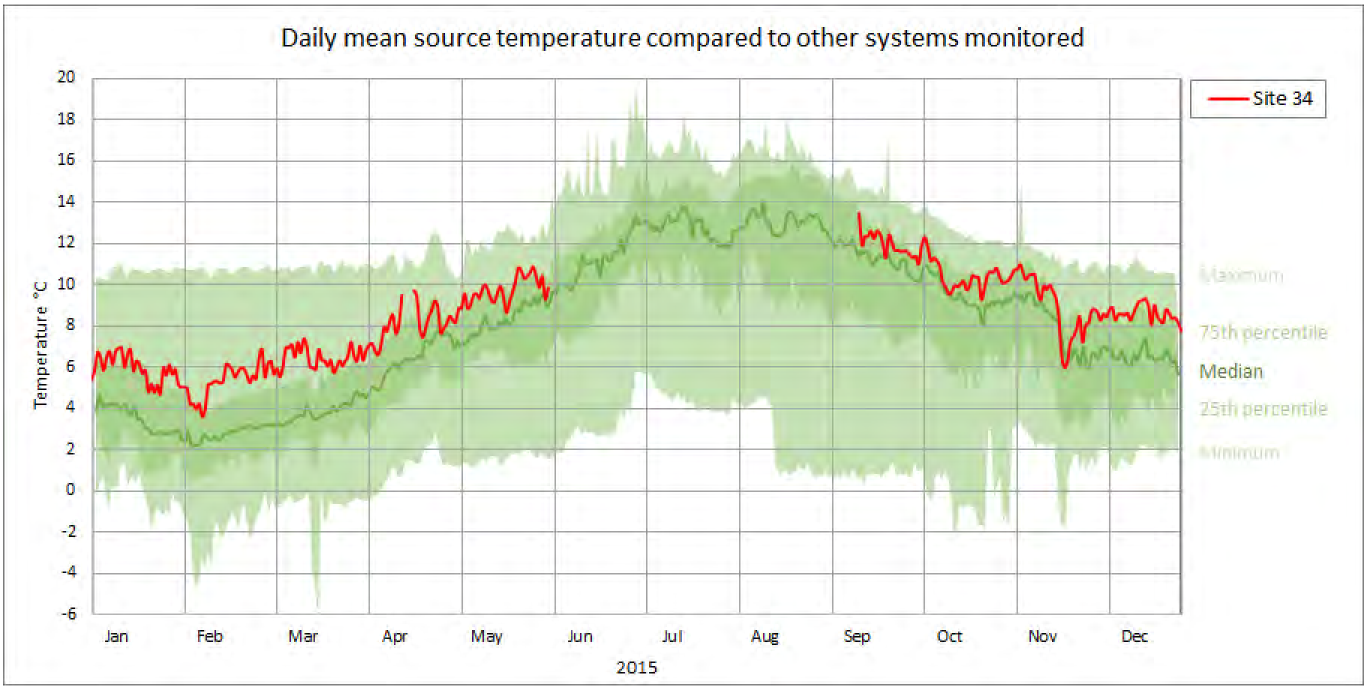

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 34 is shown in red)

Figure 10 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperature range on this system was average during January and February, but reduced after then when weather compensation was used (see the discussion below). The gap in the temperature data between June and September corresponds to the cooling mode operation.

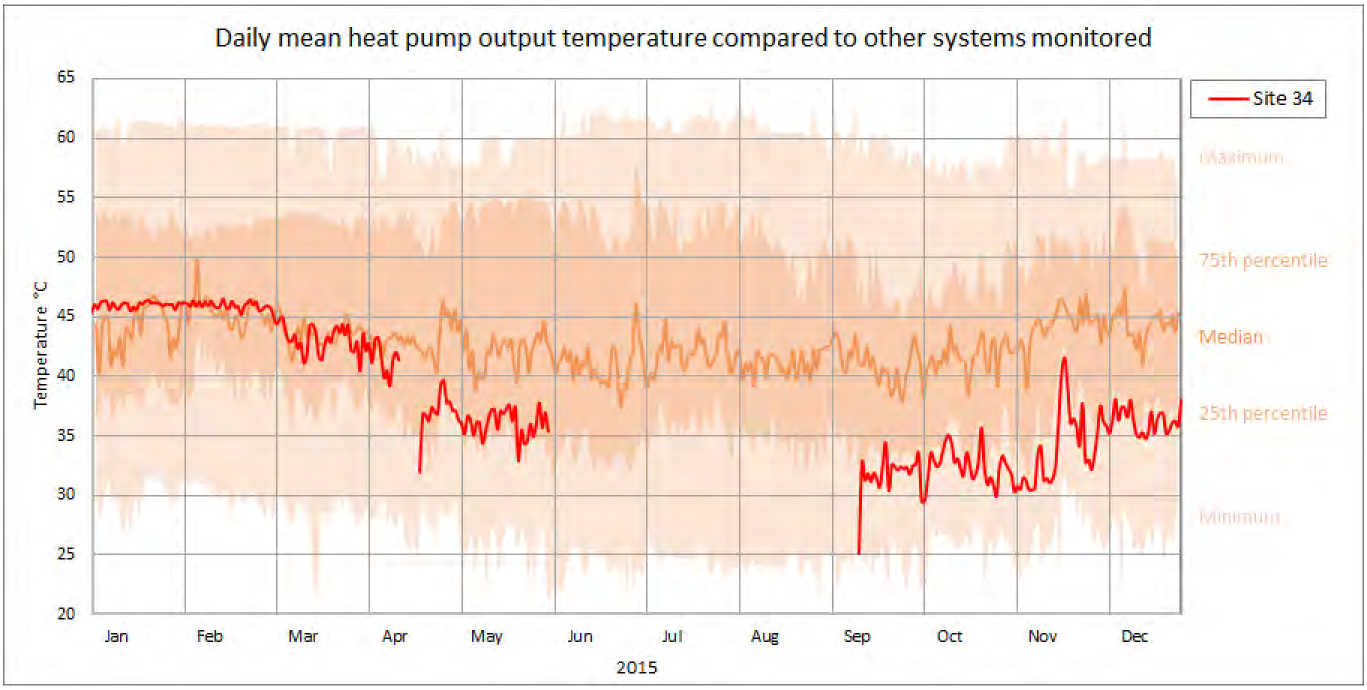

Figure 10 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 34 is shown in red)

Figure 11 shows how the output temperature of this system compares to other heat pump systems that use underfloor heating. The output temperatures on this system (plotted in red) were above average until mid-April, with a negative influence on system performance. Thereafter, the output temperatures were below average, with a positive influence on system performance. The explanation for this behaviour is discussed below.

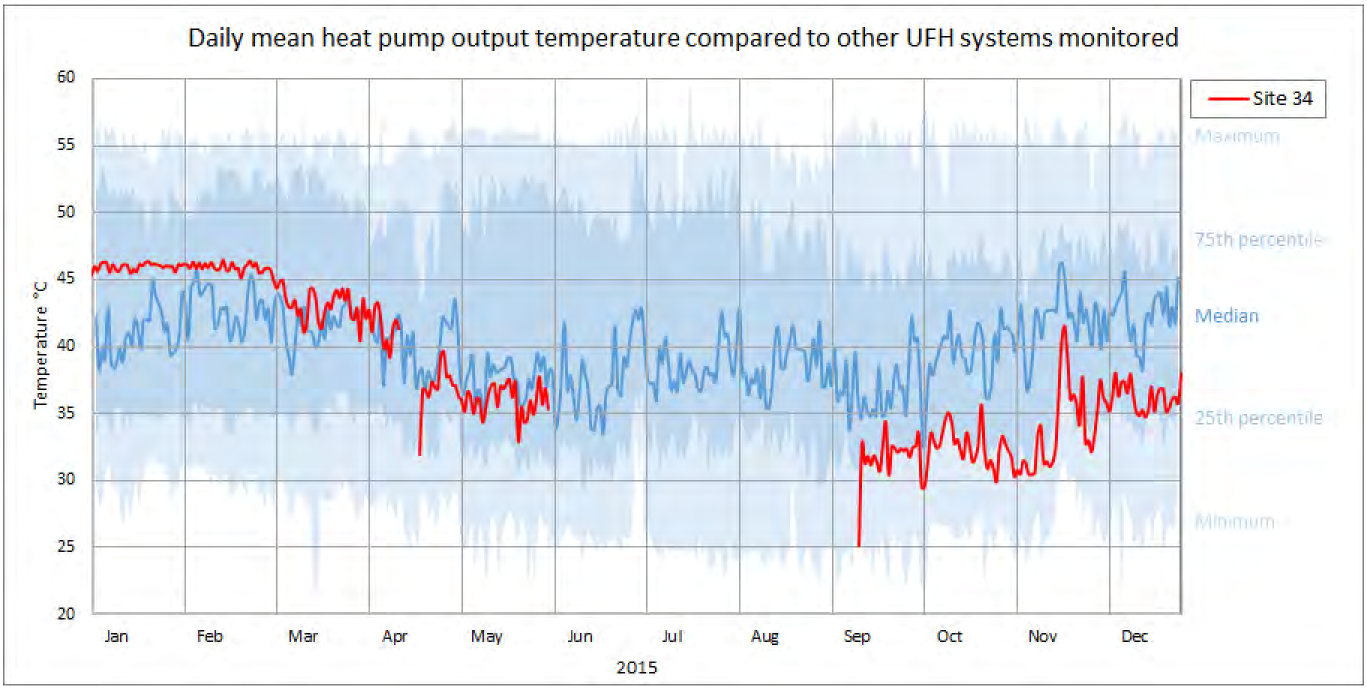

Figure 11 – Daily mean heat pump output temperature compared to those of other systems that use underfloor heating monitored in this project (site 34 is shown in red)

Weather compensation behaviour

Figure 12 shows the weather compensation behaviour during the year. During January and February, the daily mean heat pump output temperature was constant. From March onwards, weather compensation appears to have been used with the output temperature reducing as the outdoor temperature increased. This explains the improved SPF$_{H4}$ after March (see Figure 3).

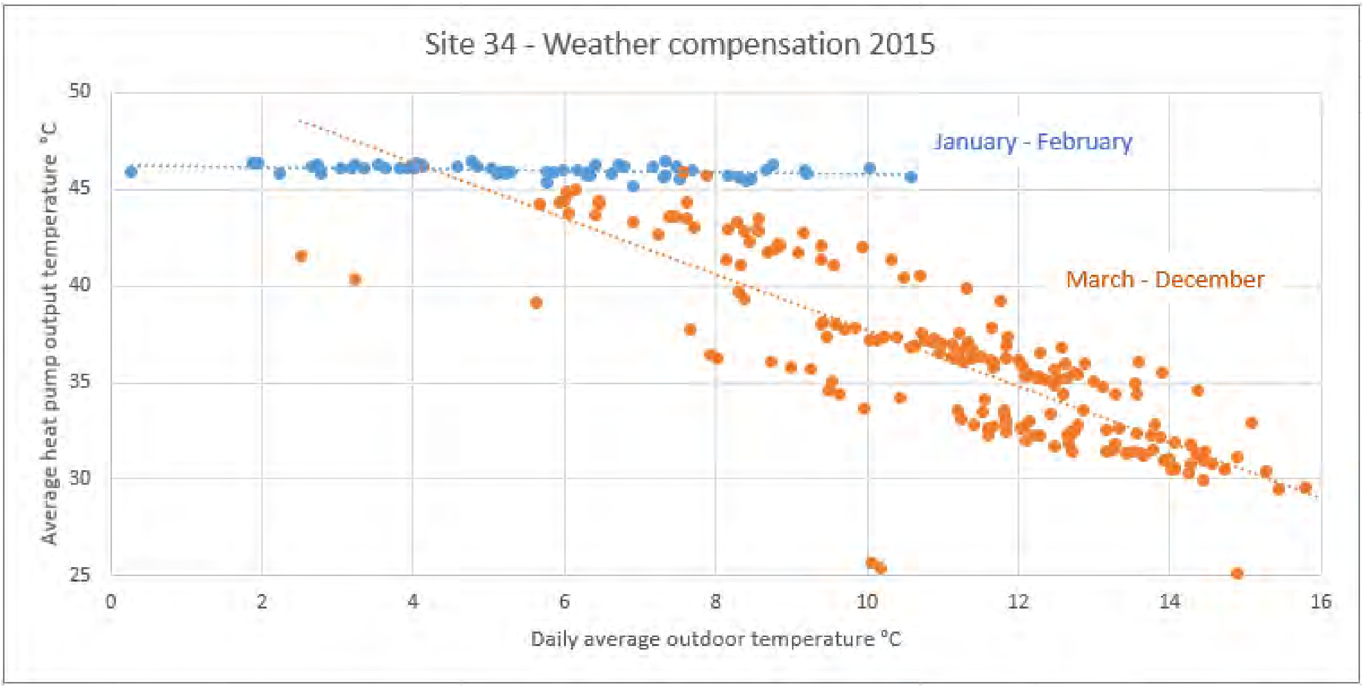

Figure 12 – Weather compensation behaviour

Comments

The performance of this system (SPF$_{H4}$ = 2.23) was just average when compared with other systems providing space heating only that were monitored in the project (SPF$_{H4}$ range: 1.42 to 4.10, median value 2.23).

Given the favourable operating conditions (high source temperatures, potentially low sink temperatures), the performance of this system seems low. This is partly explained by weather compensation not having been used during January and February, but the main reason is probably the high electricity use of the brine pump.

Aspects of this system that positively influenced its performance are:

- The brine temperature from the boreholes was always above 2 °C, and above average throughout the year, compared to other systems monitored in this project (at or above the 75th percentile of the range of values for all systems monitored).
- There was no measurable temperature loss through the 2-pipe buffer tank.
- Weather compensation was used from March onwards to reduce the output temperature when the outdoor temperature was higher.

Aspects of the system that may have negatively influenced its performance include:

- The brine pump used 16.6% of the total electricity used by the heat pump system, which was high compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
  The full brine flow rate should only be needed when both heat pump compressors are running, which only happened for 7% of the total heat pump run time in 2015. So, for 93% of the time, a lower brine flow rate would be adequate and reduced pump speed should reduce the overall electricity use of the brine

pump[6] by around 60% – yielding an annual energy saving of around 3220 kWh and a potential cost saving of £470 per annum[7]. The overall SPF_{H4} would be increased by approximately 7%.

- The buffer pump and heating circulating pumps used 9.5% of the electricity, which was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).
- The heat pump output temperature during the first part of the year may have been higher than necessary (as discussed above in the section on weather compensation behaviour). It may have been possible to reduce the output temperature by several degrees, by adjusting the controls. This would have yielded an improvement in performance.
- Heating and cooling modes were both used during some days in the summer. This should be unnecessary and may have been due to incorrect control settings.

The extent to which the brine temperature is boosted when in heating mode as a result of heat being rejected to the boreholes during cooling mode is unknown. The temperature of the brine flow to the heat pump seems to follow the outdoor air temperature quite closely, so it could be deduced that the effects of any seasonal heat storage in the ground are, on this system, quite small. It is considered, therefore, that the annual system performance values (in heating mode) presented above are unlikely to be significantly higher than if the system were not used for cooling in warm weather.

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[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

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[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

[5] “Quarterly Energy Statistics (https://www.gov.uk/government/collections/quarterly-energy-prices),” DECC.

[6] Carbon Trust, “Variable speed drives (ctg070),” Carbon Trust, 2011.

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[6] See the Carbon Trust report “Estimating savings from VSDs” [6].

[7] Assuming an electricity unit cost of 14.7 p/kWh [5].

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 35

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 35 and performance results from 12 consecutive months of monitoring data.

Site 35 is a terrace of three houses built in 2013. A pair of heat pumps (total thermal capacity 20 kW) installed in an outdoor plant room extract heat from vertical boreholes in the garden area and provide space heating and domestic hot water via underground pipes. Underfloor heating is installed in the ground floor rooms and oversized radiators are used on the upper floors. The domestic hot water cylinder in each house is heated by hot water from the heat pumps, boosted when required using an immersion heater.

The seasonal heating performance factors measured over a year of operation (1st January to 31st December 2015) were:

SPFH2	[Heat delivered by the heat pumps] -- Electricity used by: [heat pumps] + [brine pump]	2.38
SPFH4	Heat from: [heat pumps] + [buffer & SH circ pumps] + [immersion heaters] - [heat loss from buffer tank & undergound pipes] -- Electricity used by: [heat pumps] + [brine pump] + [buffer & SH circ pumps] + [immersion heaters]	1.54

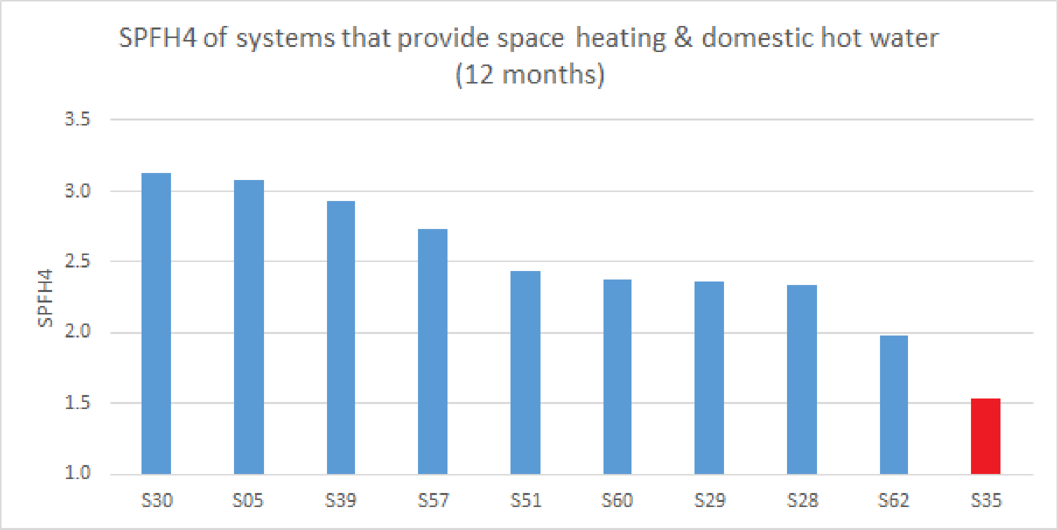

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of the system that negatively influenced its performance include:

- The heat losses from the heat distribution system between the heat pumps and the houses (mainly the buffer tank and the underground pipes) amounted to 25% of the total heat generated by the heat pumps. Most of this was lost from the underground pre-insulated pipes – an estimated 22.6% of the total heat output from the heat pumps.

- The temperature of the heat pump output was at the same high level throughout the year, because of the need to provide heat for domestic hot water. This precluded the use of weather compensation which could have improved overall performance.
- The electricity used by the brine and heating circulating pumps was high compared to other systems monitored. This was partly due to the brine pump and both buffer pumps running at times when neither heat pump was running – which also caused unnecessary electricity use and heat loss.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	35
Survey date	12/03/2014
Monitoring installed	15/07/2014
G/WSHP	GSHP
Building type	3 dwelling houses
Location	Rural
Heat pump capacity kWTH	20
Number of heat pumps	2
Number of compressors	2
Heat source	Vertical boreholes: 5 x 90 – 140 m
Heat emitters	Underfloor heating + oversized radiators
DHW	Yes
Auxiliary heat	Immersion heaters in DHW cylinders
Source pump	External to heat pumps: 390 W max
Buffer pumps	External to heat pumps: 2 pumps of 93 W max
SH circulating pumps	2 pumps in each house: 1 of 100 W used to draw hot water from the buffer tank; 1 of 50 W used to circulate the underfloor heating
Buffer tank	400 litre 4-pipe
DHW cylinders	3
Control	Room thermostats + heat pump controller + programmer
Weather compensation	No
Heat meter type	Ultrasonic
No. of heat meters	4
Heat meter interface	Pulse (1 kWh/pulse)
Comments	

Table 1 – System details

This site comprises a terrace of three dwelling houses, built in 2012.

The application entails extracting heat from the ground to provide space heating and domestic hot water to modern, well-insulated houses in a location with the highest average outdoor temperatures of all sites monitored – annual mean 12.5 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). A common heat delivery circuit reduces the opportunity for the heat pumps to operate with low output temperature. The underground pre-insulated pipes could be expected to lose a significant proportion of the heat from the heat pumps. The performance of the system would be expected to be less than average.

Heat pump and monitoring systems

Two heat pumps (installed at the time of construction, total thermal capacity 20 kW) are installed in a small outdoor plant room located approximately 10 m from the houses, and provide hot water to the houses for space heating (SH) and for domestic hot water (DHW) via a total of approximately 26 metres of underground insulated pipes. The heat emitters are underfloor pipes on the ground floor and oversized radiators on the upper floors.

The heat source comprises 5 boreholes (90 – 140 m deep) in the garden/parking area in front of the houses.

A 400-litre 4-pipe buffer tank is installed in the plant room. Hot water from the buffer tank is drawn off as required by the circulating pumps in the houses. Each house has two circulating pumps – one for space heating and one for domestic hot water. Each house also has an immersion heater in the domestic hot water cylinder, used as required by the occupants.

The system was originally designed to supply heat to a fourth house that has been built on an adjacent site. However, that house was built with a separate heating system, so the heat pump installation is probably now somewhat oversized.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1]. The outdoor air temperature is also monitored.

It was not possible to install monitoring equipment in house 1. The energy use by the circulating pumps and immersion heater in this house has been estimated as the mean of the other two houses. It was also only possible to install monitoring on one of the house heat meters.

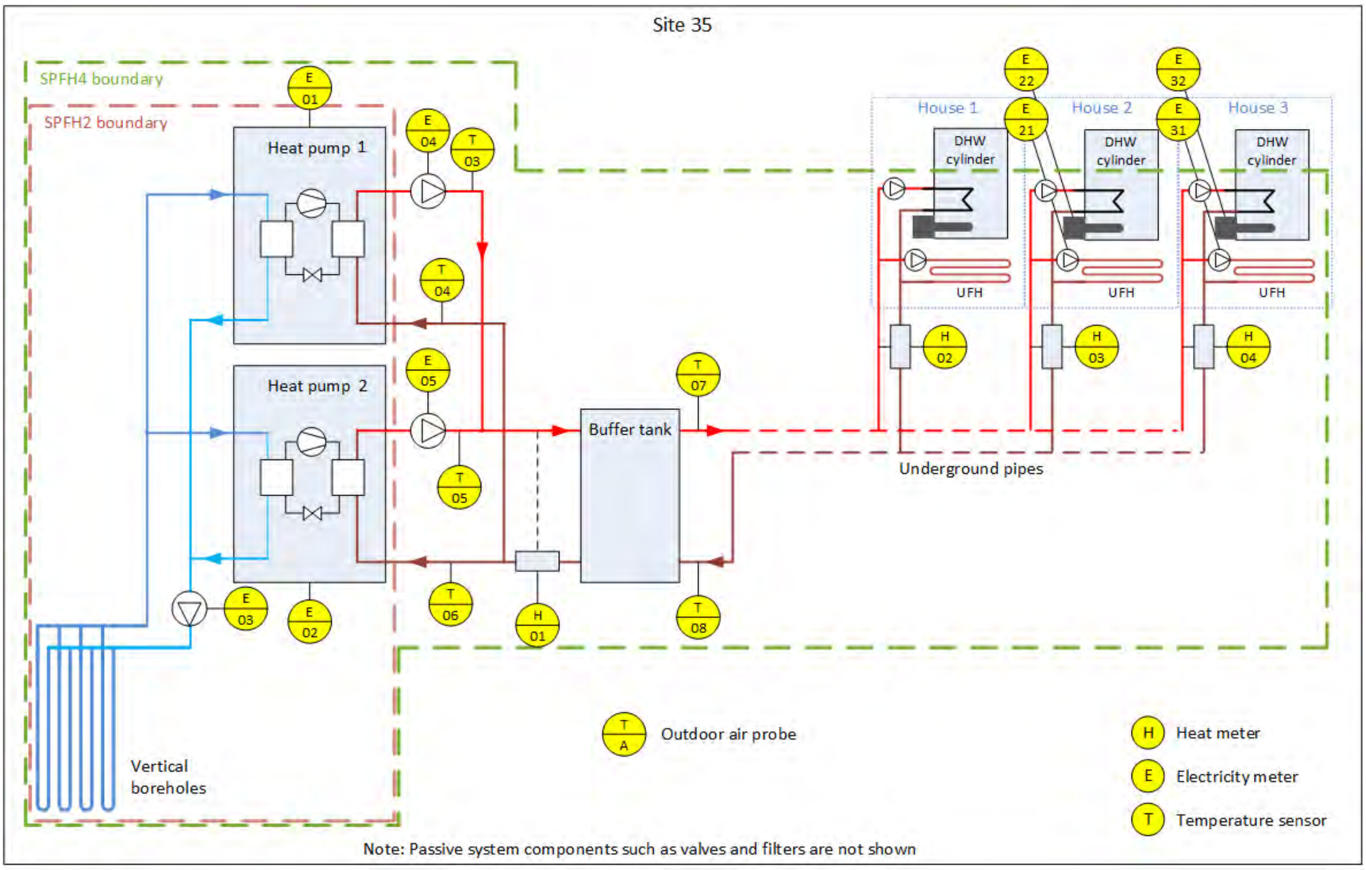

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

One of the heat meters previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. This heat meter is installed between the heat pump and the buffer tank. It uses an

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

ultrasonic flow meter installed in the return pipe, with matched temperature sensors installed in pockets in the flow and return pipes. The calculator is battery-powered. Monitoring was via the pulse interface.

Three other heat meters are installed on this system: one at the supply to each house. These are used to account for the heat losses from the underground pipes and the buffer tank.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of mean heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters and excluding the heat losses from the buffer tank and the underground pipes.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counters connected to the heat meters were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.
- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat measured by heat meter H01]} - \text{[heat added by buffer pumps]}}{\text{Electricity used by: [heat pumps]} + \text{[brine pump]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

$$\text{SPFH4} = \frac{\begin{array}{c}\text{[Heat output from heat pumps] – [heat loss from buffer tank \& underground pipes]} \\ \text{+ [heat added by circ pumps in houses] + [heat added by immersion heaters]}\end{array}}{\text{Electricity used by: [heat pumps] + [brine pump] + [buffer \& SH circ pumps] + [immersion heaters]}}$$

- The heat added by the circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank and the underground pipes were determined from the readings from all four heat meters[4].

The number of 1-minute intervals selected as valid for analysis was 525 563, which represents 99.99% of the 12-month period.

The SPFH2 and SPFH4 values for this system, measured between 1st January and 31st December 2015, are shown in Table 2.

SPFH2	2.38
SPFH4	1.54

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 1.54 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPFH2 and SPFH4 values for the system. Note that the energy used by the pumps and immersion heaters in one house has been estimated as being the mean of the energy used by the similar equipment in the other two houses.

There was a very big difference between the SPFH2 and SPFH4 values. This is mainly attributable to the large heat loss from the underground pipes and the buffer tank – measured at 25% of the heat pump output.

The SPFH2 values were lower during warmer weather in the summer months. This can be explained by the reduced load factor and shorter heat pump run times during warm weather, when the heat pumps were used mainly to provide domestic hot water.

The SPFH4 values during the summer were extremely low – below 1.0 which is unusual, but is explained by the heat loss from the underground pipes and buffer tank being greater than the heat demand from the houses.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[4] The readings for all heat meters were kindly supplied by the proprietor.

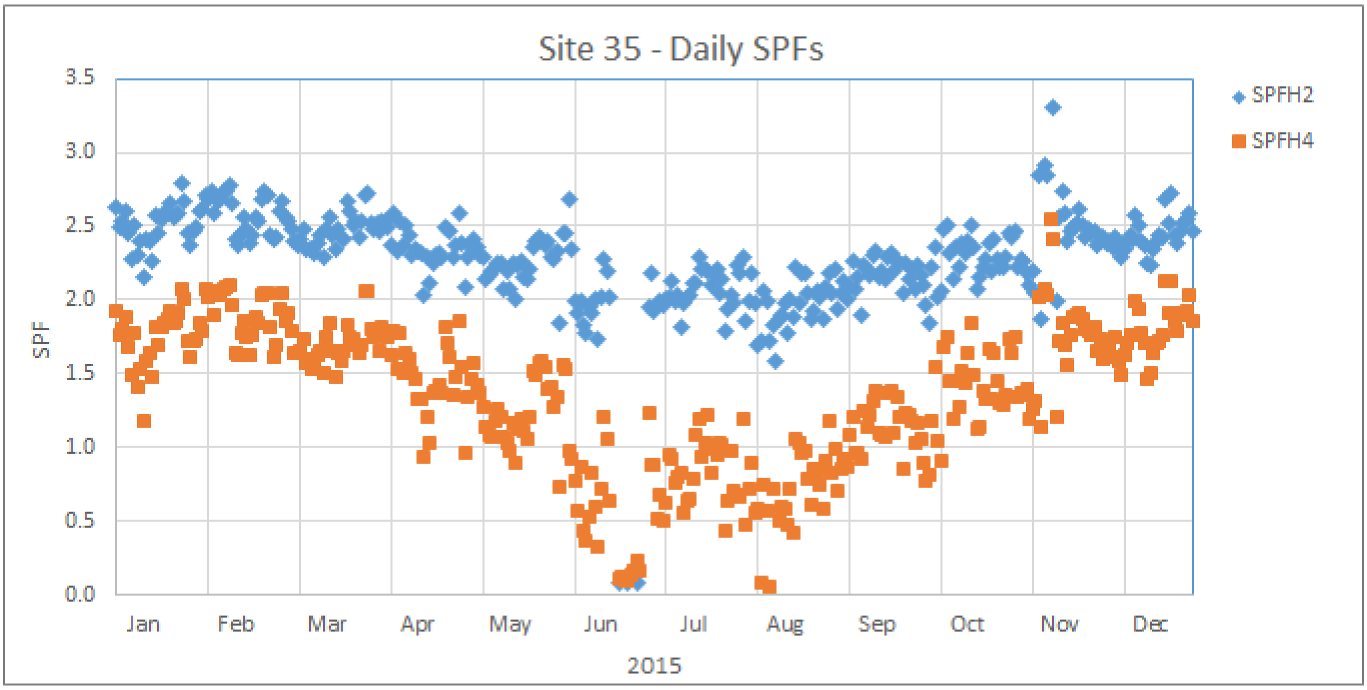

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump water from the source, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output[5] from the heat pump system. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. There was demand for heat all year, although this was for domestic hot water only during the period 18th – 30th June when the heat pumps were not used.

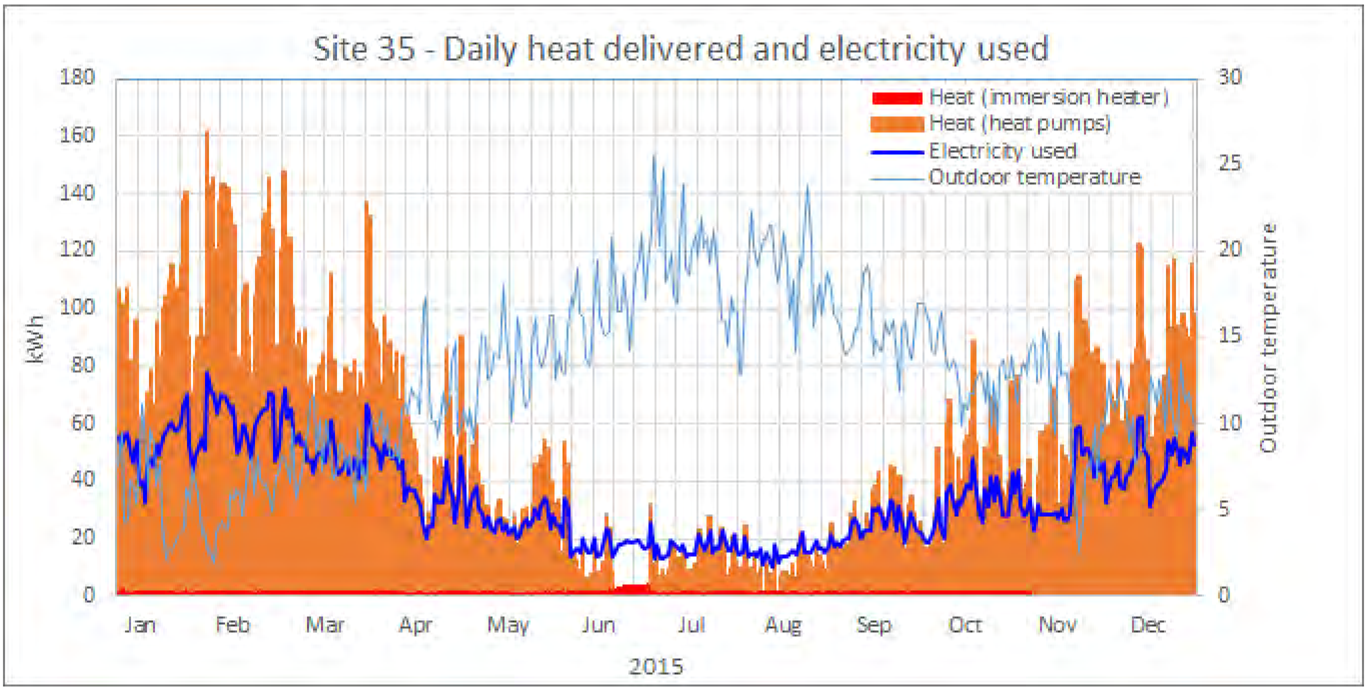

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

It was not possible to determine the breakdown of heat delivered to space heating and to domestic hot water on this system.

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The energy used by the brine and heat circulating pumps is quite high in comparison to other systems monitored in this project.

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[5] This is the "useful" heat output – i.e. after the heat losses from the buffer tank and underground pipes has been deducted.

The brine pump accounted for 11.6% of the electricity used by the total heat pump system. This was above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%) and would have had a negative influence on the system performance.

The buffer pumps and the space heating circulating pumps together accounted for an estimated 13.7% of the total which was also above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a negative influence on the system performance.

The estimated electricity used by immersion heaters was 5.5% of the total[6].

Between 18th and 30th June the brine pump and the buffer pumps were running continuously (although the heat pumps were not running) – presumably because of incorrect control settings. The immersion heater use was also higher than usual during the same period.

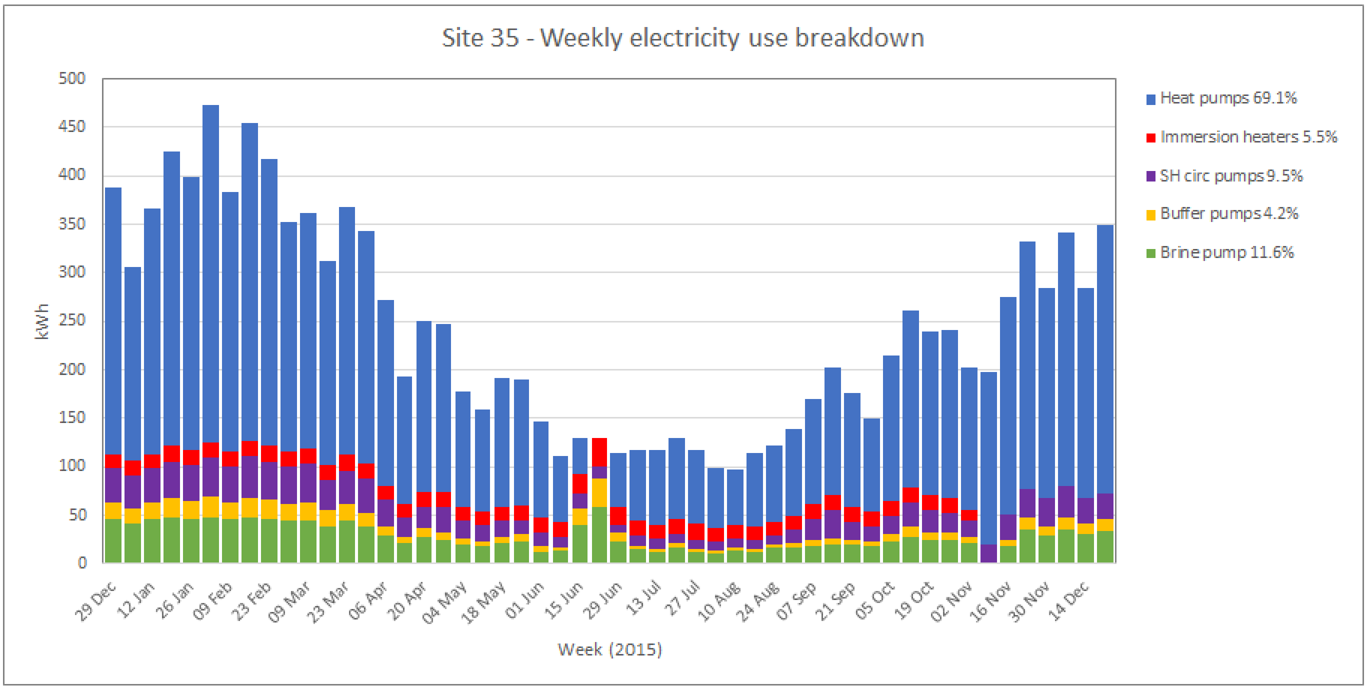

Figure 5 – Weekly electricity use breakdown

Immersion heater use

It is difficult to estimate the immersion heater use because the heater in house 2 was used for an hour every day at the same time (04:00) until 7th November, but not at all thereafter. The reason for the sudden cessation of use is not known.

The immersion heater in house 3 was not used at any time during the year, and there is no monitoring equipment in house 1.

The data shown in Figure 5 is based on the assumption that the use in house 1 is the mean of the other two houses.

---

[6] This was measured in two of the houses and estimated for the third house. If only the measured use is taken into account, this was 3.6% of the total electricity.

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 20th January when the outdoor temperature was between -3 and +12 °C. Heat pump 1 was in use, as shown by the graph of the heat pump supply power. Heat pump 2 was not used.

The temperature of the output from the heat pump to the buffer tank was between 42 and 57 °C. The output from the buffer tank to the houses was between 37 and 51 °C. The loss of temperature through the 4-pipe buffer tank was high – between 5 and 6 °C.

It appears that the heat demand from the houses was at a maximum between 06:00 and 10:30. During this time the heat pump was running continuously, with the output temperature falling steadily to 42 °C at 08:16. The temperature of the output to the houses dropped to 37 °C. Thereafter, the temperatures increased steadily until the heat pump stopped at 10:34.

The immersion heater in house 2 was on between 04:00 and 05:00, using 1.44 kWh[7].

The bottom section of Figure 6 shows the operation of the circulating pumps as a stacked graph: the brine pump (common to both heat pumps), the two buffer pumps and the circulating pumps in houses 2 and 3. It can be seen that the brine pump and buffer pump 2 (which is connected to heat pump 2) were running at times when the heat pump was not running. The reason for this is not known. The effect of running buffer pump 2 would probably have been to circulate heat from the buffer tank into the pipework and condenser of heat pump 2, thereby introducing an unintended heat loss.

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[7] The immersion heater is rated at 3 kW. It was switched on and off several times by the thermostat.

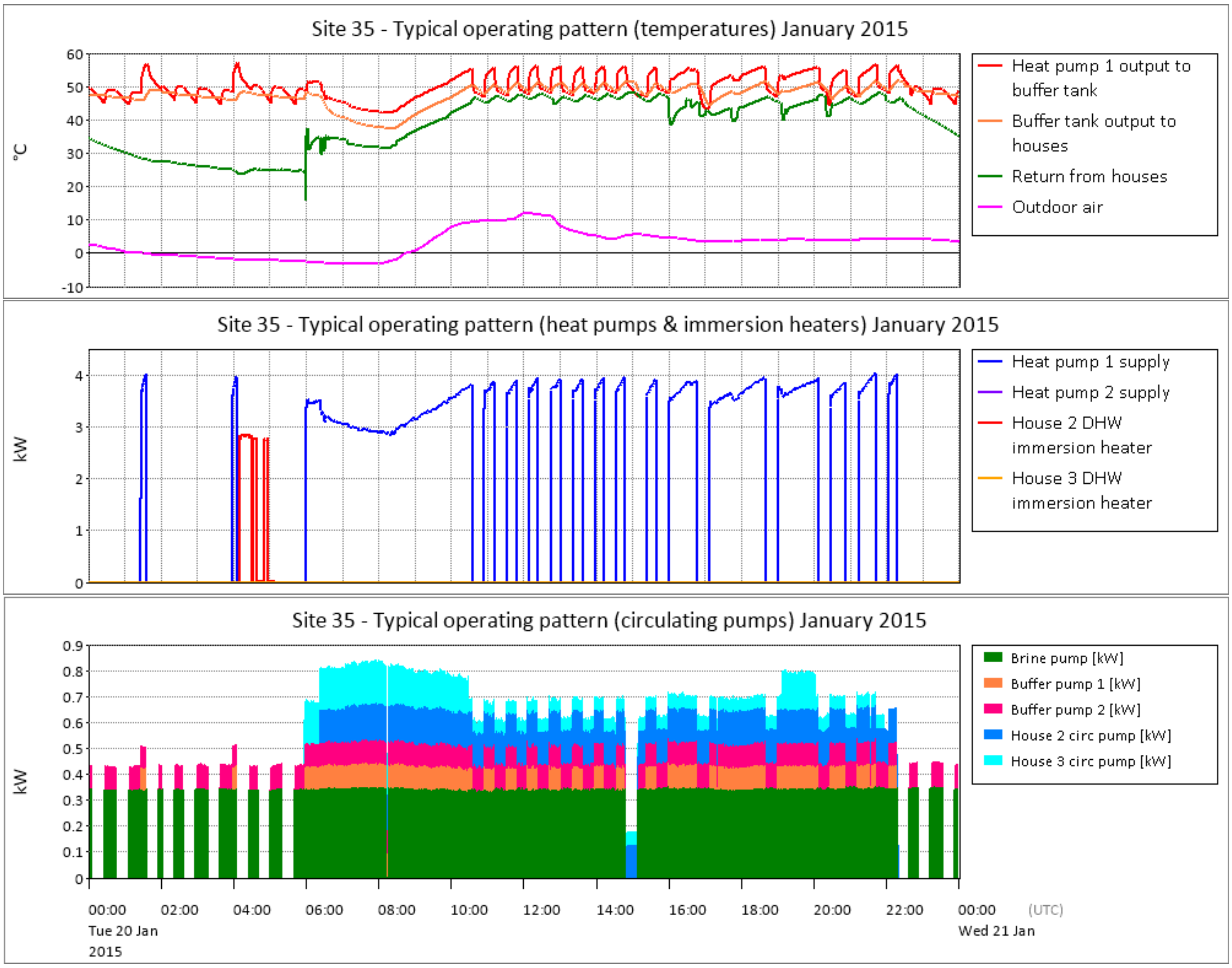

Figure 6 – Operating pattern on 20th January 2015

Figure 7 shows the pattern on 20th July when the outdoor temperature was between 11 and 26 °C. This time, heat pump 2 was in use. The output from the heat pump was up to 56 °C, and the output to the houses was between 45 and 52 °C. The temperature loss through the buffer tank was between 5 and 6 °C.

As in January, the brine pump and both buffer pumps were run at times when the heat pump was not running.

The immersion heater in house 2 was in use between 03:00 and 04:00, using 1.29 kWh.

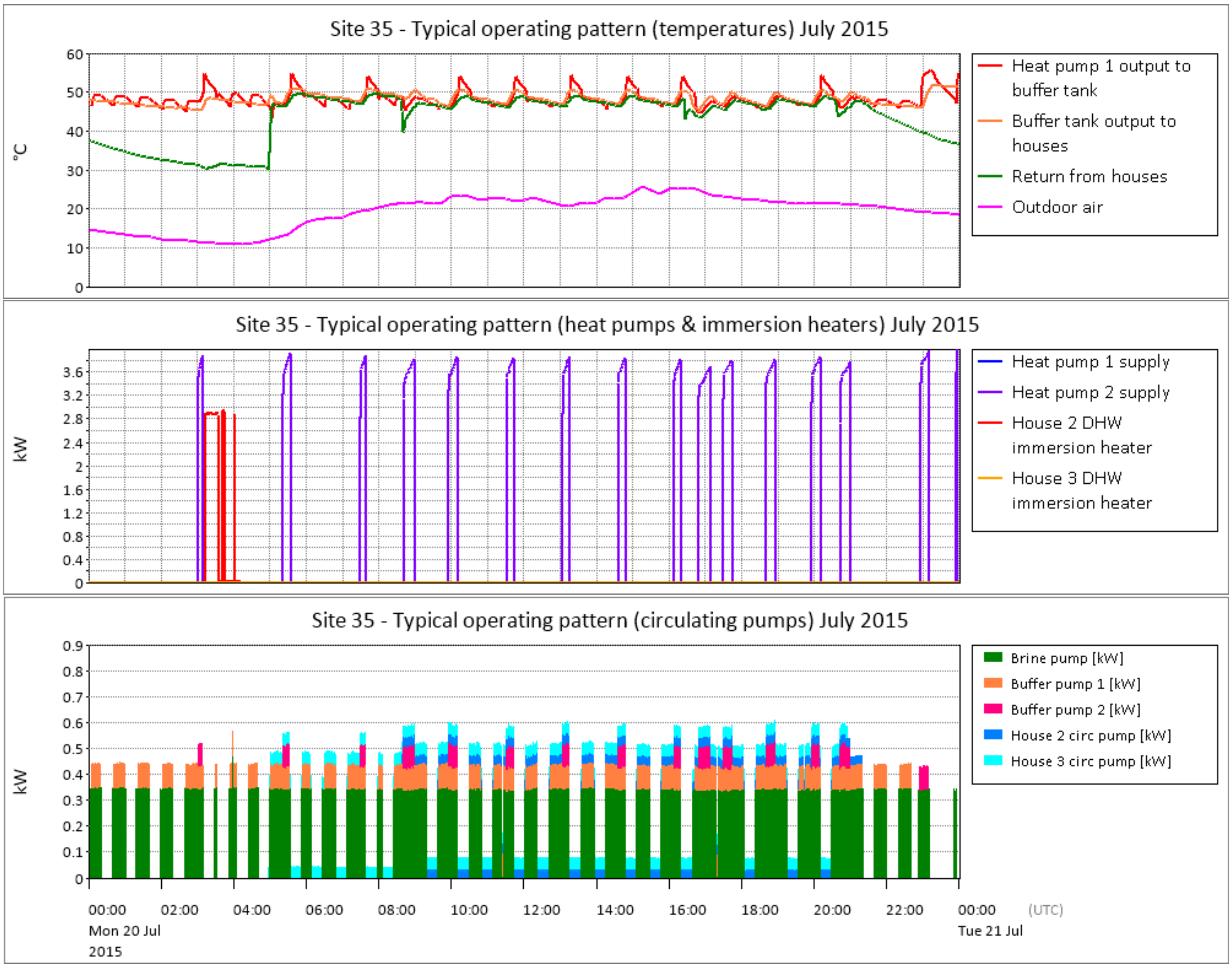

Figure 7 – Operating pattern on 20th July 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[8]. For clarity, the brine and heat pump output temperatures have been plotted only for times when the heat pump was running. The buffer tank output and return temperature data for January are not available because of a premature battery failure in the sensor.

The temperature of the output from the heat pump[9] to the buffer tank was always in the range 47 to 57 °C. The output from the buffer tank to the underground pipe to the houses was in the range 45 to 51 °C until 3rd April, when it increased to 55 °C for some unknown reason.

Because hot water supplied to the houses was used to heat the domestic hot water cylinders, it was maintained all year within the above range, and there was no opportunity of using weather compensation to reduce the temperature for space heating during mild weather.

The heat pumps were not run between 18th and 30th June, although the brine pump and the buffer pumps appear to have run continuously during this period. The reason for this is not known.

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[8] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

[9] Only one heat pump was used at a time.

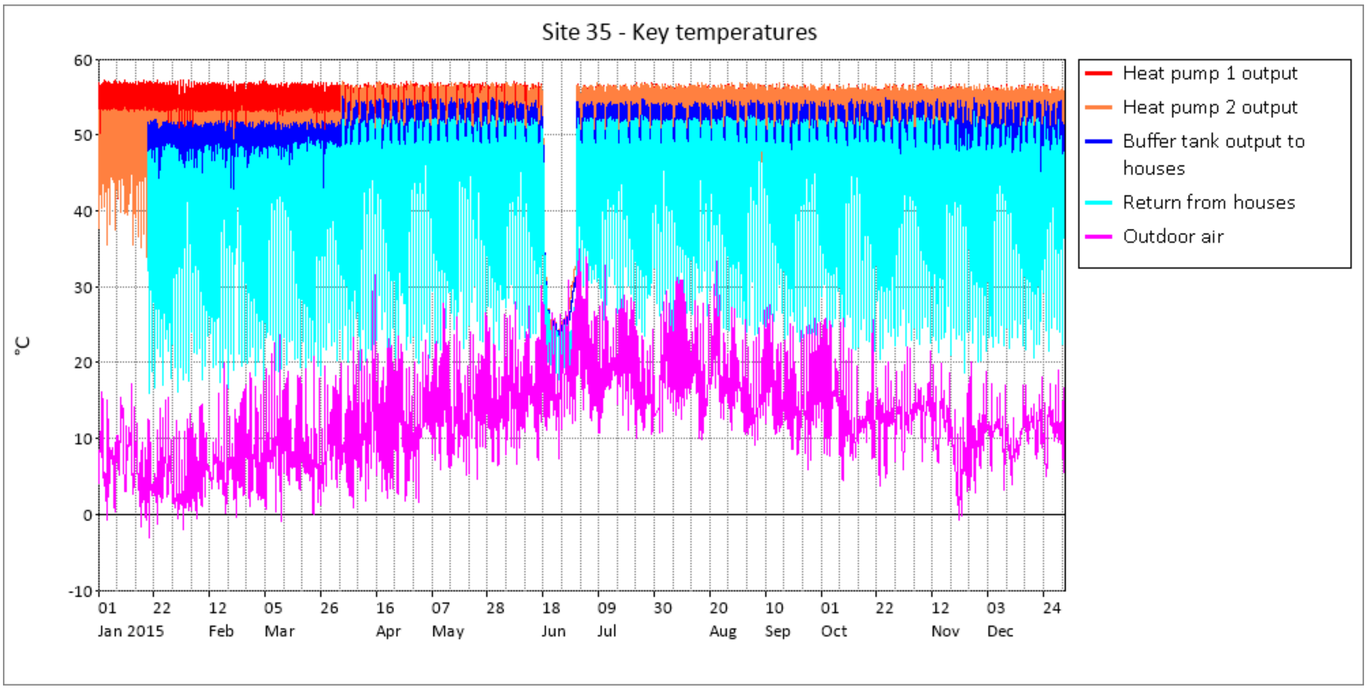

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperature on this system was higher than average. This would have had a negative influence on the system performance.

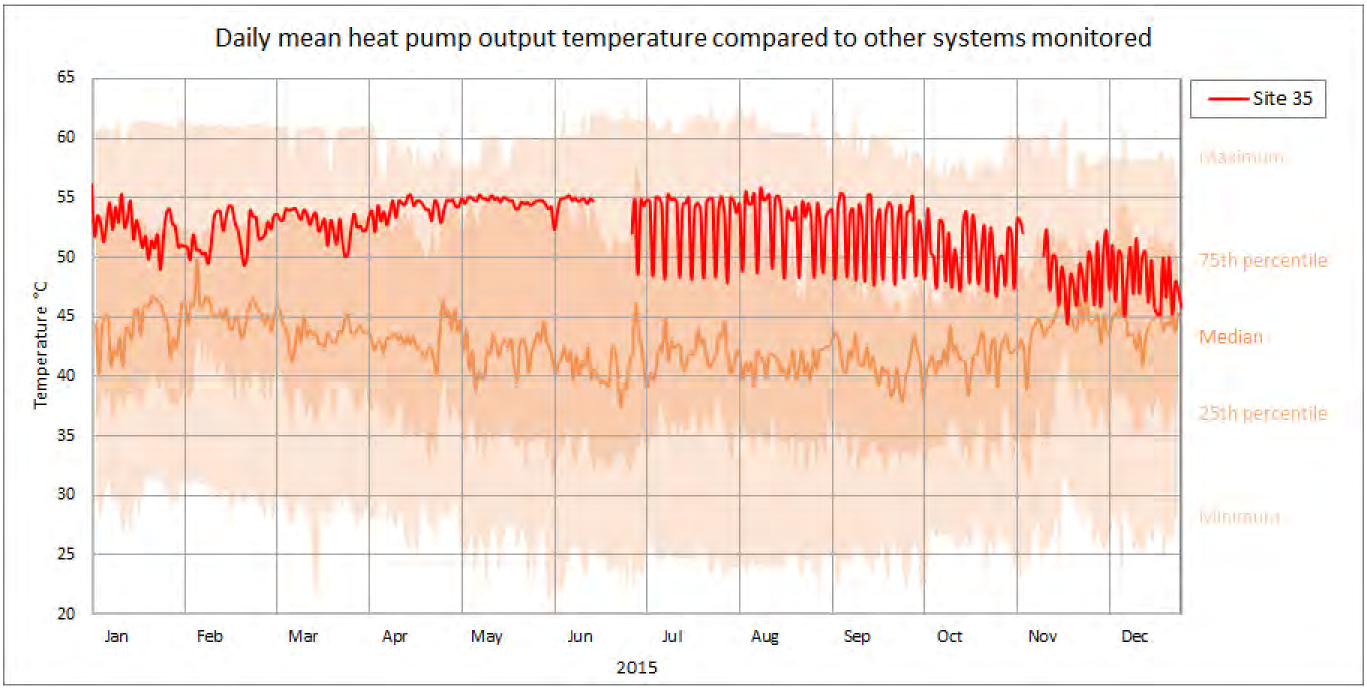

Figure 9 – Daily mean heat pump output temperature compared to those of other systems monitored in this project (site 35 is shown in red)

Figure 10 shows how the output temperature of this system compares to other heat pump systems that use underfloor heating. The output temperatures on this system (plotted in red) were well above average, which would have had a negative influence on system performance, although it should be noted that oversized radiators are used on the upper floors of this site.

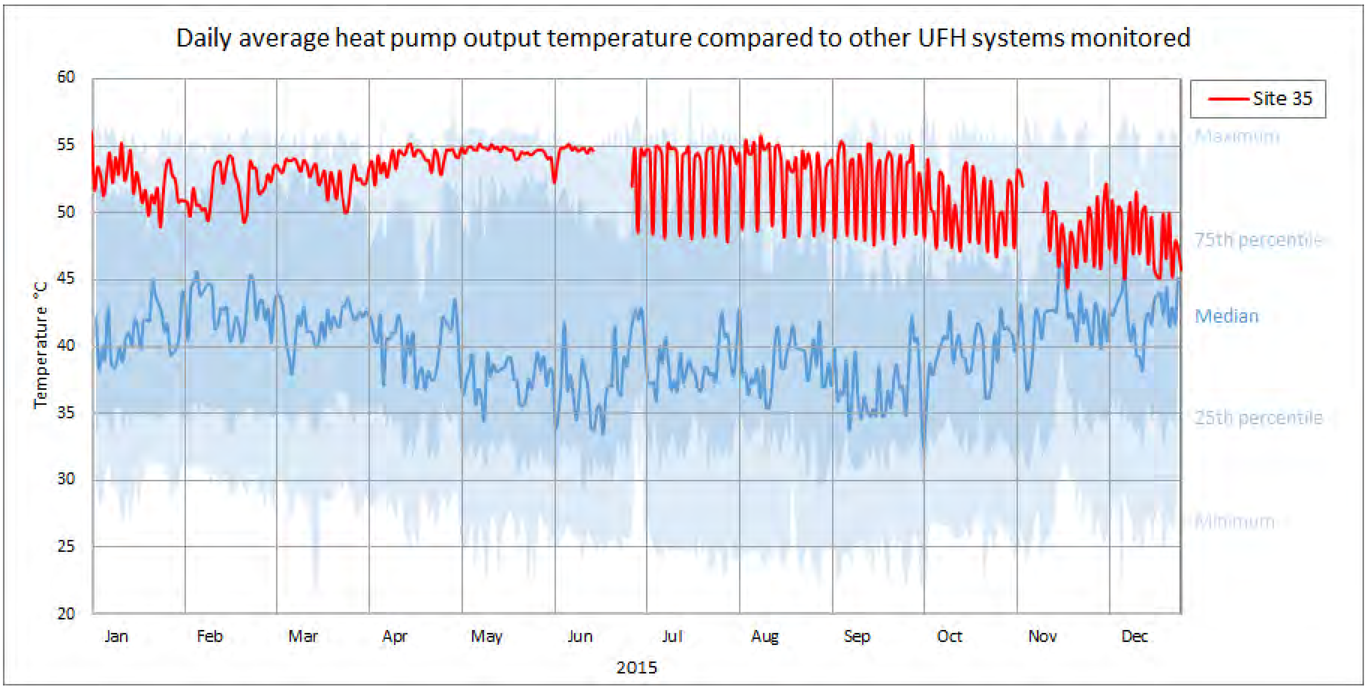

Figure 10 – Daily mean heat pump output temperature compared to those of other systems that use underfloor heating monitored in this project (site 35 is shown in red)

It is notable that, from July onward, the daily mean output temperature periodically dropped by several degrees. The reason for this is not known, but it appears to be related to the operational pattern of the buffer pumps – as shown in Figure 11. The top graph shows the hourly average heat pump output temperature. The middle and lower charts show the tapestry of operation of the heat pumps and their respective buffer pumps. Heat pump 1 was in use only on 1st July; heat pump 2 was used thereafter. However, buffer pump 1 was running at times on some days. On those days, the mean output temperature was approximately 4 °C lower. This suggests that hot water from heat pump 2 was being pumped through the condenser of heat pump 1, with a resultant loss of heat. This would have had a negative influence on the system performance.

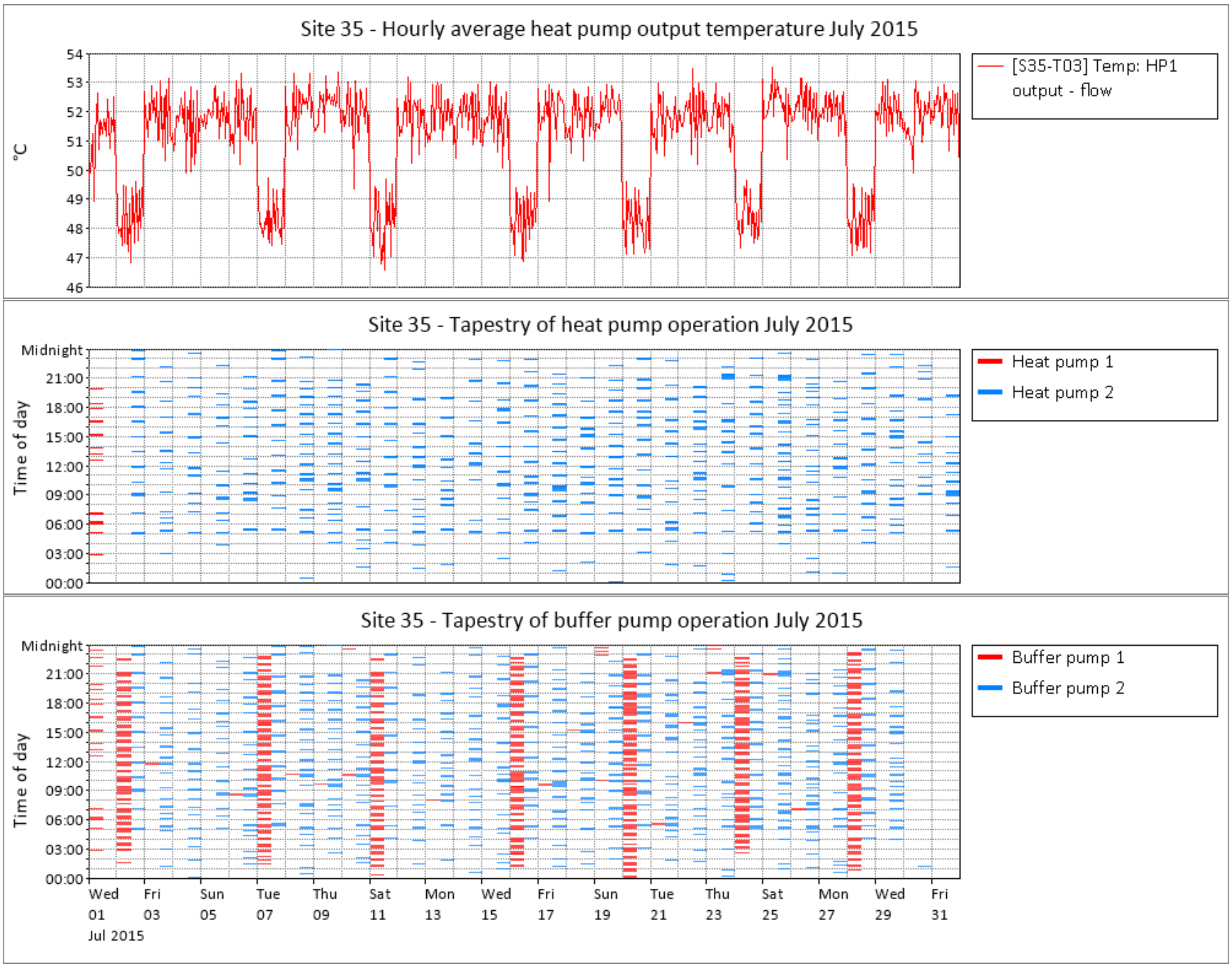

Figure 11 – Heat pump output temperature and tapestry of heat pump and buffer pump operation in July

Comments

The performance of this system (SPFH4 = 1.54) was the lowest of the systems providing space heating and domestic hot water that were monitored in this project (SPFH4 range: 1.54 to 3.13, median value 2.41).

Aspects of the system that may have negatively influenced its performance include:

- The heat losses from the heat distribution system between the heat pumps and the houses (mainly the buffer tank and the underground pipes) amounted to 25% of the total heat generated by the heat pumps. Most of this was lost from the underground pre-insulated pipes – an estimated 22.6% of the total heat output from the heat pumps.
- The temperature of the heat pump output was at the same high level throughout the year, presumably because of the need to provide heat for domestic hot water. This has precluded the use of weather compensation which could give improved annual performance.
- The electricity used by the brine and heat circulating pumps was high. This may be partly because the brine pump and both buffer pumps were run at times when neither heat pump was running. This introduced some unnecessary heat losses as well as incurring unnecessary electricity use. There appears to be potential for the control strategy to be optimised, which could yield an improvement in performance.

- The use of the immersion heater in house 2 was high. The data suggests that this immersion heater was not providing additional benefit and could have been switched off with negligible impact on the temperature and availability of domestic hot water in the house.
- There was a significant loss of temperature (generally 5 – 6 °C) through the 4-pipe buffer tank. It is possible that a different buffer tank arrangement would reduce this loss and give an improvement in system performance. However, buffer tank design is a complex topic and is outside the scope of this report.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 37

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 37 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 37 is public hall / sports pavilion built in 2012.

The ground-source heat pump (thermal capacity 17 kW) extracts heat from 880 m of horizontal ground loops, and provides space heating via underfloor coils on the ground floor and radiators on the first floor, as well as domestic hot water for general use and for showers.

Seasonal performance factors are not presented because characteristics of the heat meters, previously installed for the Renewable Heat Incentive and used to monitor this system, have led to unacceptably high uncertainties of measurement of the heat delivered.

Aspects of this system that positively influenced its performance are:

- The source temperature was high – well above average compared to other systems in the monitored sample.
- The temperature of the heat pump output to space heating was below average compared to other systems in the monitored sample.
- The brine pump used only 2.6% of the total heat pump system electricity, which was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the heat pump output to domestic hot water was often very high. This was because of concerns about Legionella control, and necessitated extensive use of the immersion heater.
- The heating circulating pump ran continuously throughout the year.

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[1] The heat meter installation on this system uses strap-on temperature sensors. This technique is known [1] to be prone to unacceptably large measurement errors and the performance values could therefore not reliably be determined.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

SiteID	37
Survey date	24/2/2014
Monitoring installed	28/5/2014
G/WSHP	GSHP
Building type	Village hall / sports pavilion
Capacity kWTH	17
Number of heat pumps	1
Number of compressors	1
Heat source	Horizontal ground loops. 880m
Heat emitter	Underfloor heating (ground floor); radiators (first floor)
DHW	Yes
Auxiliary heat	7kW immersion heater inside the heat pump
Source pump	Integrated into the heat pump: 35 – 185 W variable-speed
Buffer pump	Integrated into the heat pump: 10 – 75 W variable-speed
SH circulating pump	External to the heat pump: 70 W max
DHW circulating pump	External to the heat pump: 78 W max
Buffer tank	200-litre 4-pipe
DHW cylinders	2 cylinders: one 500-litre for normal use; additional 750-litre cylinder for use on days when the demand for hot water is expected to be higher than normal. (Note: the additional 750-litre cylinder was drained and disconnected on 2nd June 2015.)
DHW distribution pump	Yes: controlled by a timeswitch (times varied during the project)
Control	Room thermostats (ground floor) + thermostatic radiator valves (first floor) + timeswitch for additional DHW + heat pump controller
Weather compensation	Yes
Heat meter type	Mechanical (intended for use with antifreeze/water mixture)
No. of heat meters	2
Heat meter interface	Pulse (100 Wh/pulse)
Comments	Strap-on temperature sensors and mechanical flow meters are used for heat metering. These were accepted for RHI metering at the time of installation.

Table 1 – System details

Site 37 is a public hall / sports pavilion built in 2012.

The application entails extracting heat from the ground to provide space heating and domestic hot water to a modern, well-insulated building in a location with slightly below-average outdoor temperatures – annual mean 9.4 °C (the range for all systems monitored was 8.1 – 12.5 °C, median 10.3 °C). The system performance would be expected to be average or better.

Heat pump and monitoring systems

A single heat pump of 17 kW thermal capacity, installed inside the pavilion in a first-floor plant room, is used to provide both space heating (SH) and domestic hot water (DHW).

Heat is extracted from 880 metres of horizontal ground loops at a depth of approximately 1.2 metres in the field adjacent to the pavilion. The manifold of the ground loops is approximately 50 metres from the heat pump.

The heat emitters are underfloor pipes on the ground floor and radiators with thermostatic valves on the smaller first floor area.

A 200-litre 4-pipe buffer tank is installed between the heat pump output and the heating circuit.

Domestic hot water production

The system has two domestic hot water cylinders[2]. The main 500-litre cylinder (no. 1) is always in use, while the secondary 750-litre cylinder (no. 2) is used at times when there is an expected high demand for domestic hot water for showers.

The cold mains water enters the bottom of domestic hot water cylinder no. 2 and thence from the top of that cylinder to the bottom of cylinder no. 1.

The high-temperature water from the heat pump is normally fed only to the heating coil in cylinder no.1. The heating coil in cylinder 2 is fed via a 3-port diverter valve from the return leg of the coil in cylinder 1. In practice, this arrangement causes the water in cylinder 2 never to be as hot as the water in cylinder 1. (See the schematic in Figure 1.)

The heat pump has two hot water outlets: one for space heating (via an external buffer tank), the other for heating the domestic hot water cylinders. A 3-port valve inside the heat pump diverts the output to either the space heating or the domestic hot water coils.

The manufacturer’s manual for the heat pump states that the maximum output temperature is 65 °C when using the compressor, or 70 °C when using the immersion heater.

Legionella sterilisation issues

After the monitoring equipment had been installed, the heat pump proprietor became concerned about the sterilisation of the domestic hot water. From the temperature data being recorded, it emerged that it was very unlikely that either of the domestic hot water cylinders was being heated to 60 °C (as recommended for Legionella prevention).

In January 2015, temperature sensors were installed at the top of each domestic hot water cylinder to provide additional information about the likely temperature in each cylinder.

Correspondence between the proprietor and the heat pump manufacturer and the installer eventually led to the heat pump controller being reconfigured to ensure that the temperature of domestic hot water cylinder 1 was raised to 60 °C or higher for at least part of each day. This resulted in the immersion heater being used much more than previously, to generate the necessary temperature from the heat pump. The consequences of the increased immersion heater use are notable in the performance results shown below.

At the same time, the proprietor observed that domestic hot water cylinder 2 might not actually be needed, as the domestic hot water requirement seemed to be less than had initially been expected. Also, as the heat pump system (as installed) seemed unable to raise the temperature in domestic hot water cylinder 2 to anywhere near

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[2] DHW cylinder no. 2 is no longer in use: it was drained and disconnected on 2nd June 2015.

60 °C, but at times actually maintained the temperature within the Legionella risk range, it was decided to stop heating domestic hot water cylinder 2.

At the time monitoring commenced, the immersion heaters in the domestic hot water cylinders were not connected to an electricity supply. However, these have now been connected for emergency use only. The supply to these heaters remains unmetered and the system proprietor has confirmed that they were not used during the monitoring period.

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and to domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular "E" symbols) were installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") were monitored at key points in the system using surface-mounted probes[3]. The outdoor air and ground temperatures were also monitored.

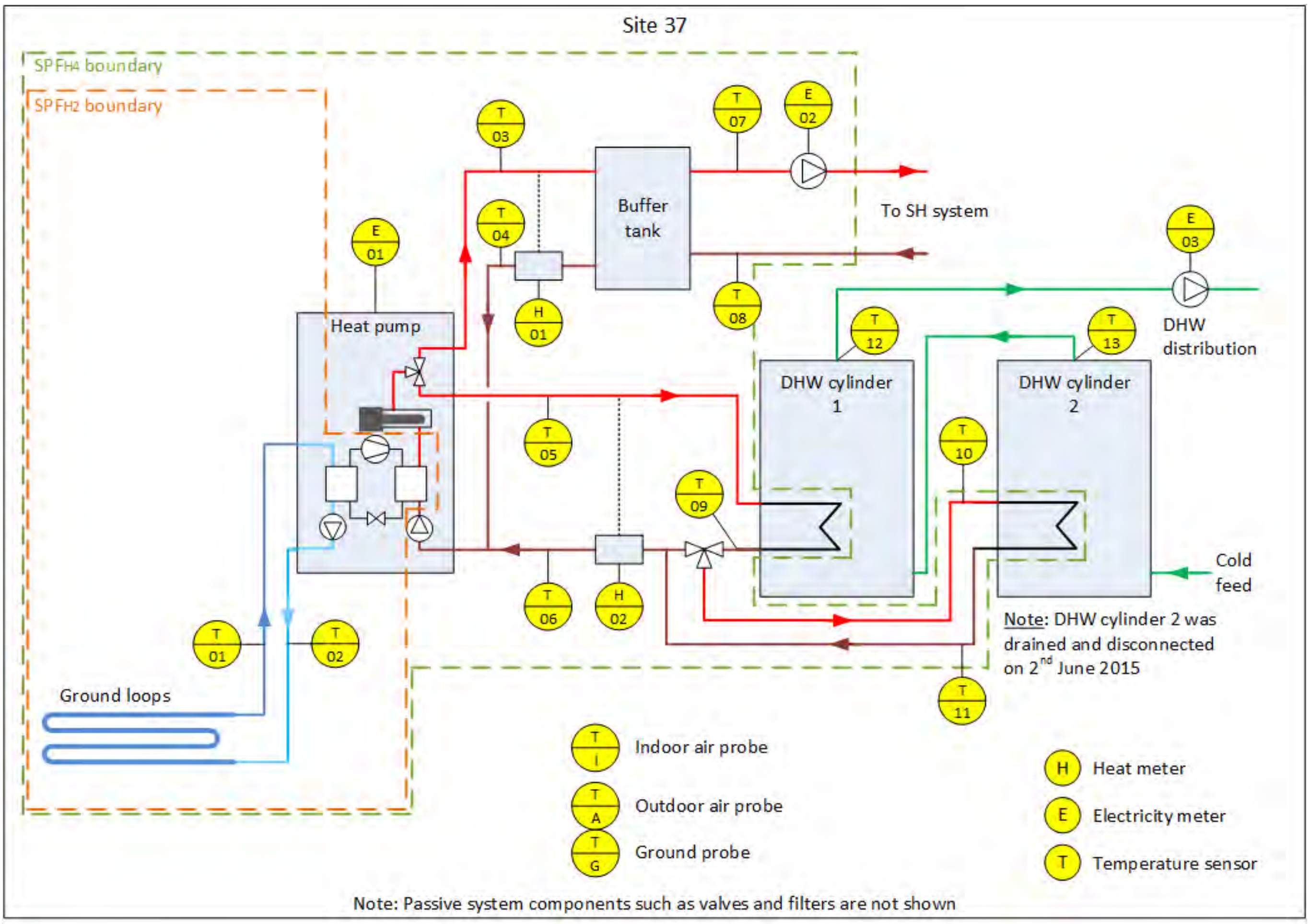

Figure 1 – System schematic showing the monitoring instrumentation installed

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[3] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pump. Two heat meters are installed: one measures the heat supplied to the buffer tank (space heating); the other measures the heat supplied to the domestic hot water cylinders.

The heat meters are of a type that uses mechanical multi-jet turbine flow meters and strap-on temperature sensors. Although the use of strap-on temperature probes was as recommended by the meter manufacturer at the time of installation, it is known from subsequent research [1] that this technique can result in large measurement errors.

The heat calculators on this system were of a type intended for use with antifreeze in the working fluid. However, it is not known whether any antifreeze was present in the heating circuit. This may have caused further error in the heat metering.

Monitoring was via the pulse interfaces of the heat meters.

Because of the heat metering issues, it has not been possible to determine the system performance with any useful degree of accuracy.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump including the internal source pump, but excluding the internal buffer pump and immersion heater.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [2].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counters connected to the heat meters were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a “raw data” database. The raw data was subsequently processed by custom software to generate a “clean” database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[4] procedures tailored to suit this heat pump system.

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[4] Structured Query Language: a programming language used for managing data held in a relational database management system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump to SH \& DHW]} - \text{[heat added by buffer pump]}}{\text{Electricity used by: [heat pump (excluding immersion heater and buffer pump)]}}$$

- This calculation required the electrical energy used by the buffer pump inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running.

- The electricity used by the immersion heater inside the heat pump was determined using digital filtering of the data from the electricity meter E01, using the technique described in Appendix H of the Interim Report [3].

- The heat added by the buffer pump was estimated as 30% (the assumed pump efficiency[5]) of the electrical energy supplied to the pump.

$$SPF_{H4} = \frac{\text{[Heat output of heat pump to SH \& DHW]} + \text{[heat added by SH circ pump]}}{\text{Electricity used by: [heat pump including internal pumps \& immersion heater]} + \text{[SH circ pump]}}$$

- The heat added by the heating circulating pump was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pump.

- The buffer tank is inside the heated envelope. The heat loss from it was deducted from the total heat output during times when the outdoor air temperature was above 15 °C (i.e. when there was output to space heating that was probably not needed).

The number of 1-minute intervals selected as valid for analysis was 517 174, which represents 98.4% of the 12-month period.

SPF results presented as relative values

Because of the heat metering issues noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors SPF_{H2} and SPF_{H4} are therefore presented in this case study as “relative” values, whereby each value is shown as an amount above or below a nominal performance.

Figure 2 shows the daily SPF_{H2} and SPF_{H4} behaviour of the system. These values represent the combined space heating + domestic hot water performance. The values during the summer months were lower, but it should be remembered that the heat load during the summer is very low – mainly only domestic hot water – so the effect of these lower values on the annual performance is very small.

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[5] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

The SPFH2 values increased somewhat after some changes were made (by a technician from the heat pump supplier) to the heat pump controller on 3rd September. Prior to that date, the buffer pump ran continuously, but after then it was run only when the heat pump compressor was running. This appears to be the reason for the improvement in SPFH2. Any consequential improvement in SPFH4 is difficult to detect because of the scatter in the daily values.

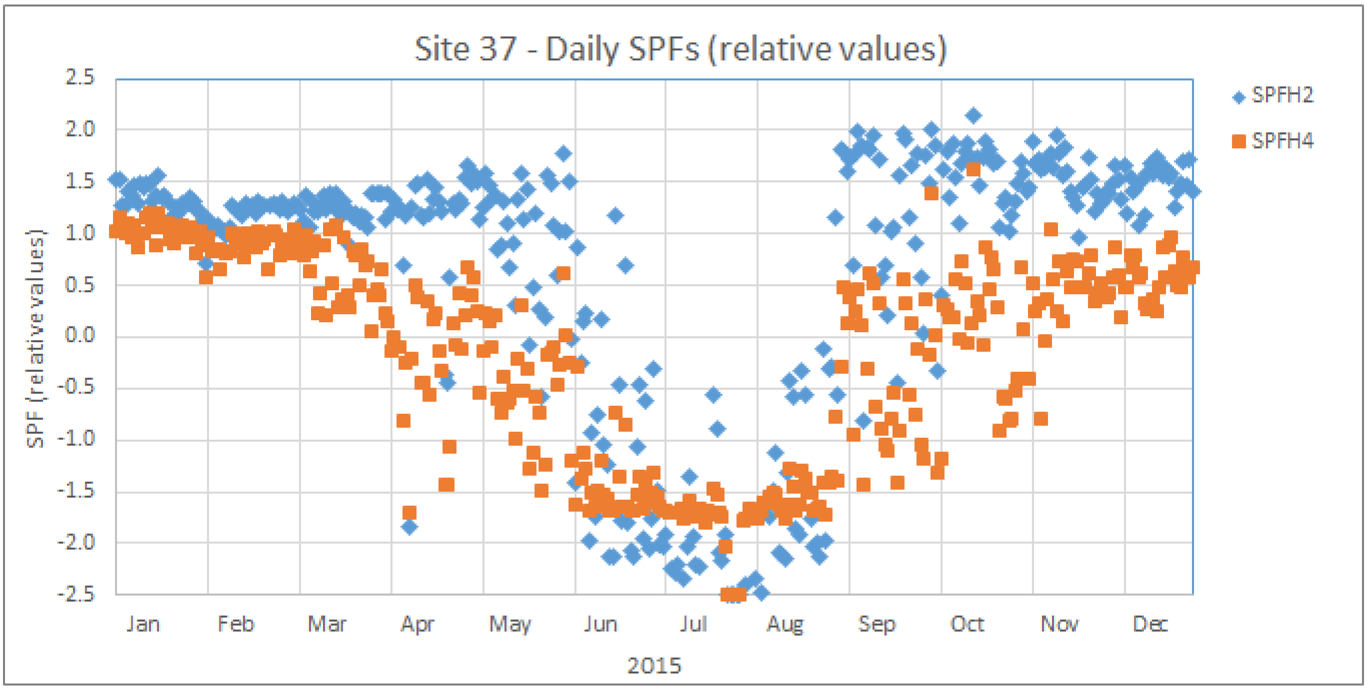

Figure 2 – Seasonal performance factors SPFH2 and SPFH4 calculated daily (for space heating + domestic hot water combined).

The heat pump in this installation provides heat for either space heating or for domestic hot water at any given time. Figure 3 show daily SPFH4 (relative) values for space heating and for domestic hot water operation. It can be seen that the performance in domestic hot water mode reduced after the adjustments were made to increase the domestic hot water temperature in February 2015.

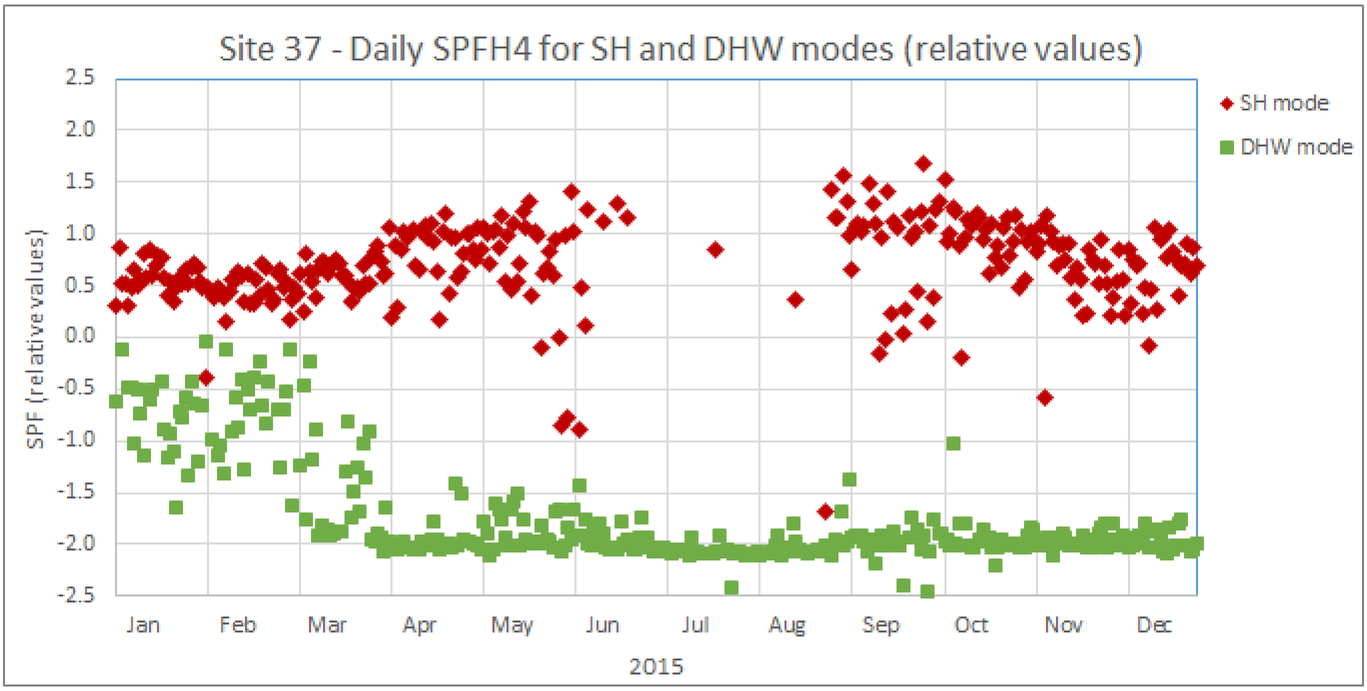

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated separately for space heating and for domestic hot water.

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the source (input) and sink (output) temperatures – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [4] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output to space heating and to domestic hot water. The electricity used by the total heat pump system and the mean daily outdoor temperature are also shown for reference. Note that the kWh values have been removed from the graph because of the high uncertainty of measurement of the heat meters.

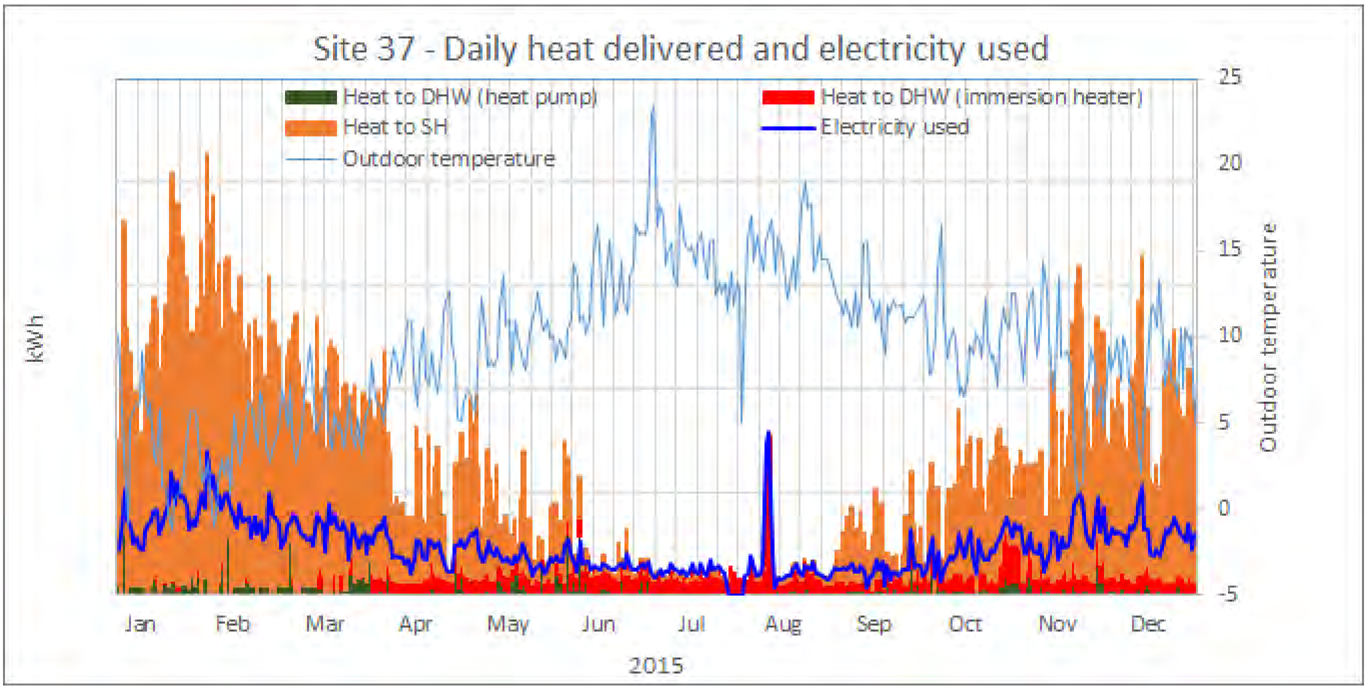

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

Table 2 shows the estimated breakdown of the heat delivered to space heating and to domestic hot water during the period 1st January – 31st December 2015.

	%
Heat delivered to space heating	79.5%
Heat to domestic hot water (from heat pump)	4.5%
Heat to domestic hot water (from immersion heaters)	16.0%

Table 2 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

A breakdown of the electricity use is shown in Figure 5.

The brine pump accounted for 2.6% of the electricity used by the total heat pump system, which was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

The space heating circulating pump ran continuously (except for a few weeks in July 2015).

The buffer pump (the heat pump output circulating pump) operating pattern appeared to change on 3rd September. Prior to that date, the buffer pump ran continuously, but after then it was apparently run only when the heat pump compressor was running. The reason for this is not known, although it is known that some alterations were made (by a technician from the installation contractor) to the heat pump controller on that day.

The buffer pump and the space heating circulating pumps accounted for 9.9% of the total electricity use, which was slightly below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a small positive influence on the system performance.

The energy used by the immersion heater increased significantly following the change during the second week in March in the control settings to increase the temperature of the domestic hot water. The high immersion heater use during first week in August is understood to have been due to additional demand for domestic hot water during an event in the hall. The immersion heater accounted for 27.3% of total electricity use. This is a high figure that would have had a negative influence on system performance.

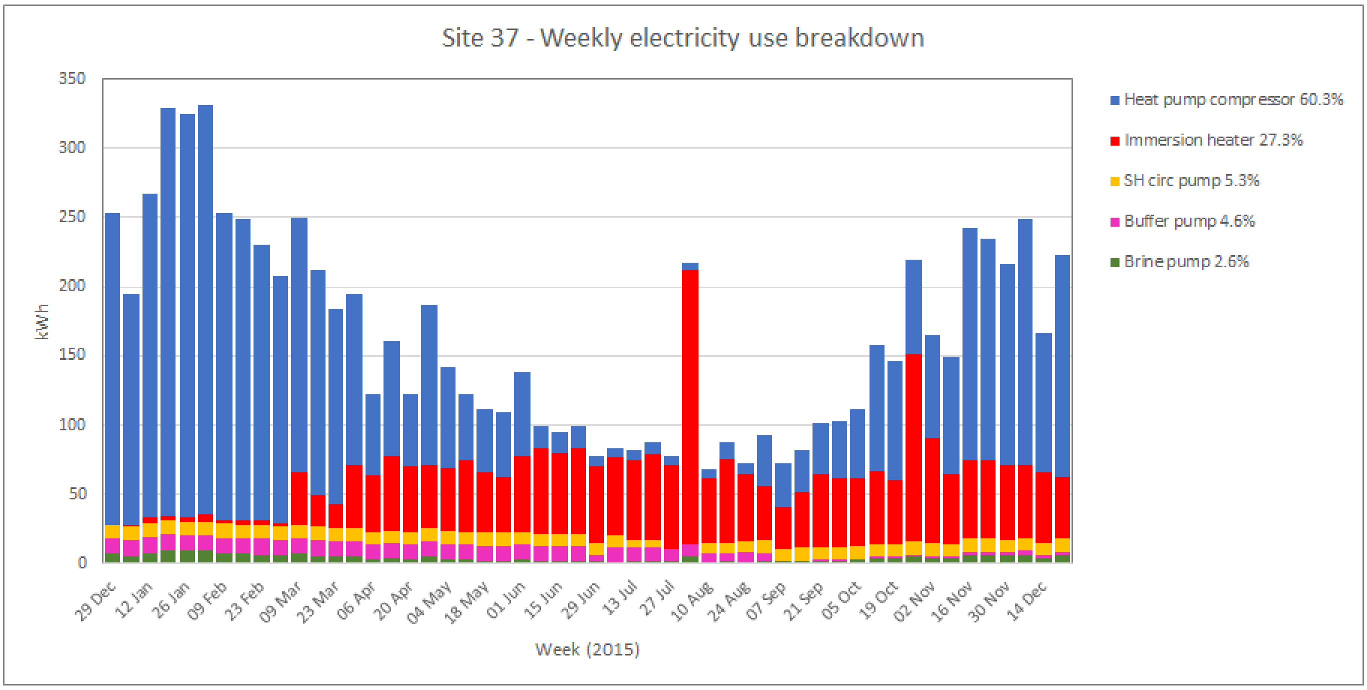

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the pattern of operation on 19th January 2015 when the outdoor air temperature was between -5 and +2 °C and the ground temperature was 6.4 °C.

The heat pump ran approximately every 90 minutes for between 25 to 50 minutes each time.

The heat pump switched to domestic hot water mode between 11:20 and 12:00, using the vapour compression system initially and then the internal immersion heater for 10 minutes to provide heat to the domestic hot water coil at a maximum temperature of 62 °C.

The buffer pump ran continuously except when the immersion heater was on and the space heating circulating pump ran all day.

The temperature of the output from the heat pump to the buffer tank was up to 49 °C, and the temperature from the buffer tank to the heating circuit was up to 44 °C. The loss of temperature through the 4-pipe buffer tank was between 1 and 4 °C.

The temperature of the brine flow to the heat pump was between 4.5 and 6 °C while the heat pump was running.

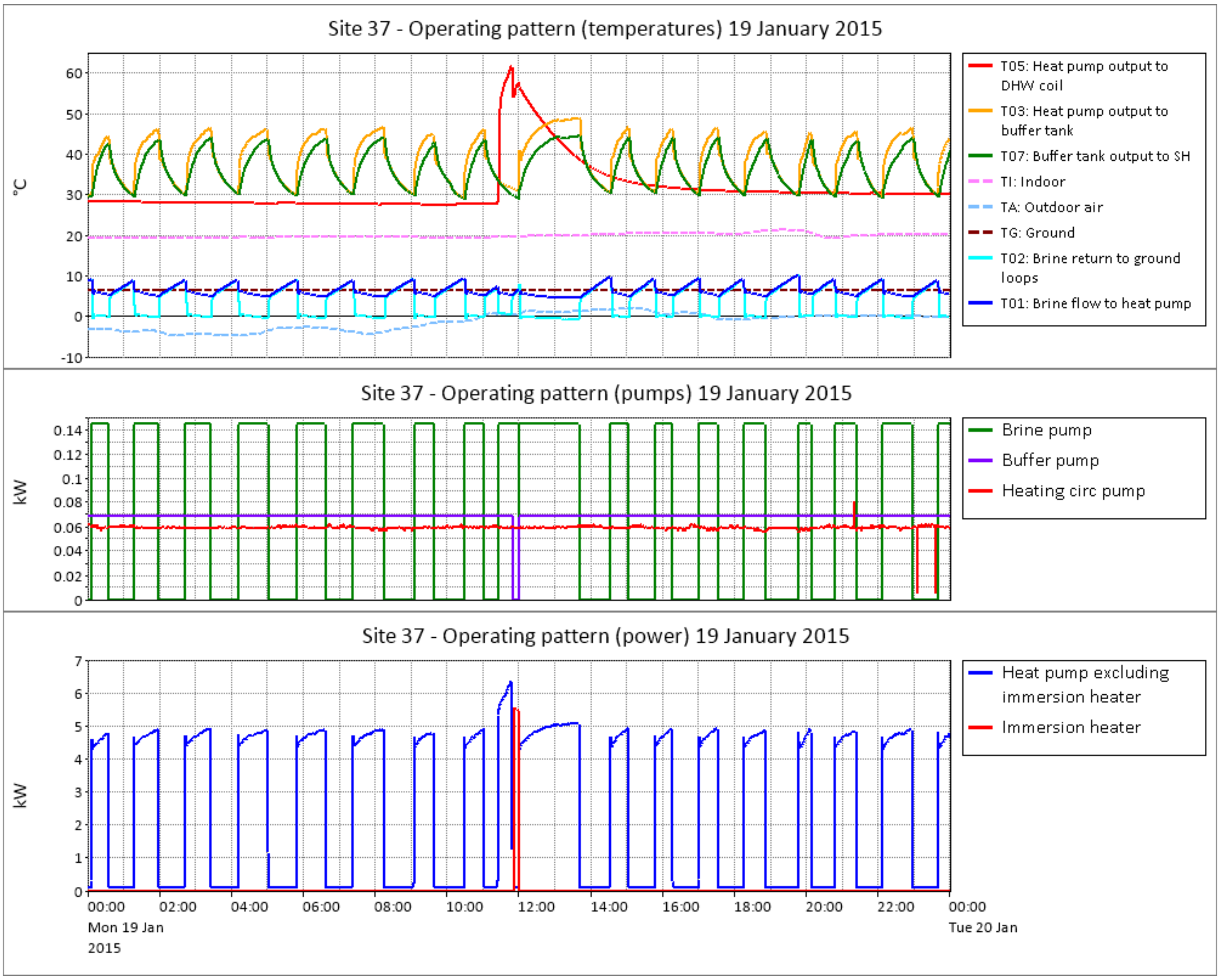

Figure 6 – Operating pattern on 19th January 2015

Concerns about the improper sterilisation (for Legionella prevention) of the domestic hot water led to the heat pump controls being adjusted during March to generate higher temperatures in the domestic hot water cylinder. This resulted in much greater use of the immersion heater in the heat pump.

Figure 7 shows the typical operating pattern on 19th May 2015 after the controls had been adjusted. Two additional temperature sensors were installed in March to record the temperature at the top of each domestic hot water cylinder. The temperature at the top of the main domestic hot water cylinder (no. 1) is shown on the graph. It can be seen that the output from the heat pump to the domestic hot water coils was up to 69 °C. The temperature at the top of the cylinder reached 63 °C and remained above 60 °C for over 10 hours.

The heat pump ran a number of times for between 10 and 20 minutes. The immersion heater was on for 90 minutes, as shown by the red line on the lower graph.

The buffer pump was running all day except while the immersion heater was on. The heating circulating pump ran all day.

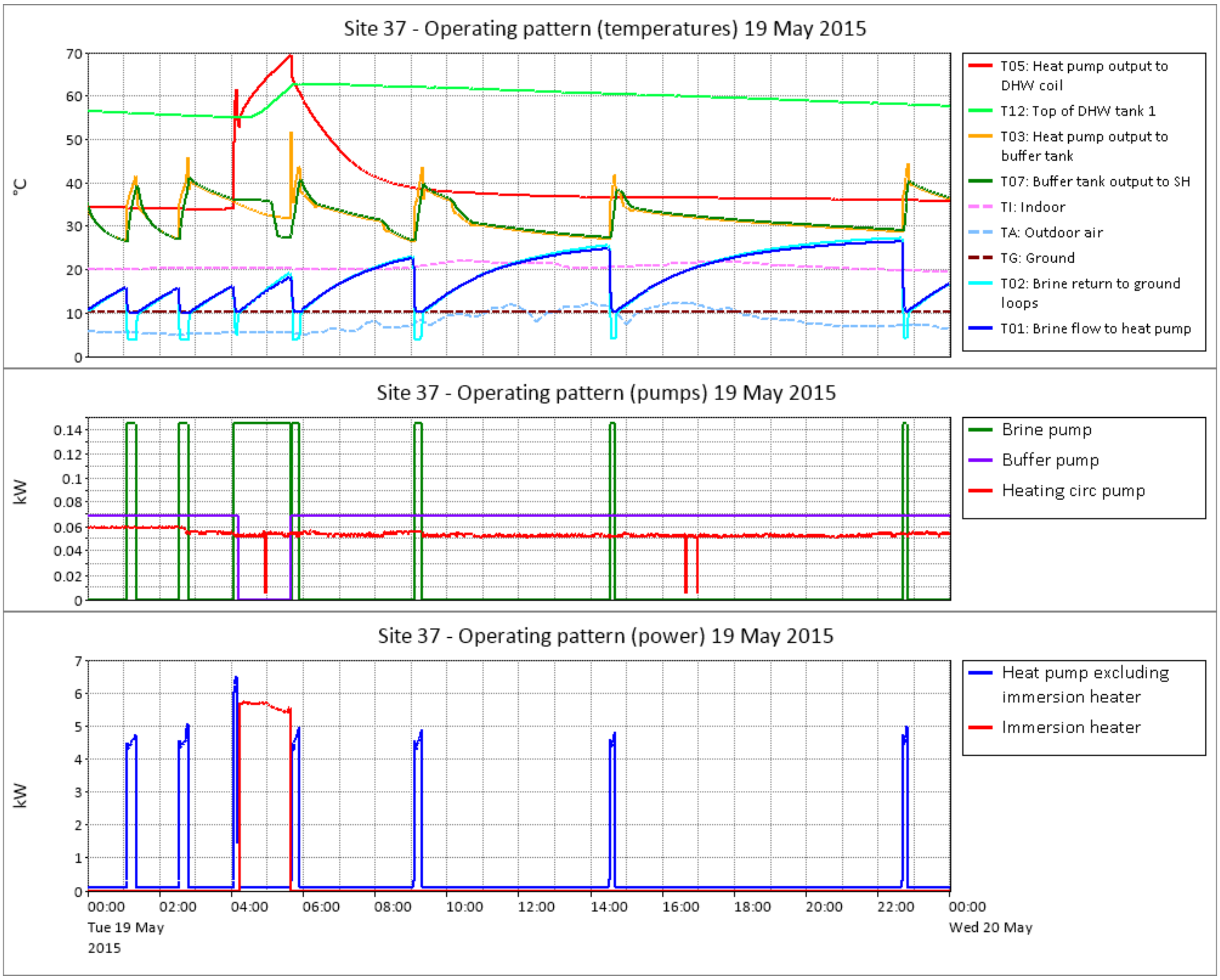

Figure 7 – Operating pattern on 19th May 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[6]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The increase in the temperatures at the top of the domestic hot water tank (light green line) and of the heat pump output to the domestic hot water coil (red line) following adjustment of the control system for Legionella control reasons can be clearly seen. A number of adjustments to the heat pump controller were made throughout the year. The details of these adjustments are not known, but the changes in temperatures related to domestic hot water can be seen.

The effect of weather compensation can be seen, whereby the heat pump output temperature was reduced as the outdoor temperature increased.

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[6] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

The temperature of the brine flow to the heat pump closely followed the ground temperature. Under warm-weather, low-load conditions it was slightly warmer than the ground. This is assumed to be due to the brine warming up in the pipe while the brine pump was stopped.

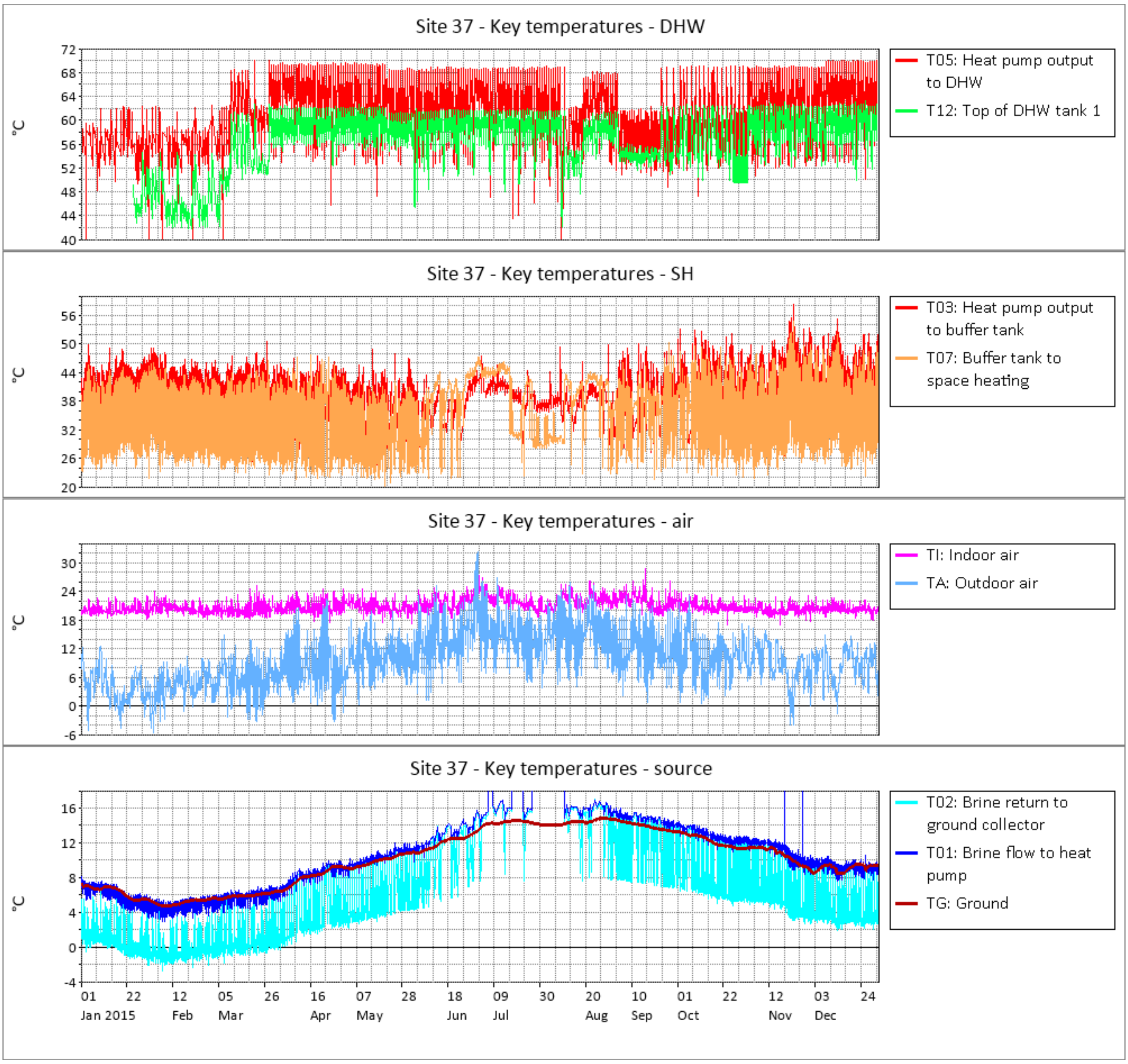

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were well above average, especially after the change in operating pattern at the end of March. This would have had a positive influence on the system performance.

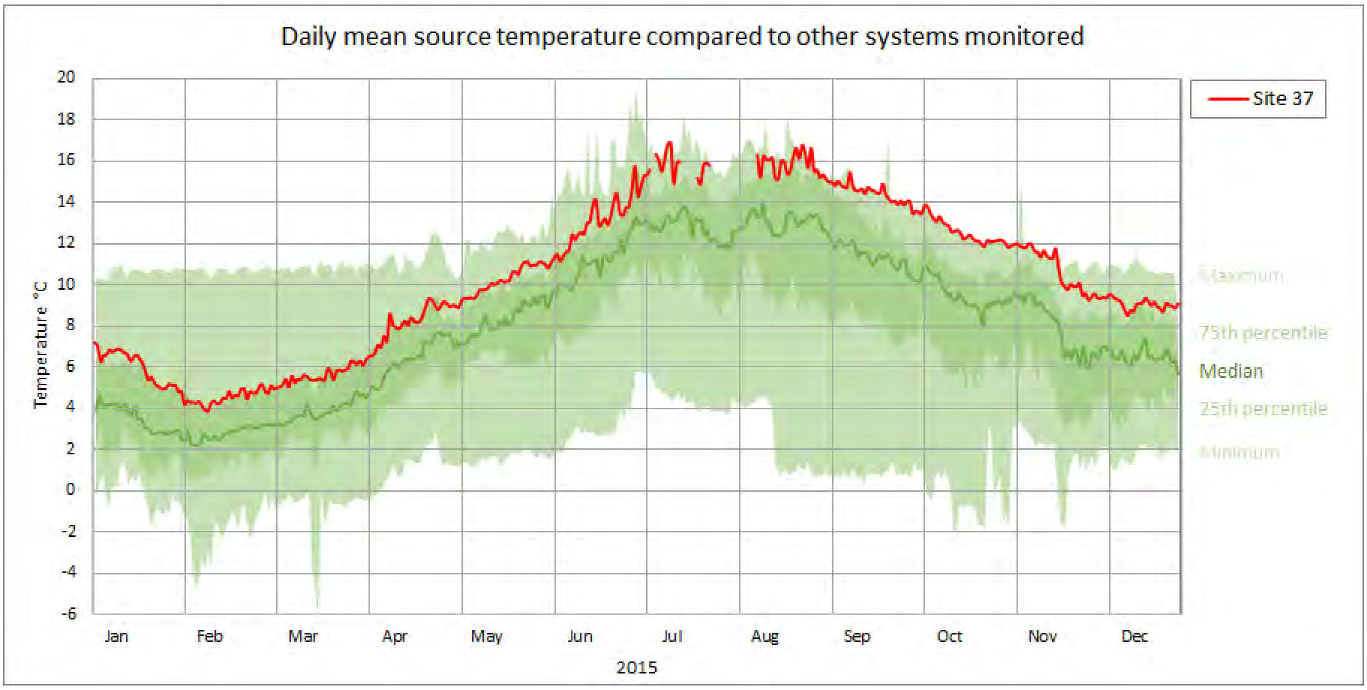

Figure 9 - Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 37 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The low temperature difference on this system indicates good collector performance.

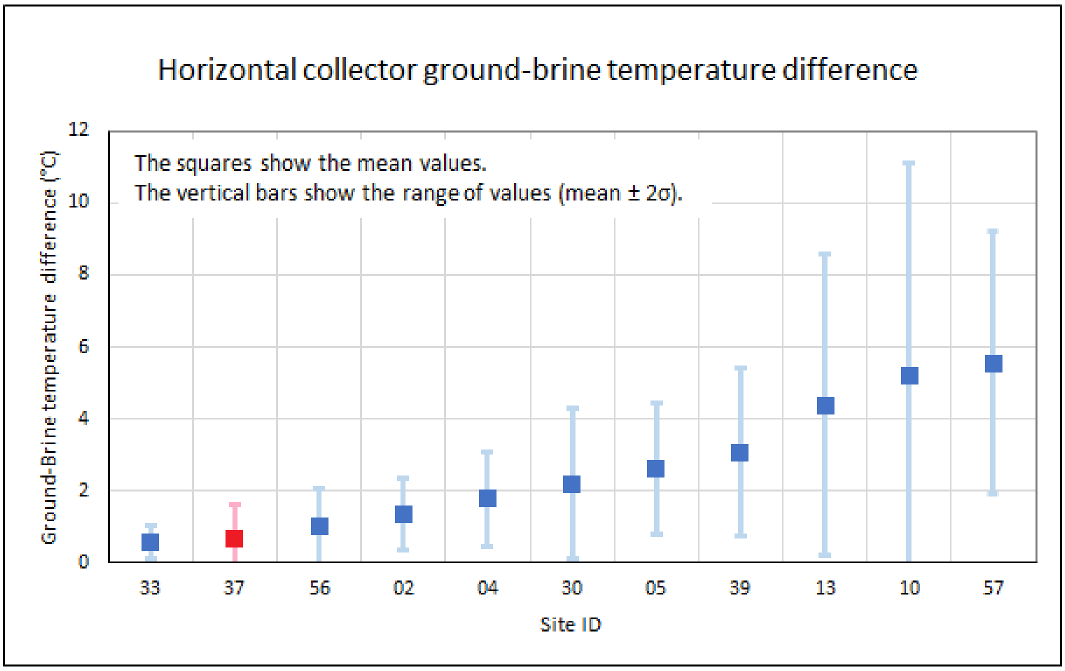

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 37 is shown in red)

Figure 11 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures on this system were below average. This would have had a positive influence on the system performance.

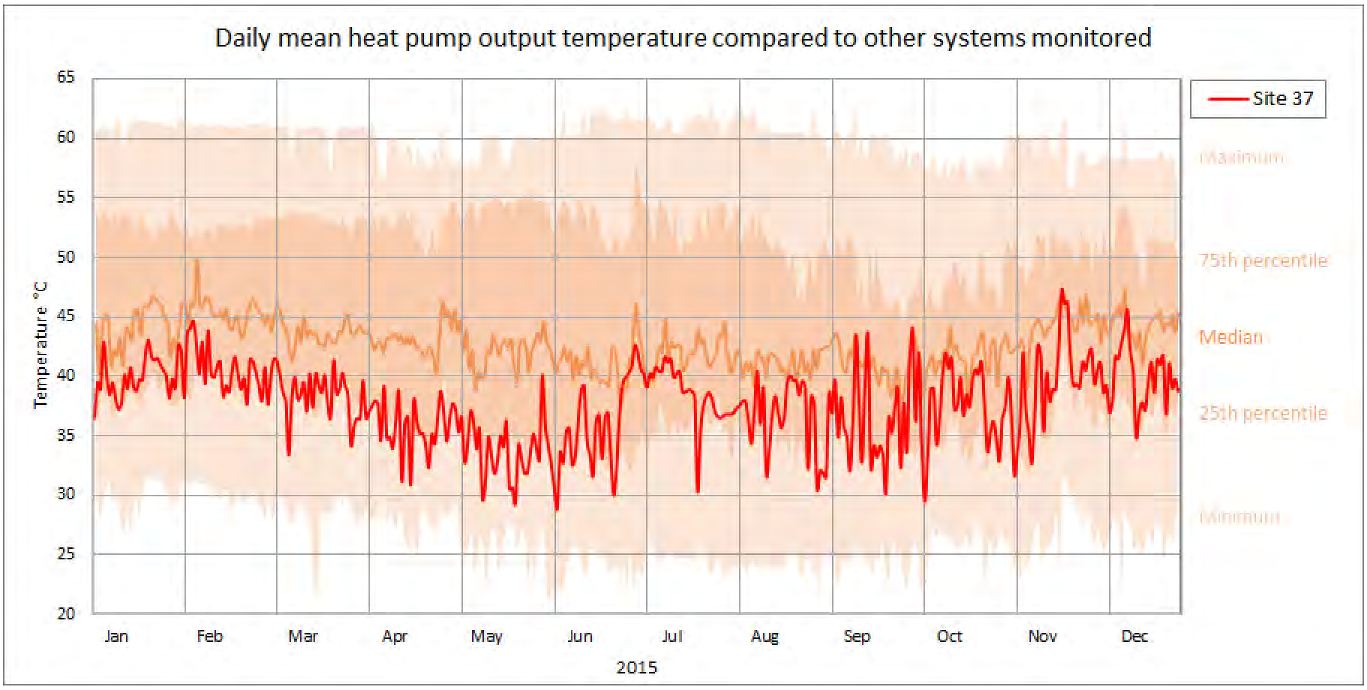

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 37 is shown in red)

Figure 12 shows how the output temperature of this system compares to other heat pump systems that use underfloor heating. The output temperatures on this system (plotted in red) were below average, which would have had a positive influence on system performance.

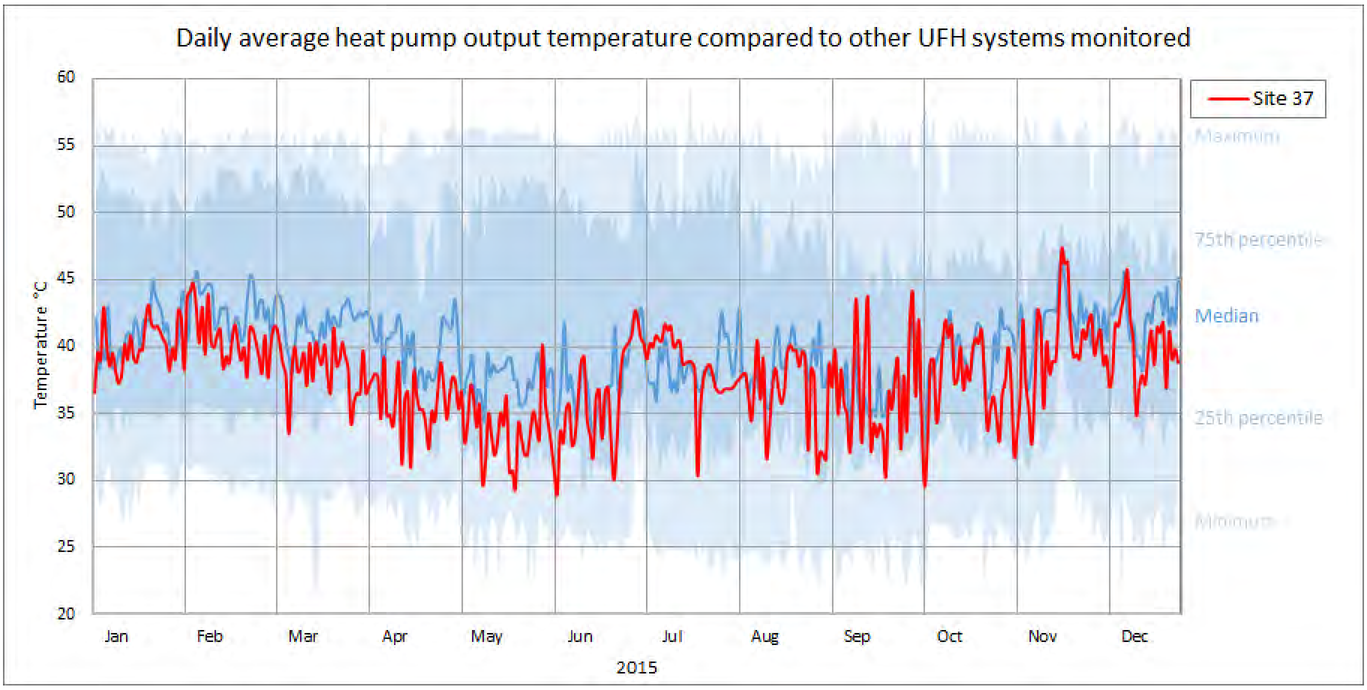

Figure 12 – Daily mean heat pump output temperature (to space heating) compared to those of other systems that use underfloor heating monitored in this project (site 37 is shown in red)

Figure 13 shows the daily maximum temperature of the output to domestic hot water, compared to other systems. After the adjustments made in March for Legionella control, the daily maximum temperatures on this system (plotted in red) were for much of the time higher than any other system monitored.

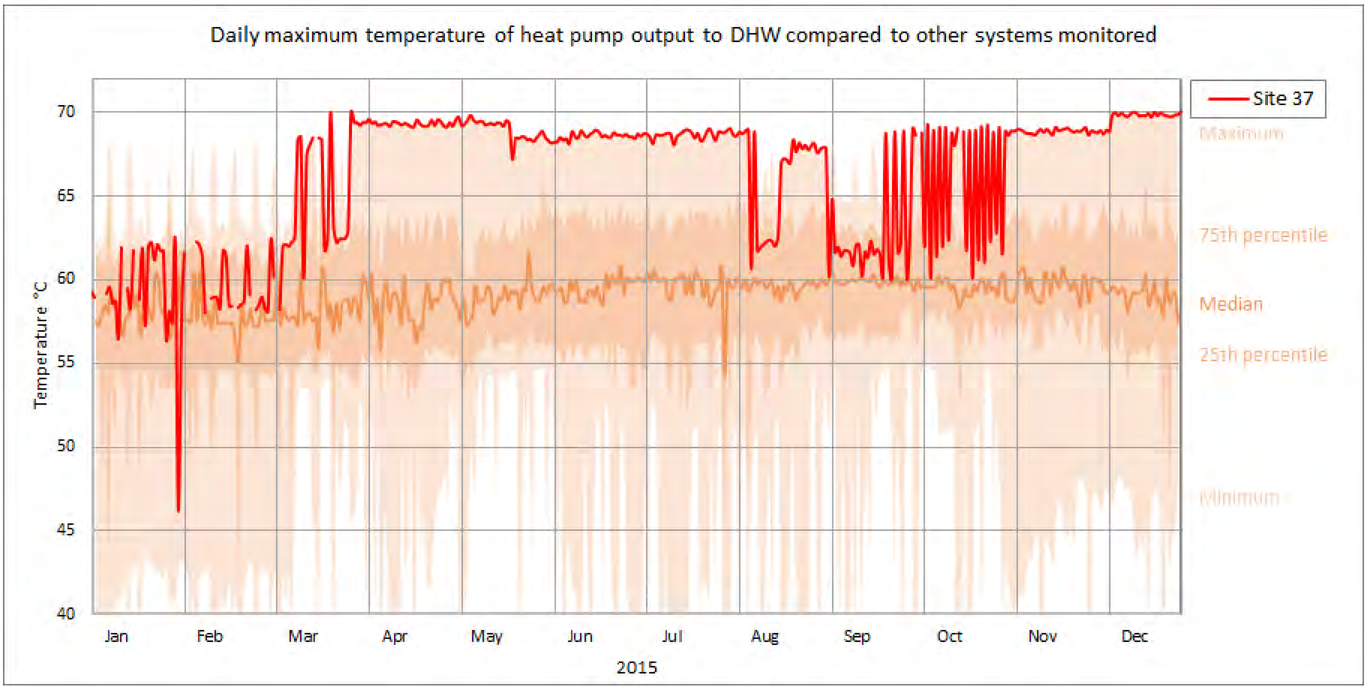

Figure 13 – Daily maximum heat pump output temperature to domestic hot water compared to other systems monitored in this project (site 37 is shown in red)

Comments

The performance of this system could not be determined with reliable accuracy because of known issues with the heat metering arrangement installed.

Aspects of this system that positively influenced its performance are:

- The source temperature was high – well above average compared to other systems in the monitored sample.
- The temperature of the heat pump output to space heating was below average compared to other systems in the monitored sample.
- The proportion of total electricity used by the brine pump was lower than average compared to other systems in the monitored sample.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the heat pump output to domestic hot water was often very high. This was because of concerns about Legionella control, and necessitated extensive use of the immersion heater. This site sometimes (perhaps once a week) requires large quantities of hot water for the showers used during sports events, while at other times only very small quantities are needed. It is not clear whether using the heat pump is the most efficient method of providing the domestic hot water. If the heat pump were used only for space heating, it would operate with a much-improved overall performance. The design of the domestic hot water system should be re-examined to consider whether a different system might be more suitable.

- The heating circulating pump ran continuously throughout the year. The controls should be altered to avoid this unnecessary waste of electricity by running the pump only when there is a demand for heating.
- There was a temperature loss of up to 4 °C through the 4-pipe buffer tank. This caused the heat pump to run with an output temperature higher than needed for the heat emitters. It is possible that a different buffer tank arrangement would provide better operating conditions. However, the design of buffer tanks is a complex topic that is outside the scope of this report.

Bibliography

[1] D. Butler, A. Abela and C. Martin, “Heat meter accuracy testing,” DECC, 2015.

[2] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[5] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 39

Prepared by GRAHAM Energy Management
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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 39 and performance results from 12 consecutive months of monitoring data.

Site 39 comprises three dwellings and first-floor offices in a rural location. A single heat pump (thermal capacity 23 kW) extracts heat from an adjacent field using horizontal ground loops and provides space heating and domestic hot water.

The seasonal heating performance factors measured over a year of operation (1st January to 31st December 2015) were:

SPFH2	[Heat delivered by the heat pump] – [heat added by the internal buffer pumps] -- [Electricity used by the heat pump excluding the internal buffer pumps]	3.02
SPFH4	Heat delivered by: [heat pump] + [immersion heater] + [heat added by heating circ pumps] – [heat loss from buffer tank] -- Electricity used by: [heat pump] + [heating circ pumps] + [immersion heater]	2.93

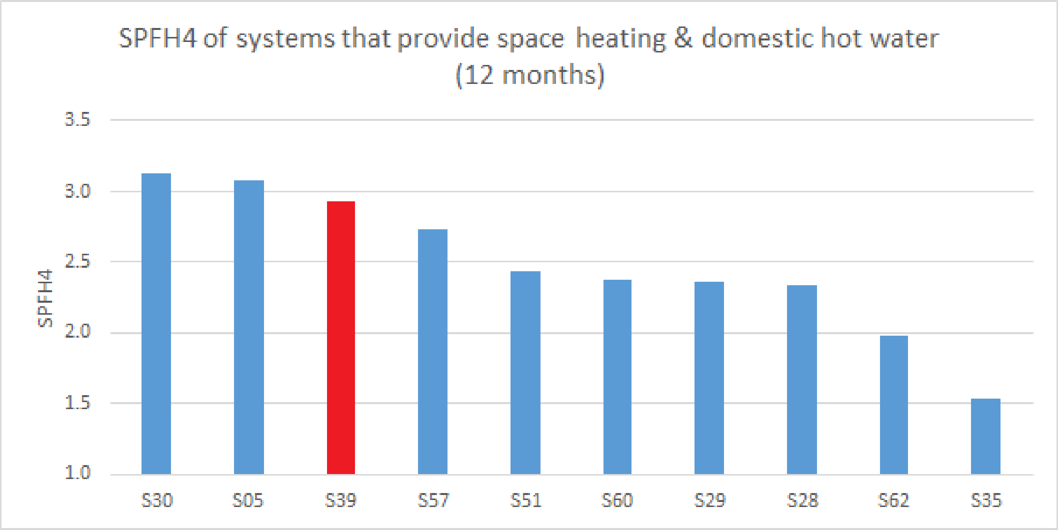

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature during warmer weather.
- The low-energy circulating pumps used only 0.3% of the electricity used by the total heat pump system.
- The buffer pumps and heating circulating pumps together used an estimated 2.9% of the total electricity, which was the lowest of all systems monitored.
- The immersion heater in the domestic hot water cylinder was not used at any time during the year.

- The temperature of the output to the domestic hot water heater coil was lower than on some other systems. The daily maximum temperature was rarely above 60 °C and more generally between 56 and 58 °C.

However, these last two points may have significance in the context of Legionella control, as the domestic hot water temperatures may not be high enough to provide disinfection.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the output to the heat emitters was not as low as might have been expected on a system designed for use with a heat pump.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	39
Survey date	11/04/2014
Monitoring installed	25/06/2014
G/WSHP	GSHP
Building type	Dwellings and first-floor offices
Location	Rural
Heat pump capacity kW_{TH}	23
Number of heat pumps	1
Number of compressors	2
Heat source	Horizontal ground loops: 3 x 400m at 1.2 m depth
Heat emitters	Radiators fitted with thermostatic valves
DHW	Yes
Auxiliary heat	9 kW immersion heater in DHW cylinder
Source pump	Internal to heat pump: 890 W max
Buffer pumps	Internal to heat pump: 2 pumps of 170 W max
SH circulating pumps	4 pumps of 45 W max
Buffer tank	300 litre 4-pipe
DHW cylinder	500 litre
Control	Heat pump controller + programmable thermostat in each building
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	2
Heat meter interface	Pulse (1 kWh/pulse)
Comments	

Table 1 – System details

This site comprises three dwellings and first-floor offices within adjoining buildings, in a rural location.

The application entails extracting heat from the ground to provide space heating and domestic hot water in buildings that have been refurbished with good thermal insulation, in a location with below-average outdoor temperatures – annual mean 9.7 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The system performance would be expected to be average.

Heat pump and monitoring system

A ground-source heat pump (thermal capacity 23 kW) is installed in a room below the offices and adjacent to one of the dwellings, to provide space heating (SH) and domestic hot water (DHW).

Heat is extracted from 3 x 400 metre horizontal ground loops at a depth of 1.2 metres, in a field approximately 100 metres from the heat pump plant room.

The heat emitters are radiators, sized for use with the heat pump and fitted with thermostatic valves.

The heat pump has two vapour-compression circuits and incorporates a brine pump and two heating circulating pumps.

A 300-litre 4-pipe buffer tank is installed between the heat pump output and the heating circuits.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures (“T”) are monitored at key points in the system using surface-mounted probes[1]. The outdoor air and ground temperatures are also monitored.

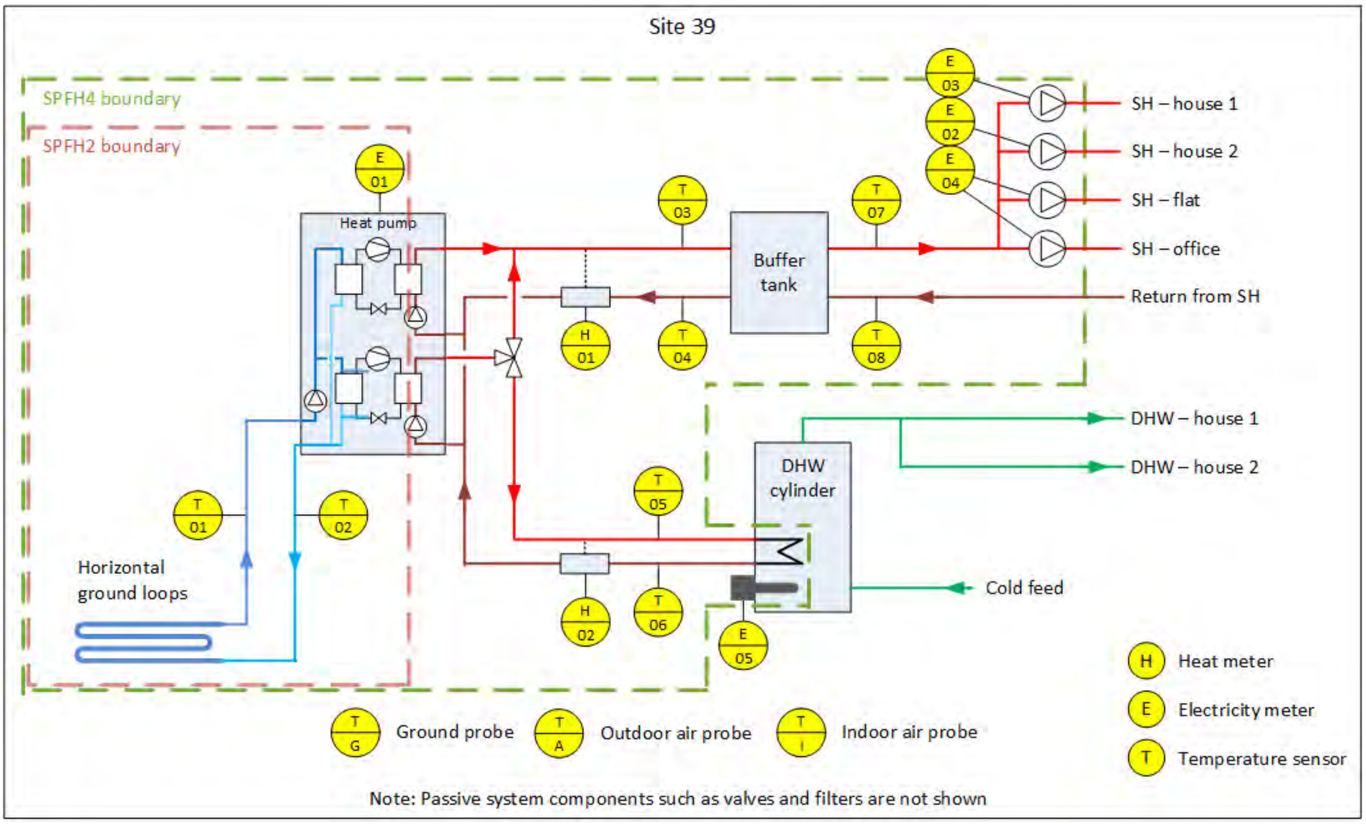

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pump. Two heat meters are installed: one between the heat pump and the buffer tank and one between the heat pump and the domestic hot water cylinder heating coil. Ultrasonic flow meters are installed in the return pipes, with matched temperature sensors installed in pockets in the flow and return pipes. The calculators are battery-powered. Monitoring was via the pulse interfaces.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump including the internal brine pump but excluding the internal buffer pumps.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$\text{SPF}_{H2} = \frac{\text{[Heat output of heat pump to SH \& DHW]} - \text{[heat added by internal buffer pumps]}}{\text{Electricity used by: [heat pump]} - \text{[internal buffer pumps]}}$$

- This calculation required the electrical energy used by the buffer pumps inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pumps, calculated for intervals that the heat pump was running.

- The heat added by the buffer pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.

$$\text{SPF}_{H4} = \frac{\begin{array}{c}\text{[Heat output of heat pump to SH \& DHW]} - \text{[heat loss from buffer tank]}\\ + \text{[heat added by SH circ pumps]} + \text{[heat added by immersion heater]}\end{array}}{\text{Electricity used by: [heat pump]} + \text{[SH circ pumps]} + \text{[immersion heater]}}$$

---

[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

- The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 524 452, which represents 99.8% of the 12-month period.

The SPFH2 and SPFH4 values for this system, measured between 1st January and 31st December 2015, are shown in Table 2:

SPFH2	3.02
SPFH4	2.93

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 2.93 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPFH2 and SPFH4 values for the system. There was a noticeable increase in the SPF values from September to November compared to earlier months. This can be explained by the ground and outdoor air temperatures being higher during the autumn months than they were during the spring (as shown below in Figure 8), with the average temperature lift (heat pump input to output) being approximately 10 °C lower.

The dips in the SPF values during the summer months are due to the low space heating demand during those periods, with the heat pump being used mainly for domestic hot water. However, the heat demand during the summer was also low, so the effect on the overall annual performance was not very significant.

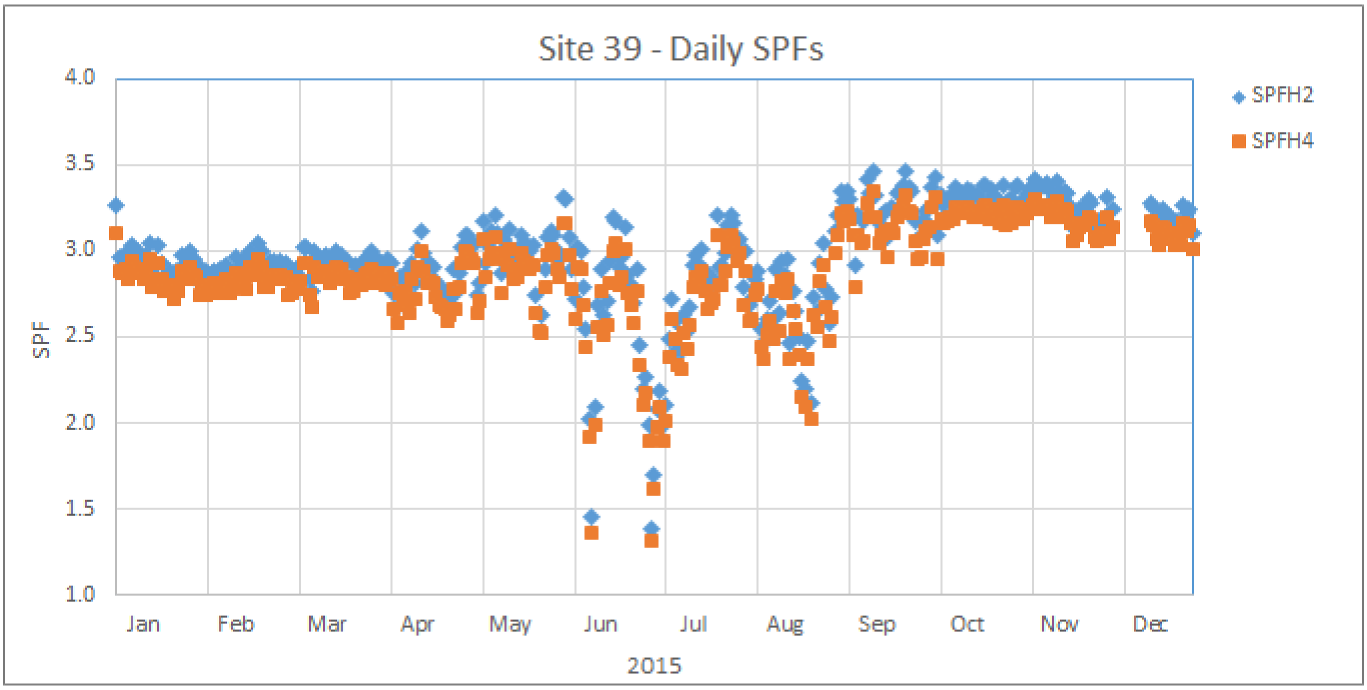

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity use by the total heat pump system and the outdoor air temperature are shown for reference.

There was demand for both space heating and domestic hot water all year. The space heating demand varied with the outdoor temperature. The domestic hot water demand varied from day to day but was similar throughout the year.

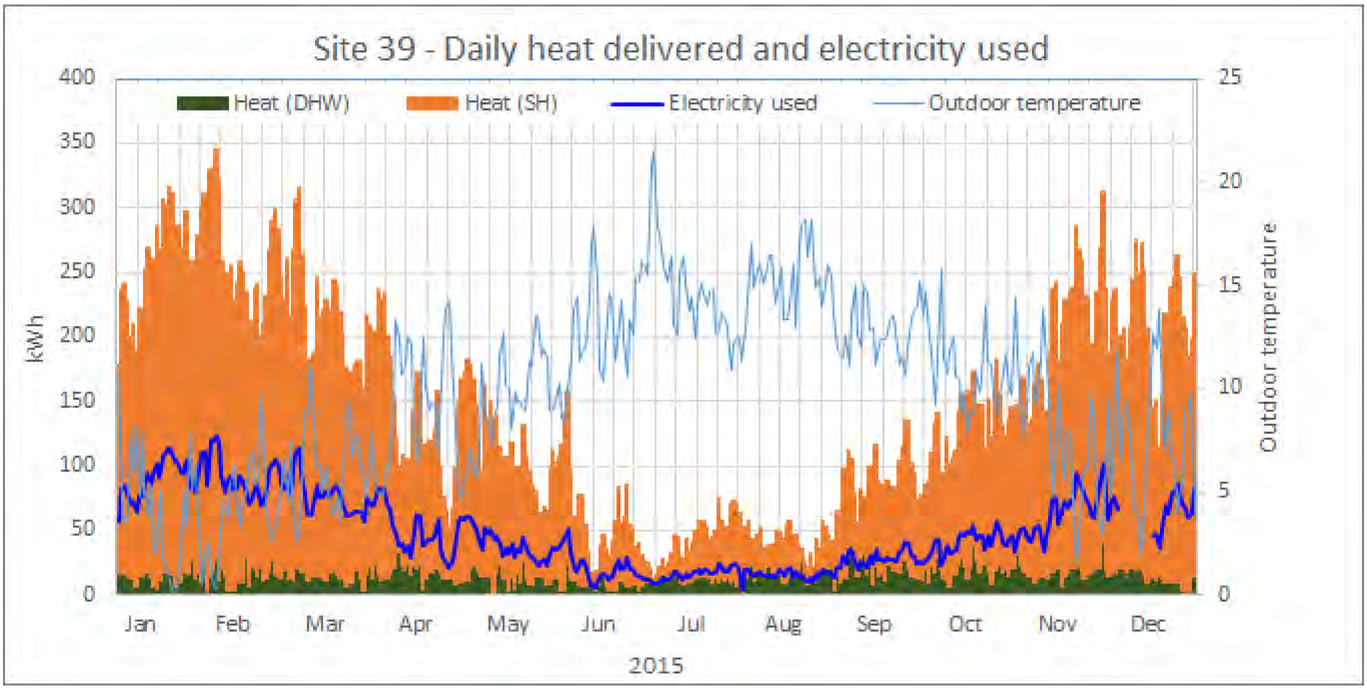

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

Table 3 shows the estimated breakdown of the heat delivered to space heating and to domestic hot water during the period from 1st January to 31st December 2015.

	%
Heat delivered to space heating	89.1%
Heat to domestic hot water (from heat pump)	10.9%
Heat to domestic hot water (from immersion heater)	0.0%

Table 3 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The very low proportion of energy used by the space heating circulating pumps (0.3%) was a consequence of the low-energy pumps installed on this system. The data for the brine pump and the buffer pumps (which are inside the heat pump and were not separately metered) have been estimated from the pump rating plates and from the heat pump manufacturer's data sheets.

The brine pump used an estimated 5.7% of the total electricity which is below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

The buffer pumps and heating circulating pumps together used an estimated 2.9% of the total electricity, which was the lowest of all systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance.

Note: the electricity data records for 7th to 21st December are incomplete, so the values for these weeks have been excluded from the chart.

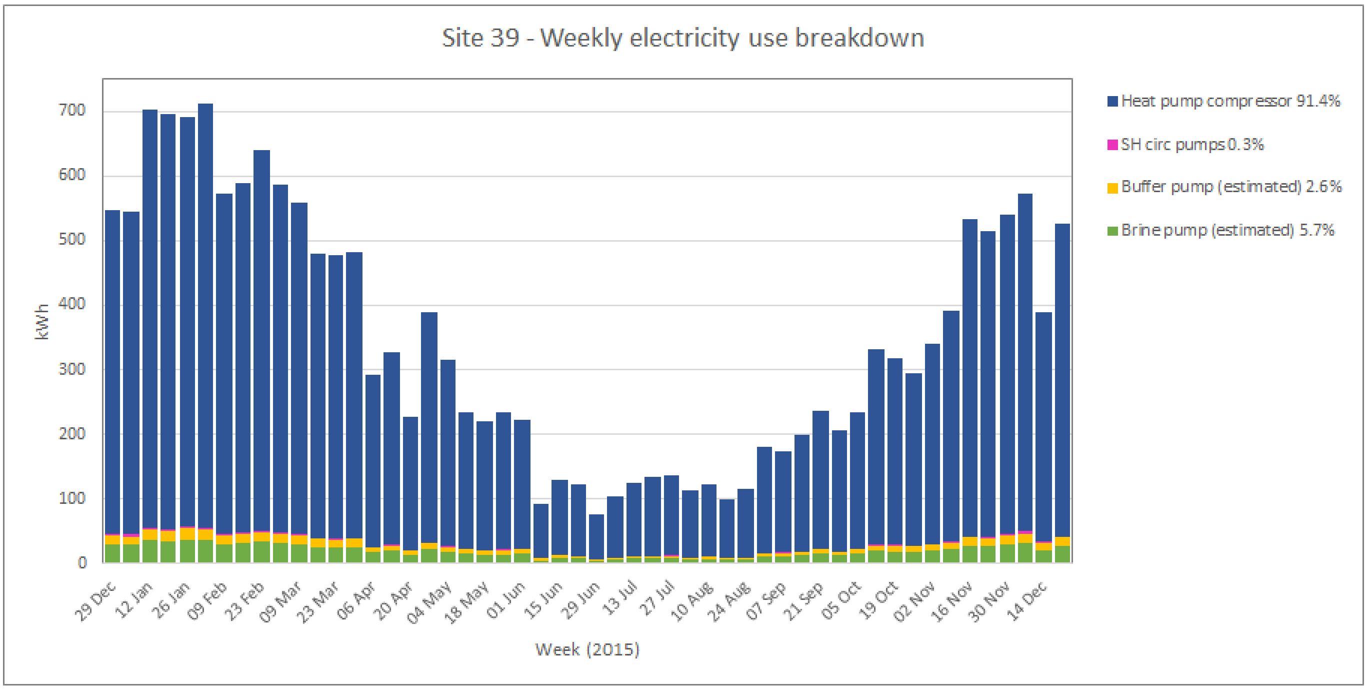

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 21st January when the outdoor temperature was between -2 and +3 °C. The temperature of the heat pump output to the domestic hot water coil was up to 60 °C, and the temperature to the buffer tank was higher – up to 63 °C. The output from the buffer tank to the space heating circuits was up to 58 °C. The loss of temperature between the heat pump output and the buffer tank output was generally around 5 °C.

The high-frequency oscillation (between 6 and 12 cycles per hour) of the temperature of the return from the heat emitters is unusual. A possible explanation is that the thermostatic radiator valves were hunting[4]. The effect of this on the system performance is not known.

The ground temperature measured 1 metre below the surface at a location remote from the ground coils was 5.3 °C. The brine flow to the heat pump was between 2 and 4 °C while the heat pump was running, and the return to the ground coils was never lower than -0.5 °C.

The lower graph shows the electrical power drawn by the heat pump. The use of one or two compressors is shown by the steps in the power.

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[4] Hunting: a term often used to describe the undesirable oscillation of a control mechanism either side of the set point.

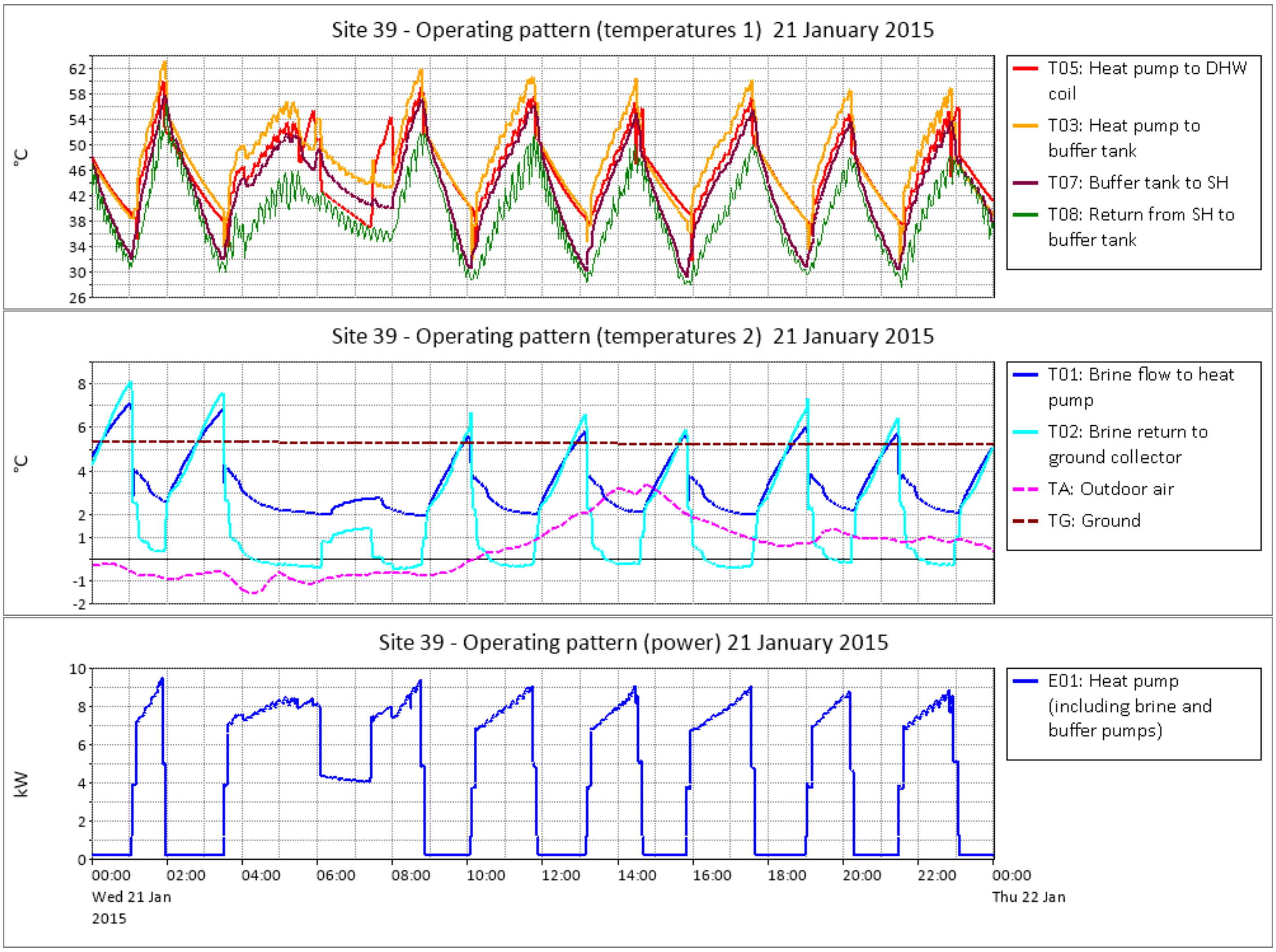

Figure 6 – Operating pattern on 21st January 2015

Figure 7 shows the typical pattern during July when the outdoor temperature was between 11 and 18 °C. The effect of the weather compensation function can be seen: the maximum output temperature to the buffer tank was (briefly) 48 °C. The output to the domestic hot water coil was up to 58 °C three times during the day as the demand for domestic hot water was satisfied.

The power drawn by the heat pump is shown on the lower graph. Apparently only one compressor was in use. The power was higher when the heat pump was working in domestic hot water mode, because of the higher output temperature.

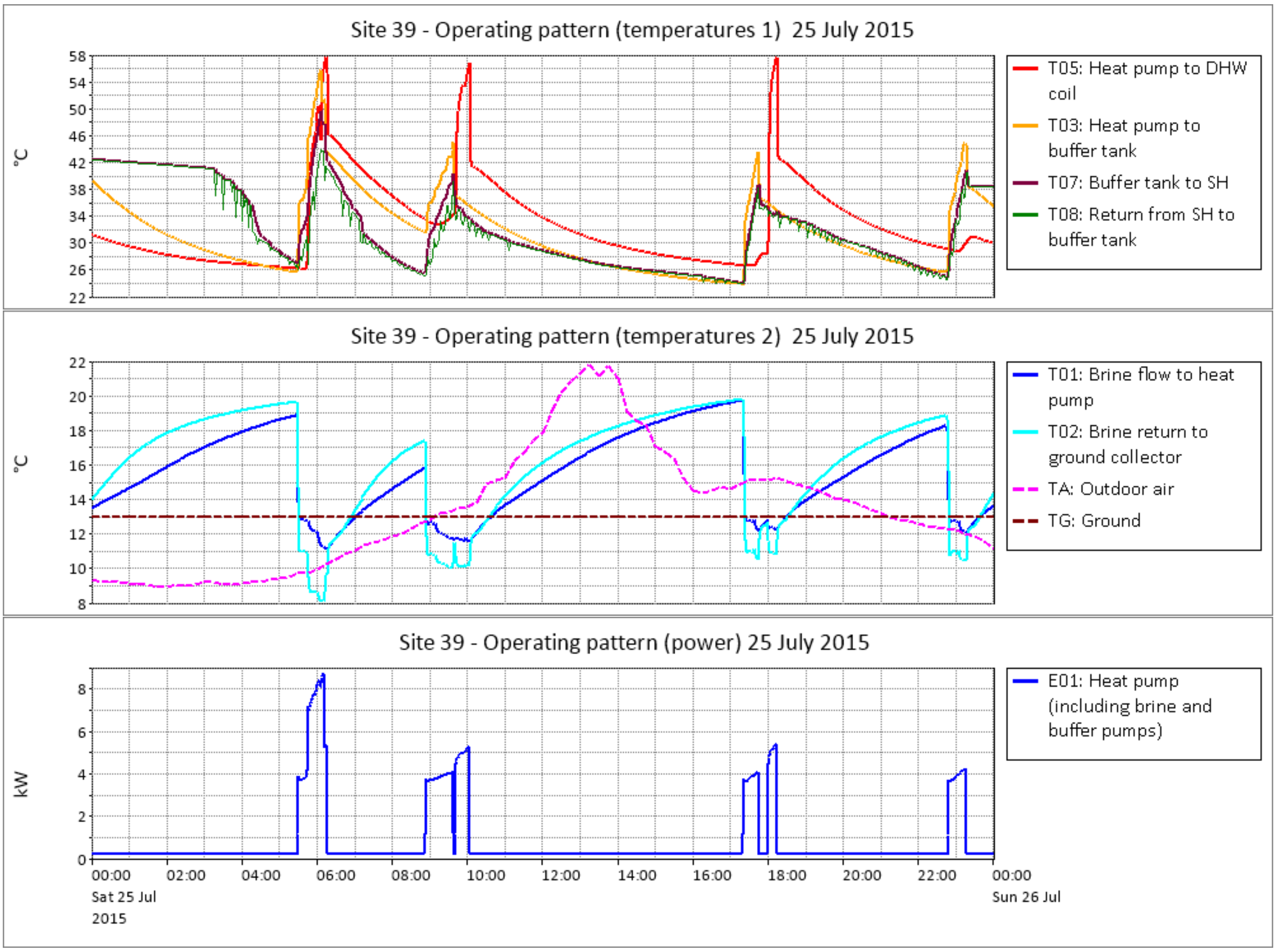

Figure 7 – Operating pattern on 21st July 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[5]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The effect of the weather compensation can be seen, with the temperature of the output to space heating being lower during warmer weather. The daily maximum temperature of the output to domestic hot water varied between 56 and 62 °C from day to day throughout the year.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

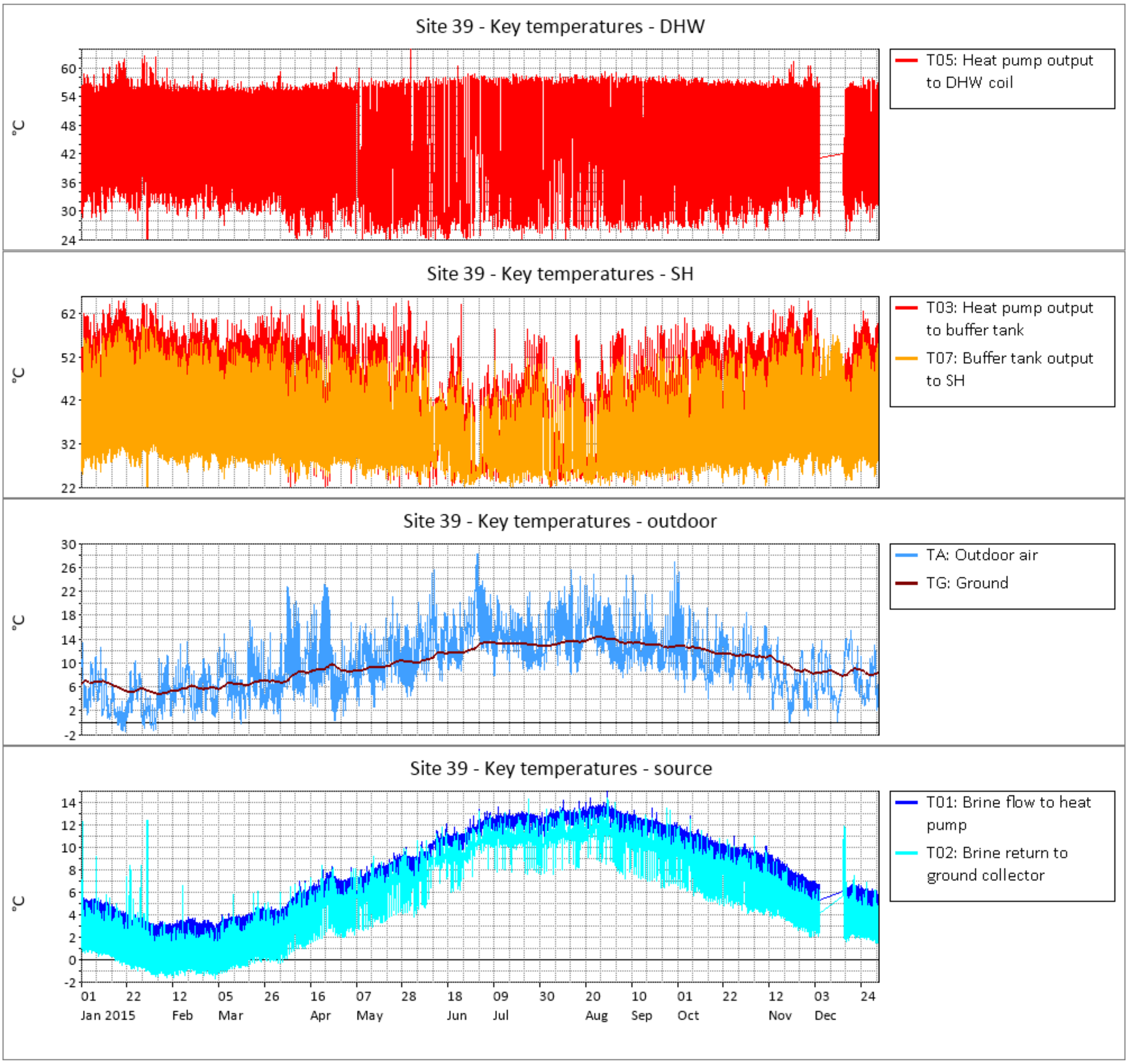

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures on this system (plotted in red) were slightly below average compared to the other systems.

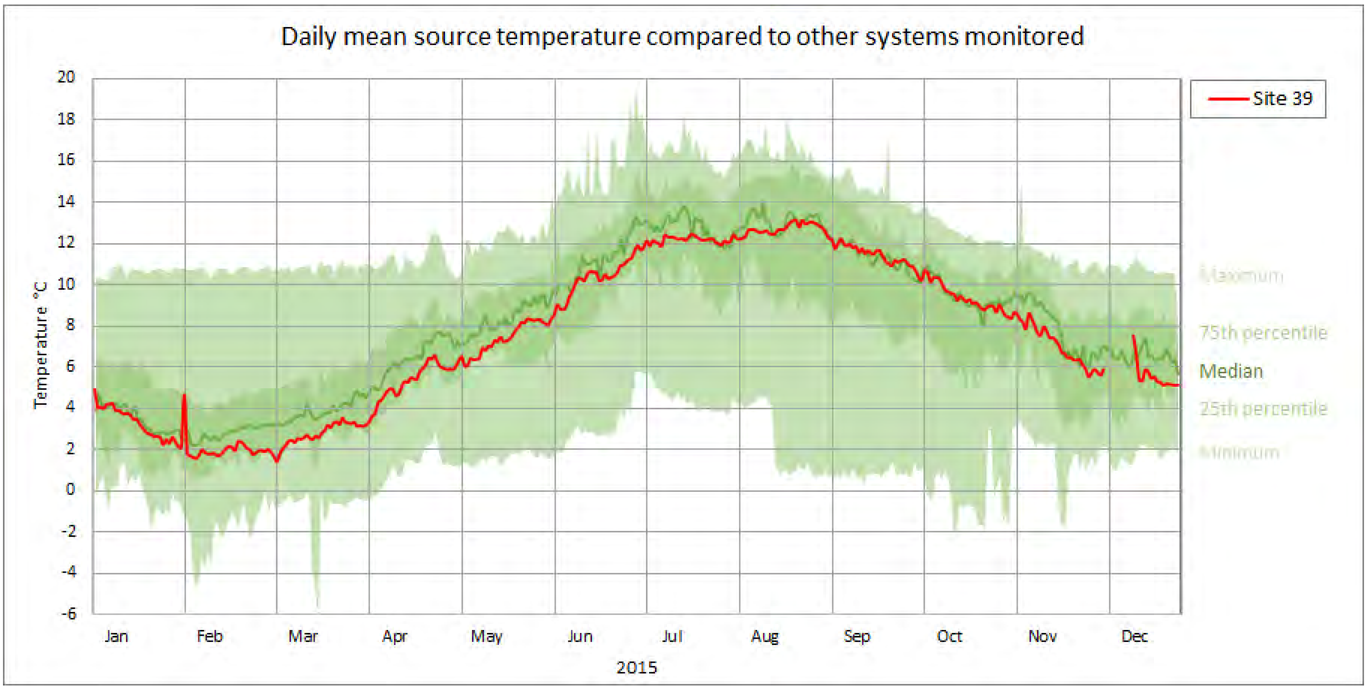

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 39 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The temperature difference on this system was above average, indicating slightly below average collector performance.

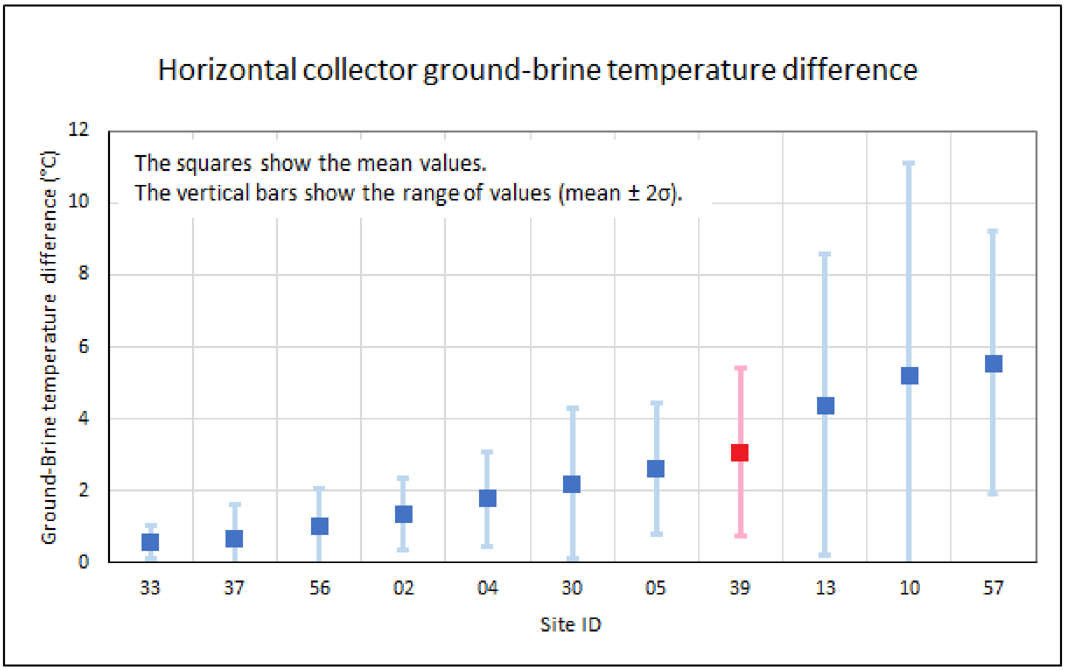

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 39 is shown in red)

Figure 11 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures on this system were slightly above average during the winter and slightly below average in the summer months, compared to other systems monitored.

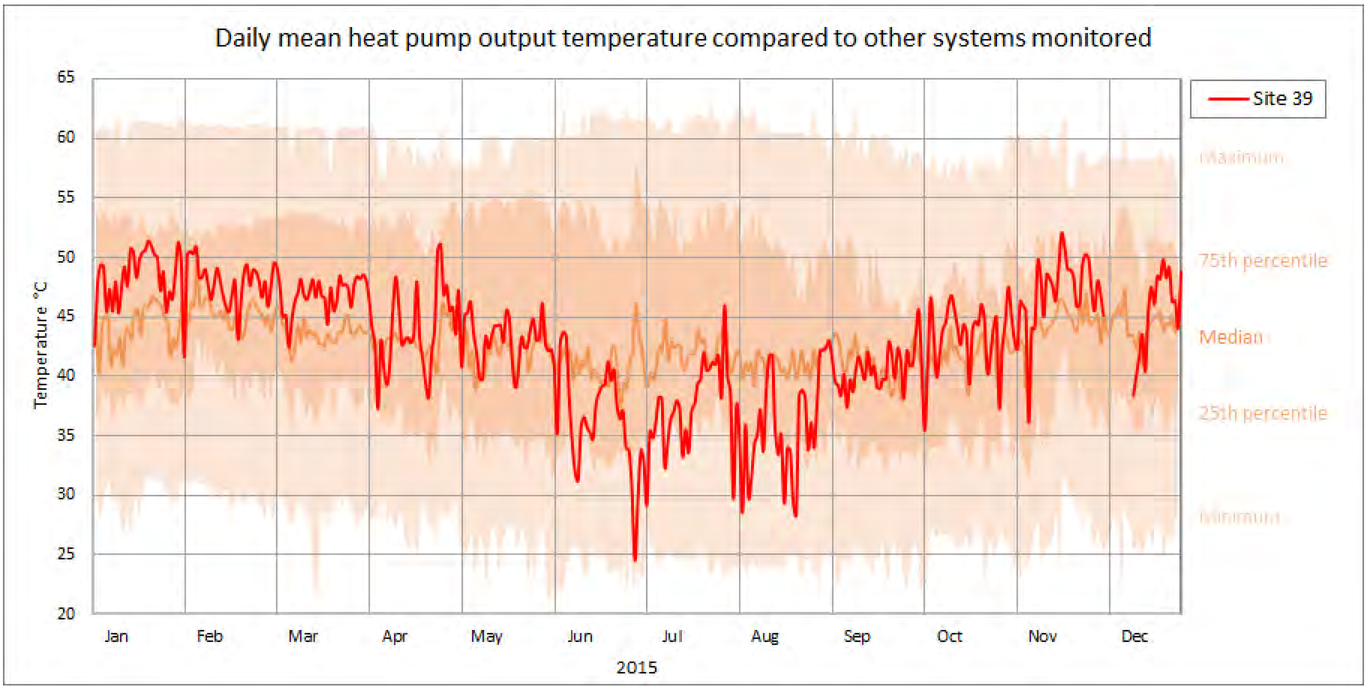

Figure 11 – Daily mean heat pump output temperature to space heating compared to those of other systems monitored in this project (site 39 is shown in red)

Figure 12 shows the daily maximum temperature of the heat pump output to the domestic hot water heating coil. In general, the temperature on this system was lower than average. This would have had a positive influence on system performance. However, it should be noted that the temperatures in the domestic hot water system may not be high enough for adequate control of Legionella[6].

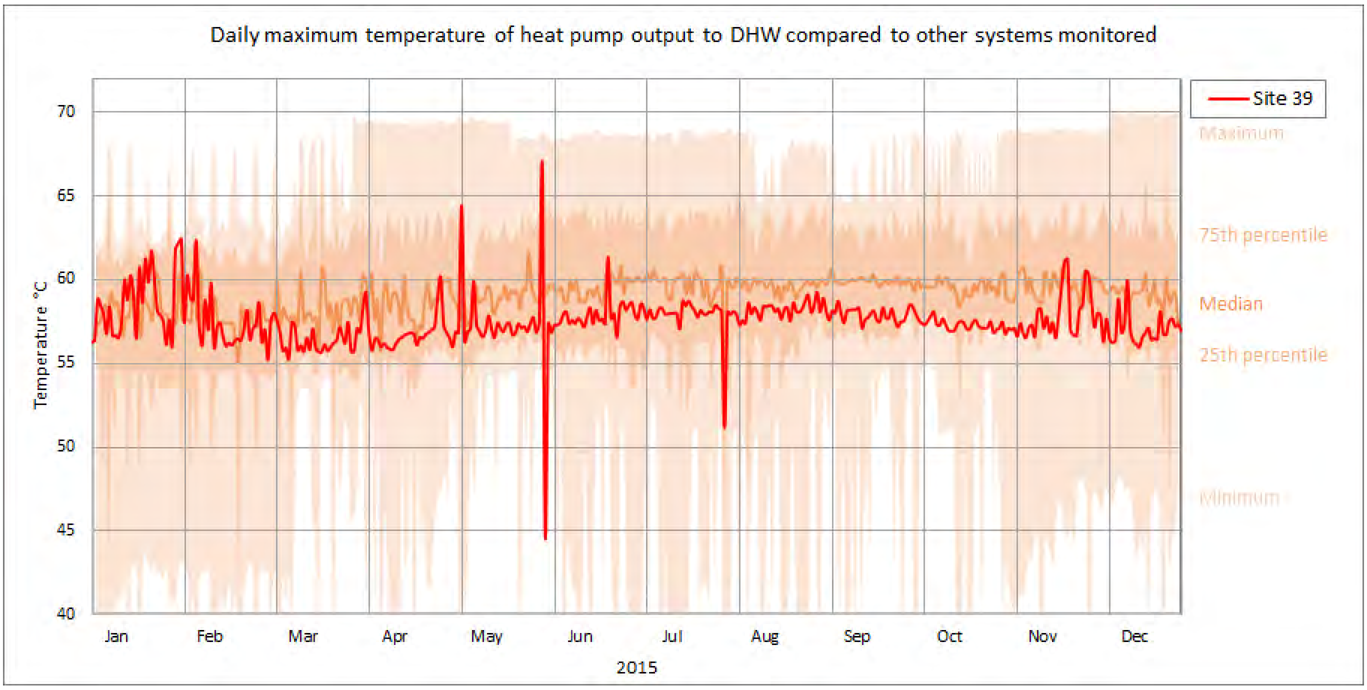

Figure 12 – Daily maximum heat pump output temperature to domestic hot water compared to those of other systems monitored in this project (site 39 is shown in red)

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[6] Legionella control is examined in more detail in the Final Report of this project [5].

Comments

The performance of this system (SPF_{H4} = 2.93) was above average compared with other systems providing both space heating and domestic hot water that were monitored in this project (SPF_{H4} range: 1.54 to 3.13, median value 2.41).

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature during warmer weather.
- The low-energy circulating pumps used only 0.3% of the electricity used by the total heat pump system.
- The buffer pumps and heating circulating pumps together used an estimated 2.9% of the total electricity, which was the lowest of all systems monitored (range 2.9% - 20.5%, median 8.8%).
- The immersion heater in the domestic hot water cylinder was not used at any time during the year.
- The temperature of the output to the domestic hot water heater coil was lower than on some other systems. The daily maximum temperature was rarely above 60 °C and more generally between 56 and 58 °C.

Note: These last two points may have significance in the context of Legionella control, as the DHW temperatures may not be high enough to provide disinfection. The recommendations of the Legionella risk assessment should be reviewed to ensure that proper disinfection is being carried out.

Aspects of the system that may have negatively influenced its performance include:

- The loss of temperature through the 4-pipe buffer tank output was high (around 5 °C). It is possible that a different buffer tank arrangement would reduce this loss and yield improved system performance. However, the design of buffer tanks is a complex topic and is outside the scope of this report.
- The temperature of the output to the heat emitters was not as low as might have been expected on a system designed for use with a heat pump. The observed oscillation of the heating return temperature suggests that there may be an issue with the heating controls. This should be investigated. A reduction in the temperature of the output to the emitters would improve the overall system performance.

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Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 40

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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Dr David Hughes asserts his moral right under the Copyright, Designs and Patents Act 1988 to be identified as the author of this work.

This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

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Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 40 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 40 is a short-term rental apartment complex comprising two buildings: one with eight apartments, the other a laundry and office.

A single heat pump (thermal capacity 31 kW) extracts heat from horizontal ground loops and provides hot water via a large central buffer tank to each of the premises for underfloor space heating and domestic hot water. The limitations of this arrangement with regard to system performance are discussed and some suggestions made for alterations that would improve the performance.

Seasonal performance factors are not presented because characteristics of the heat meters, previously installed for the Renewable Heat Incentive and used to monitor this system, have led to unacceptably high uncertainties of measurement of the heat delivered.

Aspects of this system that positively influenced its performance are:

- The source temperature was slightly above average compared to other systems in the monitored sample.
- Auxiliary heat was not used.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump output temperature was high and weather compensation could not be used because of the need to provide hot water to the combined space heating and domestic hot water system. This is a consequence of the system design.
- The brine pump accounted for an estimated 11.8% of the total electricity, which is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

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[1] The heat meter installation on this system uses strap-on temperature sensors. This technique is known [1] to be prone to unacceptably large measurement errors and the performance values could therefore not reliably be determined.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**40**
Survey date	28/02/2014
Monitoring installed	11/07/2014
G/WSHP	GSHP
Building type	Short-term rental apartments
Location	Rural
Heat pump capacity kW_{TH}	31
Number of heat pumps	1
Number of compressors	2
Heat source	Horizontal ground loops: 2.2 km at 1.2 m depth
Heat emitters	Underfloor heating pipes
DHW	Yes
Auxiliary heat	2 x immersion heaters in buffer tank
Source pump	Internal in the heat pump: 1 pump of 890 W
Buffer pumps	Internal in the heat pump: 2 pumps of 170 W
SH circulating pumps	Dual pumpset: 2 pumps of 180 W max (duty/standby, variable-speed)
Buffer tank	1800 litre 4-pipe
DHW cylinder	A thermal accumulator in each apartment provides DHW
Control	Heat pump controller, with a heating programmer and a room thermostat in each apartment
Weather compensation	No
Heat meter type	Mechanical
No. of heat meters	4
Heat meter interface	Pulse (100 Wh/pulse)
Comments	A solar thermal collector provides some heat to the buffer tank. An immersion heater is installed in each thermal accumulator, but these were isolated during the monitoring period.

Table 1 – System details

Site 40 is a short-term rental apartment complex comprising two buildings: one with 8 apartments, the other a laundry and office.

This application entails extracting heat from the ground to provide space heating (SH) and domestic hot water (DHW) to a modern well-insulated building, using a common heat distribution system that requires a constantly high heat pump output temperature. The site is located in an area with below-average outdoor temperatures – approximate annual mean 9 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The system performance would be expected to be somewhat below average.

Heat pump and monitoring systems

A single heat pump (with two compressors and a total thermal capacity of 31 kW) provides hot water to each of the premises for underfloor space heating and domestic hot water, via a central 1800-litre buffer tank. The heating pipes to the office/laundry building run underground for a distance of approximately 25 metres.

The heat source is 2200 m of horizontal ground loops at a depth of approximately 1.2 m, in a field near the entrance to the site. The ground loop manifold is approximately 200 m from the heat pump plant room.

A solar thermal collector array also provides heat to the central buffer tank.

Two immersion heaters in the buffer tank provide auxiliary heat when needed (although these have never been used during the monitoring period).

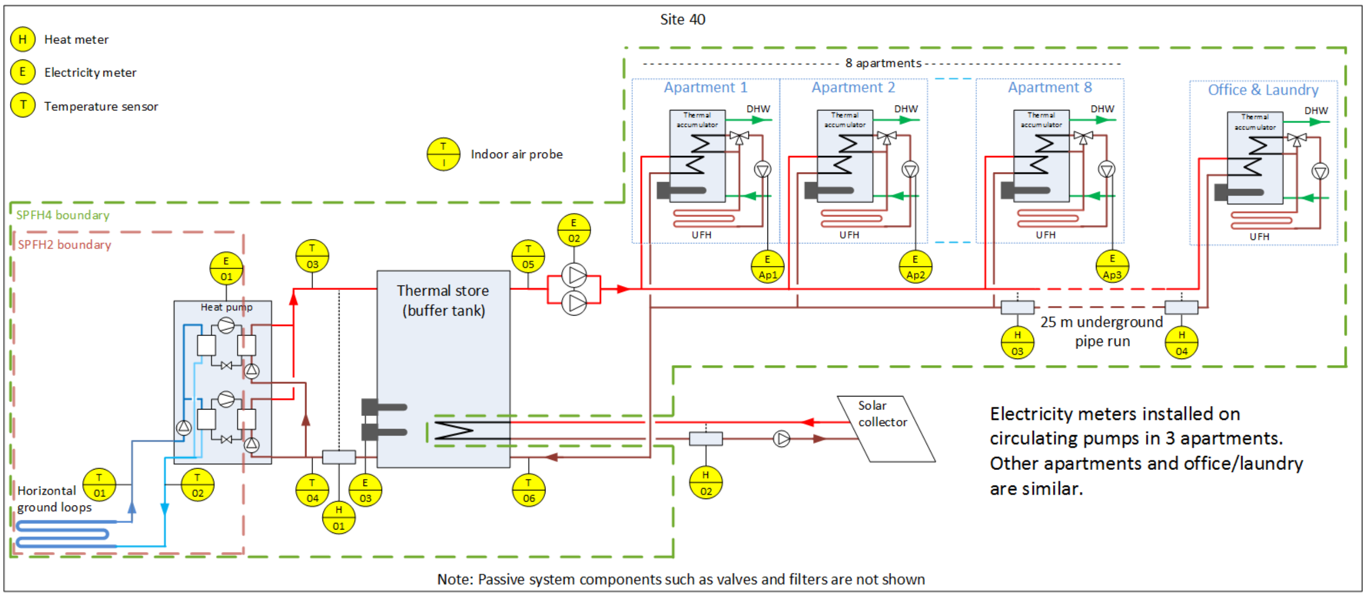
Each apartment has its own combined thermal accumulator / domestic hot water cylinder with a 3 kW immersion heater. All of these immersion heaters were isolated during the monitoring period.

Hot water is pumped from a coil in each thermal accumulator to the underfloor heating in the apartment, via a mixing valve to reduce the temperature (to approximately 30 – 35 °C).

The system is controlled by the heat pump controller, with a heating programmer and a room thermostat in each apartment.

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown. Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2].

It was found that the ZigBee® wireless technology used by the monitoring equipment presented significant difficulties with communication to all areas of this site, due to a combination of the extensive use of aluminium foil-backed thermal insulation in the building creating an effective barrier to the radio signals and to the layout of the site. Therefore, the outdoor air and ground temperatures were not recorded. The outdoor air and ground temperatures shown throughout this document have been estimated using data from other sites in similar geographical locations.



Electricity meters installed on circulating pumps in 3 apartments. Other apartments and office/laundry are similar.

Note: Passive system components such as valves and filters are not shown

Figure 1 – System schematic showing the monitoring instrumentation installed

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[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [7] for further details. Note that these temperature measurements were not used for heat metering.

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pump. Heat meter H01 is installed between the heat pump and the buffer tank. Meter H02 measures the heat supplied by the solar thermal collector. Meters H03 and H04 are installed at each end of the underground pipe to the office/laundry building, to measure the heat loss from the underground pipe.

The heat meters all use mechanical multi-jet turbine flow meters and strap-on temperature sensors. Although the use of strap-on temperature probes was as recommended by the meter manufacturer at the time of installation, it is known from subsequent research [1] that this technique can result in large measurement errors.

The heat calculators are of a type intended for use with antifreeze in the working fluid. It is understood that ethylene glycol has been added to the heating circuit, although the concentration is unknown.

Heat meters H01 and H02 were monitored via their pulse interfaces. The heat meters H03 and H04 were read manually.

Because of the heat metering issues, it has not been possible to determine the heat pump or system performance with sufficient certainty for the results to be reported.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters (if used).

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [2].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counters connected to the heat meters were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

Solar collector excluded from calculation

The SEPEMO project [3] recommends that for this type of bivalent system (heat pump + solar collector) the heat from the solar collector be included in the numerator of the SPF_{H4} calculation and the electricity used by the solar circulating pump in the denominator.

Inclusion of these values in the SPF_{H4} calculation is likely to yield very high SPF_{H4} values that are not very meaningful for comparison with systems without solar collectors – because the ratio of heat to electricity in a solar thermal system can be very high and does not have the same meaning as the SPF of a heat pump.

The SPF_{H4} results for this system do not include the heat output of or electricity used by the solar thermal collectors.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump]} - \text{[heat added by buffer pumps]}}{\text{Electricity used by: [heat pump (excluding buffer pumps)]}}$$

- This calculation required the electrical energy used by the buffer pump inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running.

- The heat added by the buffer pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pump.

$$SPF_{H4} = \frac{\begin{array}{c}\text{[Heat output of heat pump]} + \text{[heat added by SH circ pumps]} + \text{[heat added by immersion heaters]} \\ - \text{[heat loss from buffer tank]} - \text{[heat loss from underground pipes]}\end{array}}{\text{Electricity used by: [heat pump including internal pumps]} + \text{[immersion heaters]} + \text{[SH circ pumps]}}$$

- The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C. The total heat loss from the buffer tank during the monitoring period was estimated as 4.2% of the heat pump output.

- The heat loss from the underground insulated pipes to the office/laundry building was estimated using the measured flow, return and ground temperatures at each calculation interval, and published heat loss data for typical insulated pipes for underground use. The estimated heat loss from the pipes during the

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [8] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

monitoring period is 3.5% of the heat pump output. These calculations have been cross-checked with readings from heat meters H03 and H04. The meter readings indicate a slightly lower heat loss of 2.4% of the heat pump output. Considering the known heat metering issues, the agreement is reasonably good.

The number of 1-minute intervals selected as valid for analysis was 454 262, which represents 86.4% of the 12-month period.

SPF results presented as relative values

Because of the heat metering issues noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors SPF_{H2} and SPF_{H4} are therefore presented in this case study as "relative" values, whereby each value is shown as an amount above or below a nominal performance.

Figure 2 shows the daily SPF_{H2} and SPF_{H4} behaviour[5] of the system. The gaps in the data during April were due to some difficulties with the electricity monitoring equipment.

The difference between the SPF_{H2} and SPF_{H4} values is mainly due to the heat loss from the buffer tank and the underground pipes to the office/laundry building.

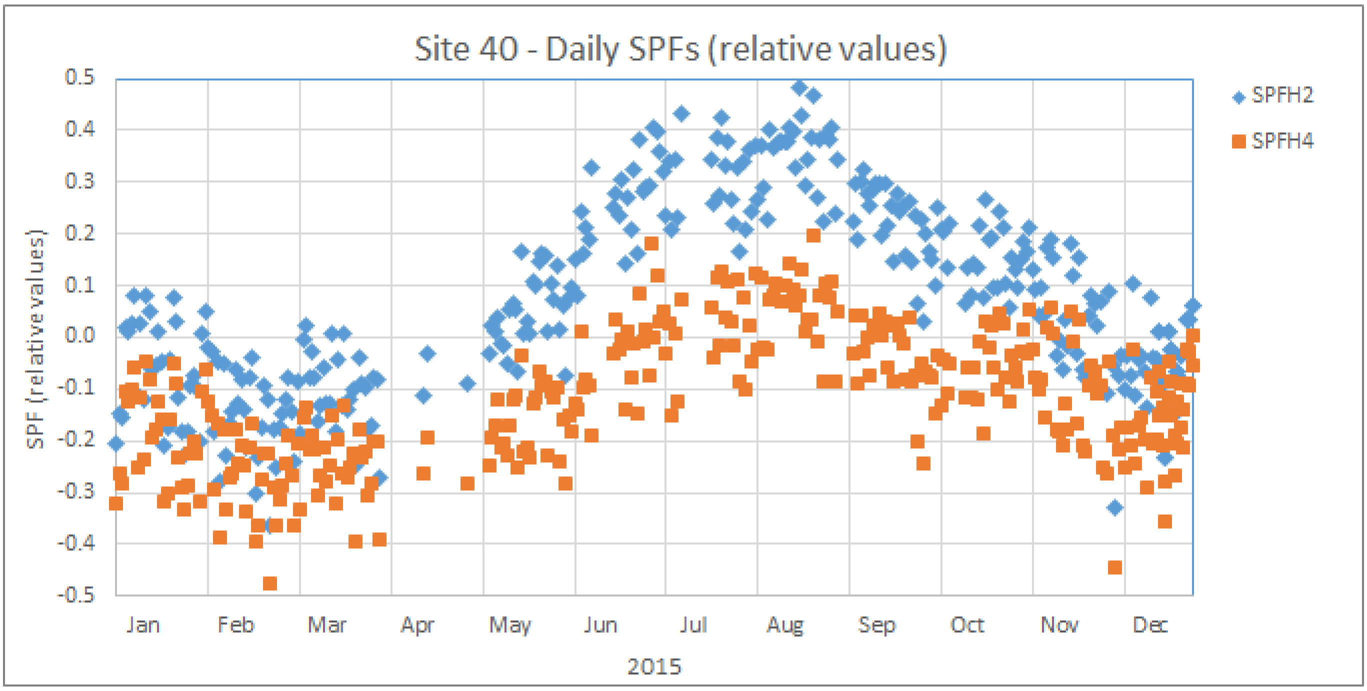

Figure 2 – Seasonal performance factors SPF_{H2} and SPF_{H4} calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

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[5] The actual values are not shown because of the high uncertainty of measurement of the heat metering on this system. Relative values are shown to give some indication of the scale of the behaviour.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [4] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 3 shows the daily heat delivered by the heat pump and the solar collector. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. It was impractical[6] to monitor the circulating pumps in all apartments, so the heat provided by the circulating pumps in the apartments has been estimated from the rated power of the pumps. Note that the kWh values have been removed from the graph because of the high uncertainty of measurement of the heat meters.

The heat from the solar collector (not included in heat pump performance calculations) was only 1.2% of the total heat delivered.

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[6] Because of the difficulties with radio communication on the site noted above.

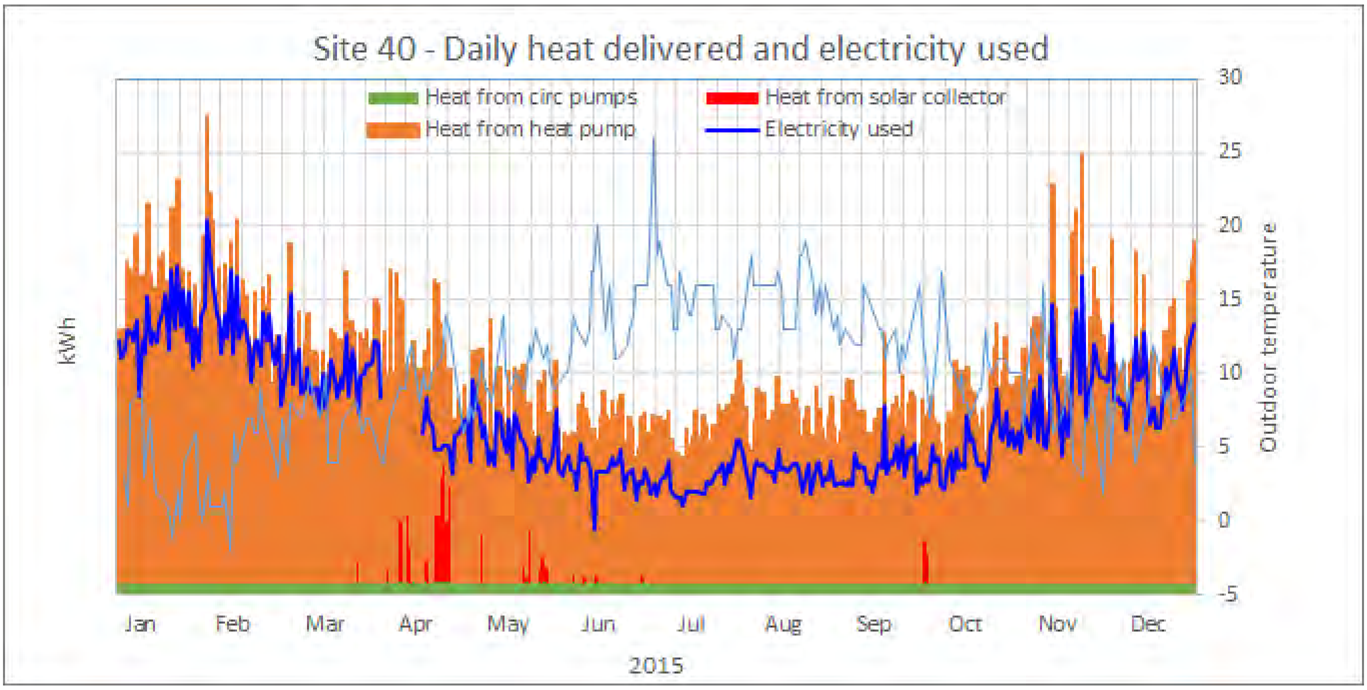

Figure 3 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

It was not possible to determine the breakdown of heat delivered to space heating and to domestic hot water on this system.

Breakdown of electricity use

Figure 4 shows the weekly breakdown of electricity use. The electricity used by the brine pump and buffer pumps was estimated from the pump ratings and analysis of the detailed electrical data recorded from the electricity monitor.

The brine pump accounted for an estimated 11.8% of the total electricity, which is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance. The high brine pumping power is probably explained by the length of the collector (2200 m) and the long pipe run from the heat pump to the collector manifold (approximately 200 m).

The buffer pump and space heating circulating pumps together used 5.4% of total electricity, which is below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance.

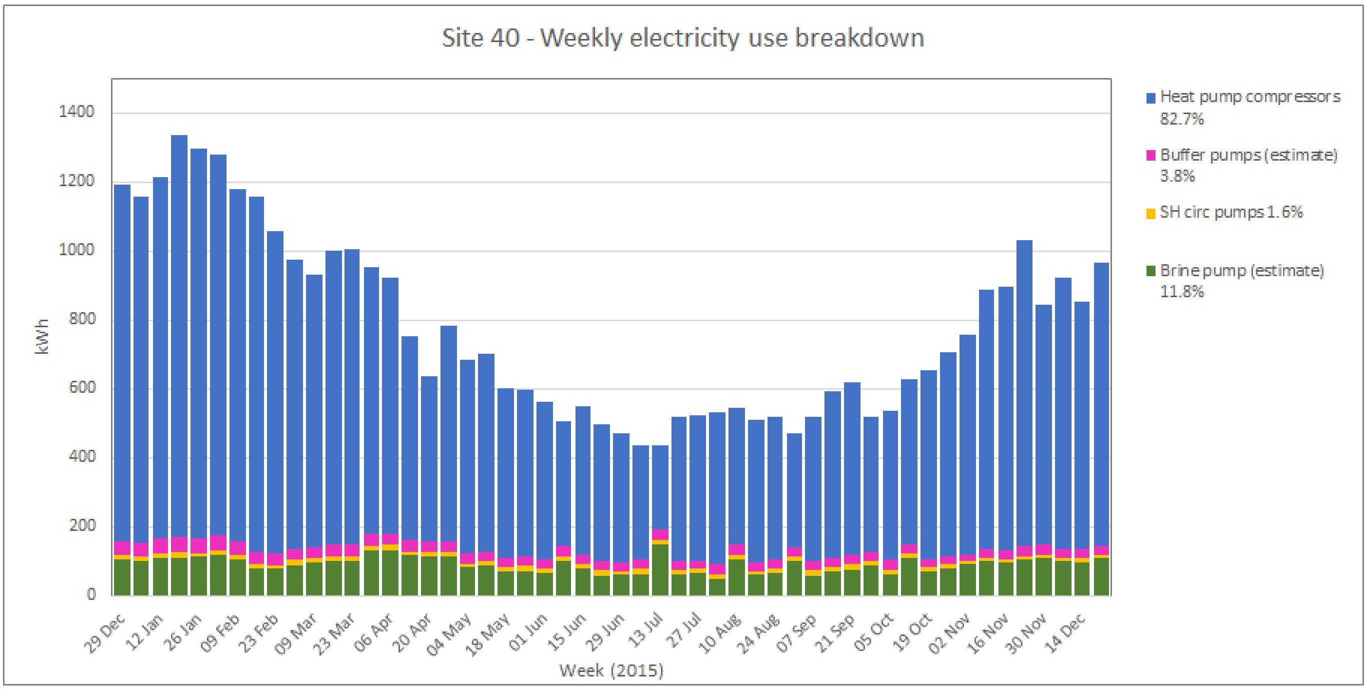

Figure 4 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 5 shows the operating pattern on 20th January 2015 when the outdoor temperature[7] was between -1 and +4 °C.

The heat pump ran three times for periods of between 1 and 8 hours, using both compressors most of the time. The heating circulating pump ran at varying speed throughout the day.

The temperature of the brine flow to the heat pump was between 3 and 5 °C while the heat pump was running (the ground temperature data is not available).

The temperature of the output from the heat pump to the buffer tank was generally always above 50 °C while the heat pump was operating, and reached 63 °C twice during the day. The pattern was similar on other days in January, with the temperature sometimes up to 63 °C three times in a day.

The loss of temperature through the 4-pipe buffer tank was generally less than 1 °C.

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[7] The outdoor air temperature was estimated from measurements at other sites in similar geographical locations.

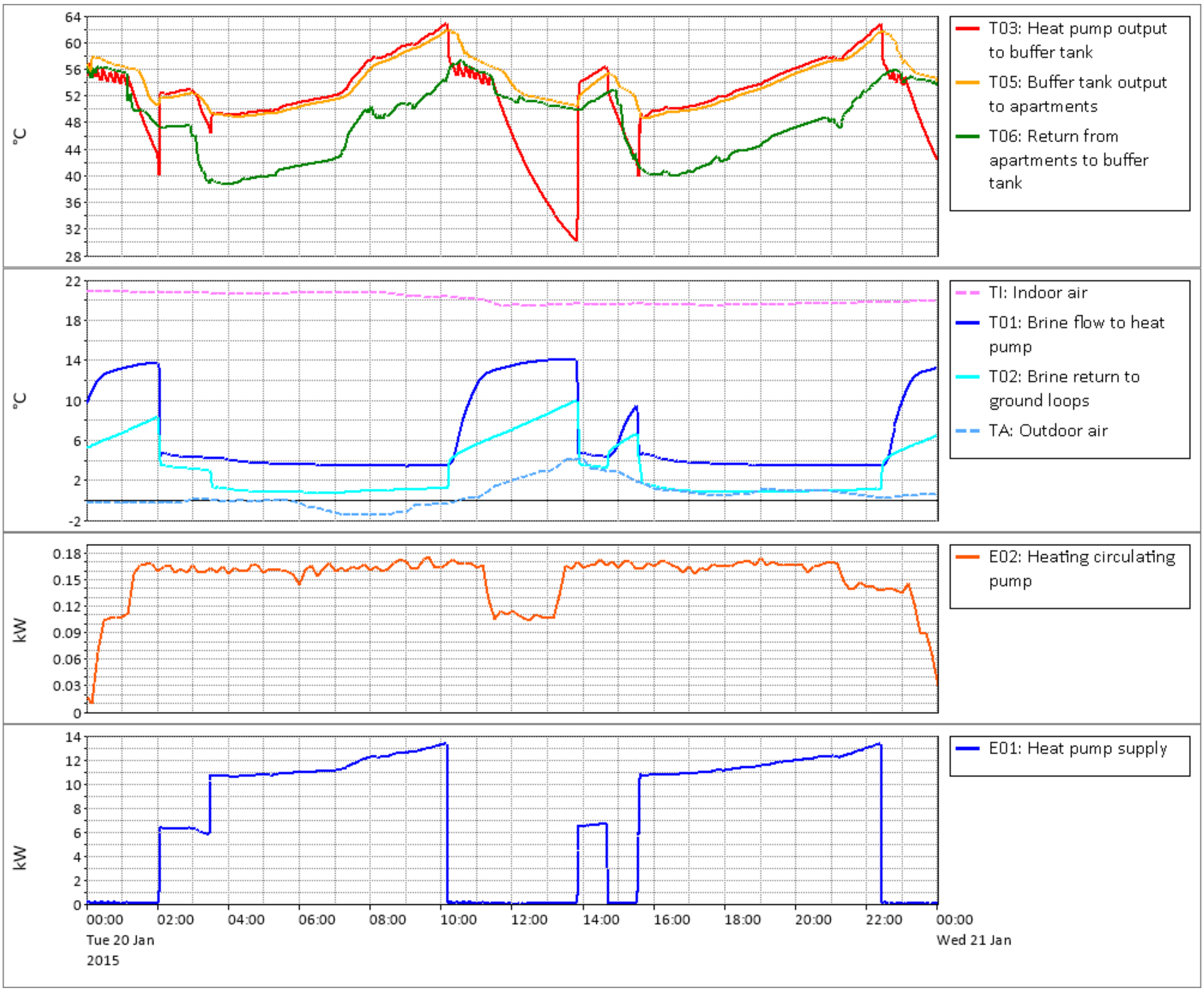

Figure 5 – Operating pattern on 20th January 2015

Figure 6 shows the operating pattern on 2nd July 2015 when the outdoor temperature was between 15 and 20 °C.

The heat pump operated for four periods of between 1 and 3 hours, using both compressors during the first run.

The temperature of the brine flow to the heat pump was between 10 and 12 °C when the heat pump was running.

The heating circulating pump ran at varying speed throughout the day, and the output temperature range was similar to that in January. The maximum during the day was 64 °C.

The loss of temperature through the buffer tank was between 3 and 4 °C.

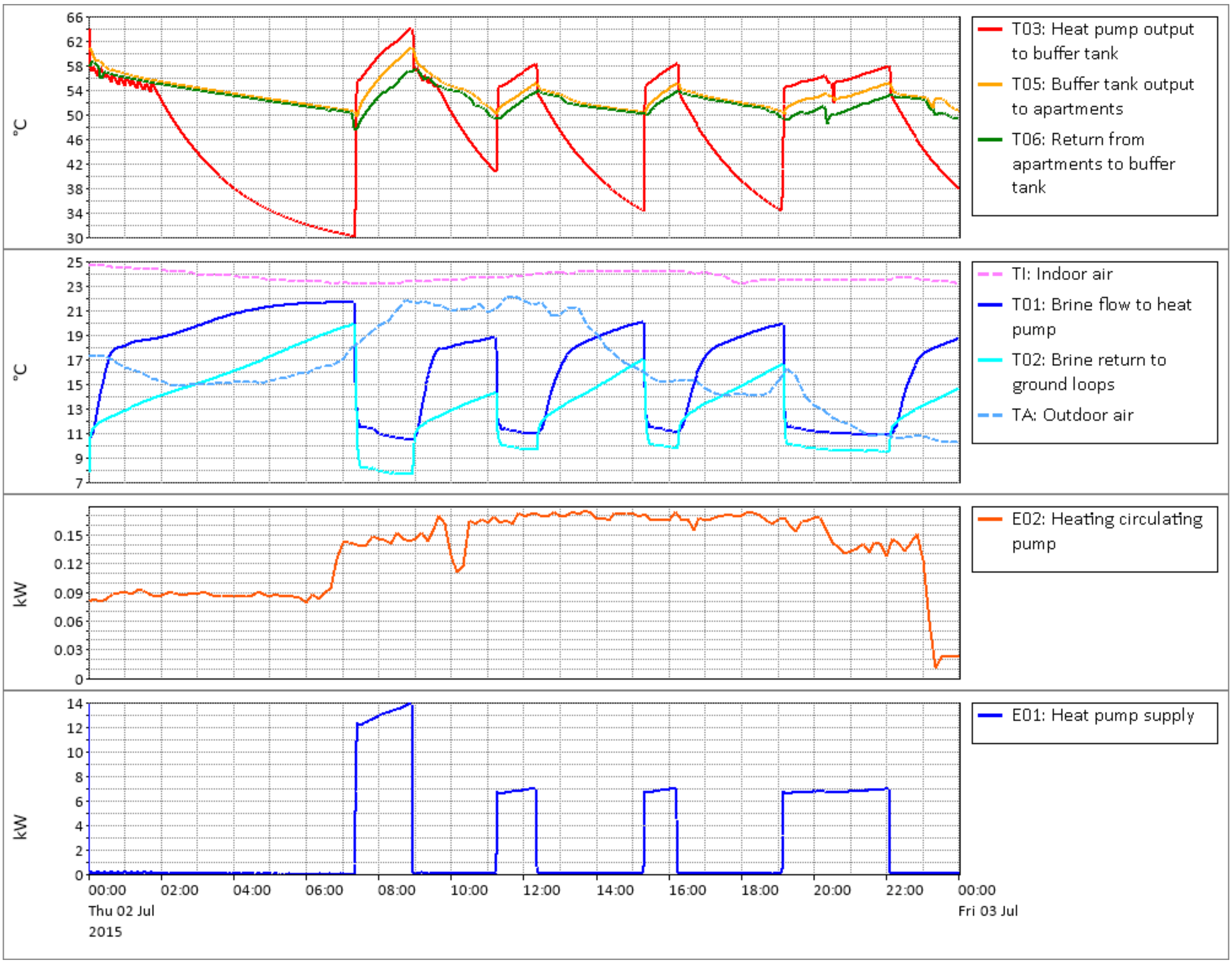

Figure 6 – Operating pattern on 2nd July 2015

Source and sink temperatures

Figure 7 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[8]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The indoor temperature was measured in one of the apartments. No readings were received from the indoor sensor after 11th August.

The temperature of the brine from the ground loops was reasonably high throughout the year, with a minimum of 2 °C in February.

The output from the heat pump to the buffer tank was fairly high – varying typically from 52 °C to 62 °C. This was needed because of the way the system works: hot water from the buffer tank is circulated to the thermal accumulators in each apartment, where the heat is used for both space heating and domestic hot water. A lower buffer tank temperature would probably be unable to supply the heat needed to each apartment.

The proprietor of the system mentioned that the buffer tank is normally maintained at 50 °C, and raised to 60 °C once a week for Legionella control. However, it appears that the heat pump output temperature was raised to

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[8] Temperatures of the heat pump system were recorded at 2-minute intervals.

over 62 °C once or more every day during January and February and again toward the end of the year, but much less frequently during the summer. This suggests that there is a problem with the configuration of the controls.

There was no opportunity for weather compensation on this system because the combined output for space heating and domestic hot water required fairly constant temperatures all year – always up to at least 58 °C.

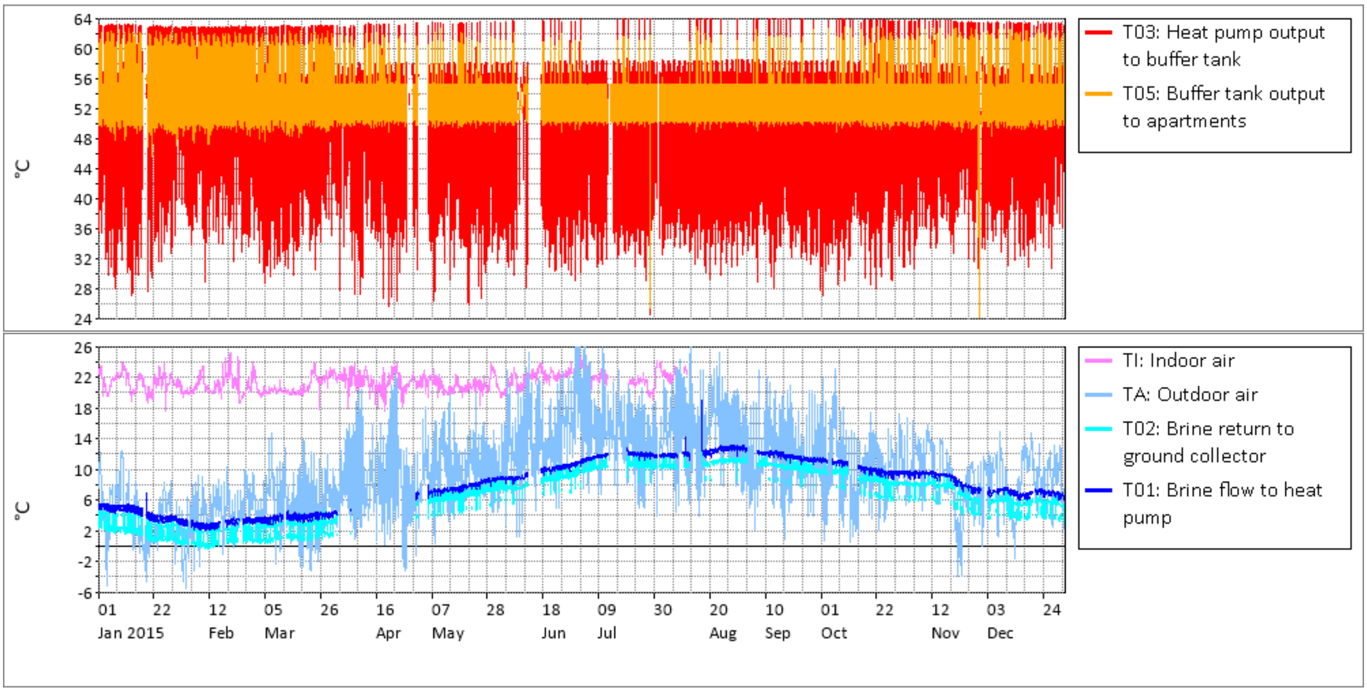

Figure 7 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 8 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were slightly above average. This would have had a positive influence on system performance.

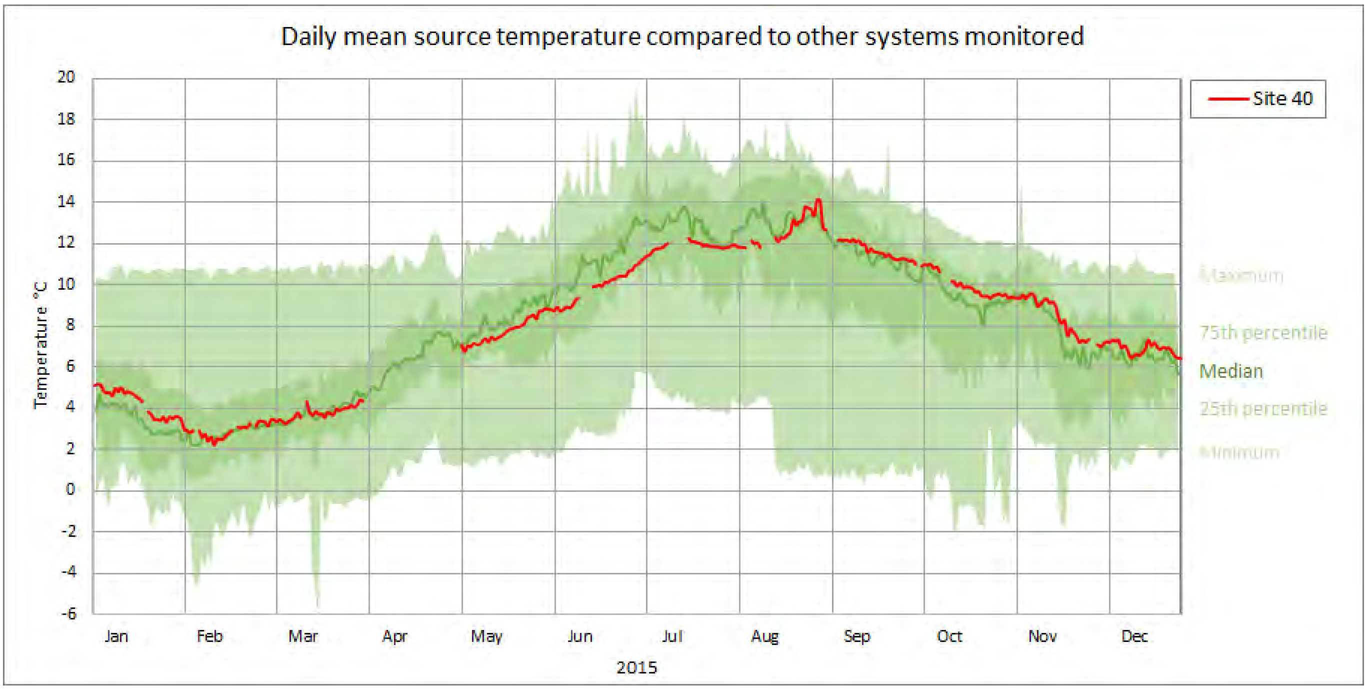

Figure 8 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 40 is shown in red)

Figure 9 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were at the upper end of the values observed on other systems. This would have had a negative effect on the system performance.

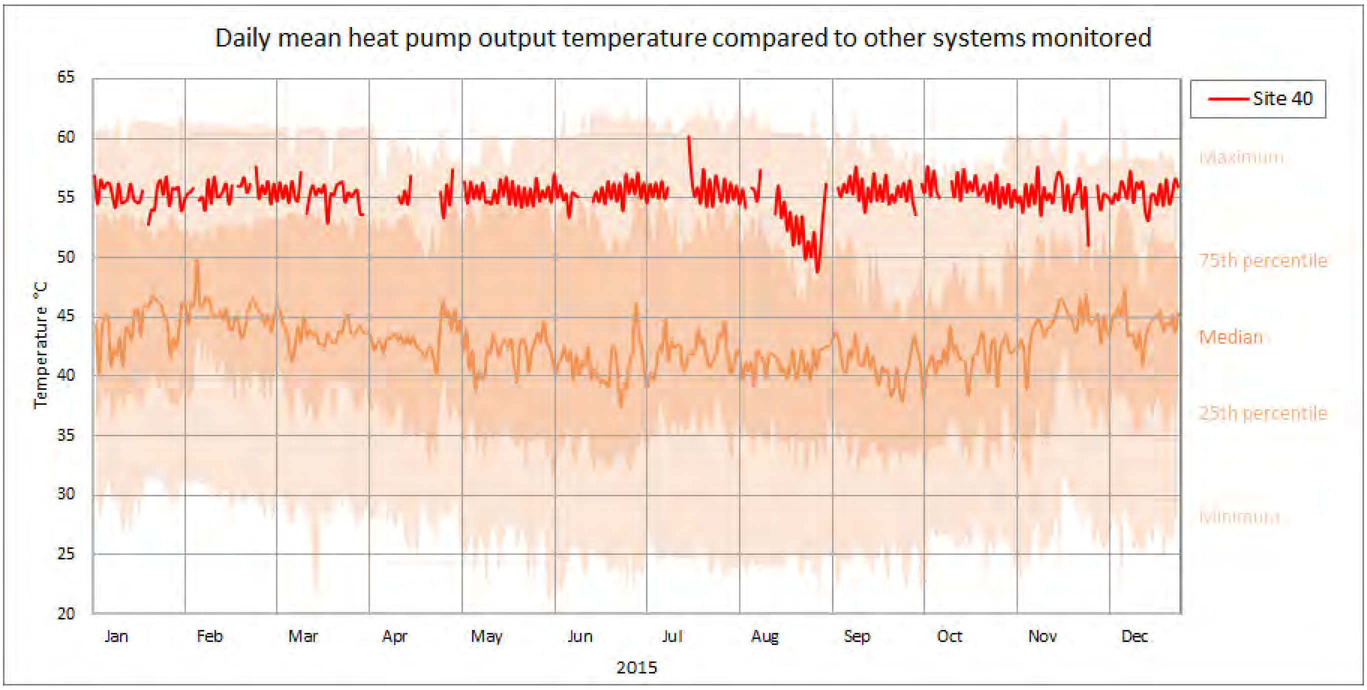

Figure 9 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 40 is shown in red)

Comments

The performance of this system could not be determined with reliable accuracy because of known issues with the heat metering arrangement installed.

Aspects of this system that positively influenced its performance are:

- The source temperature was slightly above average compared to other systems in the monitored sample.
- Auxiliary heat was not used.
- The loss of temperature through the buffer tank was low: less than 1 °C during winter operation; maximum 4 °C during warmer weather.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump output temperature was high and weather compensation could not be used because of the need to provide hot water to the combined space heating and domestic hot water system. This is a consequence of the system design.

  It would be worth investigating whether the domestic hot water would be better provided using point-of-use direct electric water heaters, so that the heat pump output temperature could be reduced and weather compensation brought into use.

  Another possibility might be to disconnect the thermal accumulators in the apartments, and feed the underfloor heating directly from the main heating distribution circuit without using mixing valves. The accumulators could then be used as conventional domestic hot water cylinders with immersion heaters. The objective of any such change would be to reduce the heat pump output temperature and allow weather compensation to be used. However, this should be approached cautiously to ensure that the system will work with reduced temperatures and that the use of direct electric water heating does not negate the improved heat pump performance.

- The brine pump accounted for an estimated 11.8% of the total electricity, which is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
  The full brine flow rate should only be needed when both heat pump compressors are running, which only happened for 24% of the total heat pump run time in 2015. The difference between the brine flow and return temperatures (the “delta-t”) was generally between 1.0 and 1.2 °C when only one compressor was running. This could probably be increased to, say, 3 °C (as per the rating conditions specified in EN14511-2 [5]) by reducing the flow rate when using one compressor. This would reduce the electricity used by the brine pump by 50% or more, decreasing the total annual electricity use by around 2000 kWh – a cost saving of £294 (assuming a unit cost of 14.7 p/kWh [6]). A suitable inverter variable-speed drive would need to be installed and the control system adapted to implement this. The ground collector heat transfer calculations would also need to be checked to ensure proper operation at the reduced flow rate.

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[5] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.,” EN 14511.

[6] “Quarterly Energy Statistics (https://www.gov.uk/government/collections/quarterly-energy-prices),” DECC.

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Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 48

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

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Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 48 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 48 is a residential care home. A heat pump (thermal capacity 14 kW) was installed to extract heat from a hybrid ground and air heat collector in order to provide space heating to underfloor heating and radiators. Domestic hot water is provided by a separate solar thermal + gas-fired system.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump was inadequately charged with working fluid (refrigerant) for part of the monitoring period. This prevented the heat pump working correctly and its performance was impaired.
- The source temperatures were lower than on most other systems monitored: generally in the lower quartile of the range of source temperatures, and lowest of all at times.
- The output temperature was unusually high between February and May following the working fluid recharge in February.
- The brine and buffer pumps ran unnecessarily during the summer period when the heat pump was not in use.

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[1] There were some operational problems with this system, and it was not possible properly to determine the system performance.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	48
Survey date	20/03/2014
Monitoring installed	10/07/2014
G/WSHP	Combined ground/air-source: see notes below
Building type	Residential home
Location	Urban
Heat pump capacity kWTH	14
Number of heat pumps	1
Number of compressors	1
Heat source	Combined ground and air heat collector
Heat emitters	Underfloor heating pipes and radiators
DHW	No
Auxiliary heat	3 kW immersion heater in heat pump (not used in normal operation)
Source pump	Internal to heat pump: 300 W
Buffer/SH circulating pump	Internal to heat pump: 150 W
Buffer tank	200 litre 2-pipe in return
DHW cylinder	N/A
Control	Heating programmer + wireless thermostatic radiator valves
Weather compensation	Yes
Heat meter type	Mechanical
No. of heat meters	1
Heat meter interface	Pulse (1 kWh/pulse)
Comments	There were operational problems with this heat pump and a full year's performance data is therefore not available.

Table 1 – System details

This site is a large detached Edwardian property that has been adapted and extended over the years to provide accommodation for up to 24 older people.

The application entails extracting heat from the ground and air to provide space heating. The site is in a location with average outdoor temperatures, but with required indoor temperatures higher than most other sites monitored. (The mean outdoor temperature at the site during the period monitored was 10.2 °C. The range for all sites was 8.1 – 12.5 °C, median 10.3 °C.) The system performance would be expected to be lower than average.

Heat pump and monitoring systems

A heat pump (thermal capacity 14 kW) was installed inside the building in 2012 to provide space heating (SH) to underfloor heating pipes on the ground floor and radiators elsewhere.

The heat source was an "Energy Fence" which is a hybrid ground and air heat collector.
Figure 1 shows the installation in the garden of the house. Approximately 2/3 of the fence is below ground.

A 200-litre 2-pipe buffer tank is installed in the return from the heating circuit.

The heat pump and buffer tank are inside the heated envelope.

Figure 1 – Energy Fence hybrid ground and air heat collector

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2]. The outdoor air and ground temperatures are also monitored.

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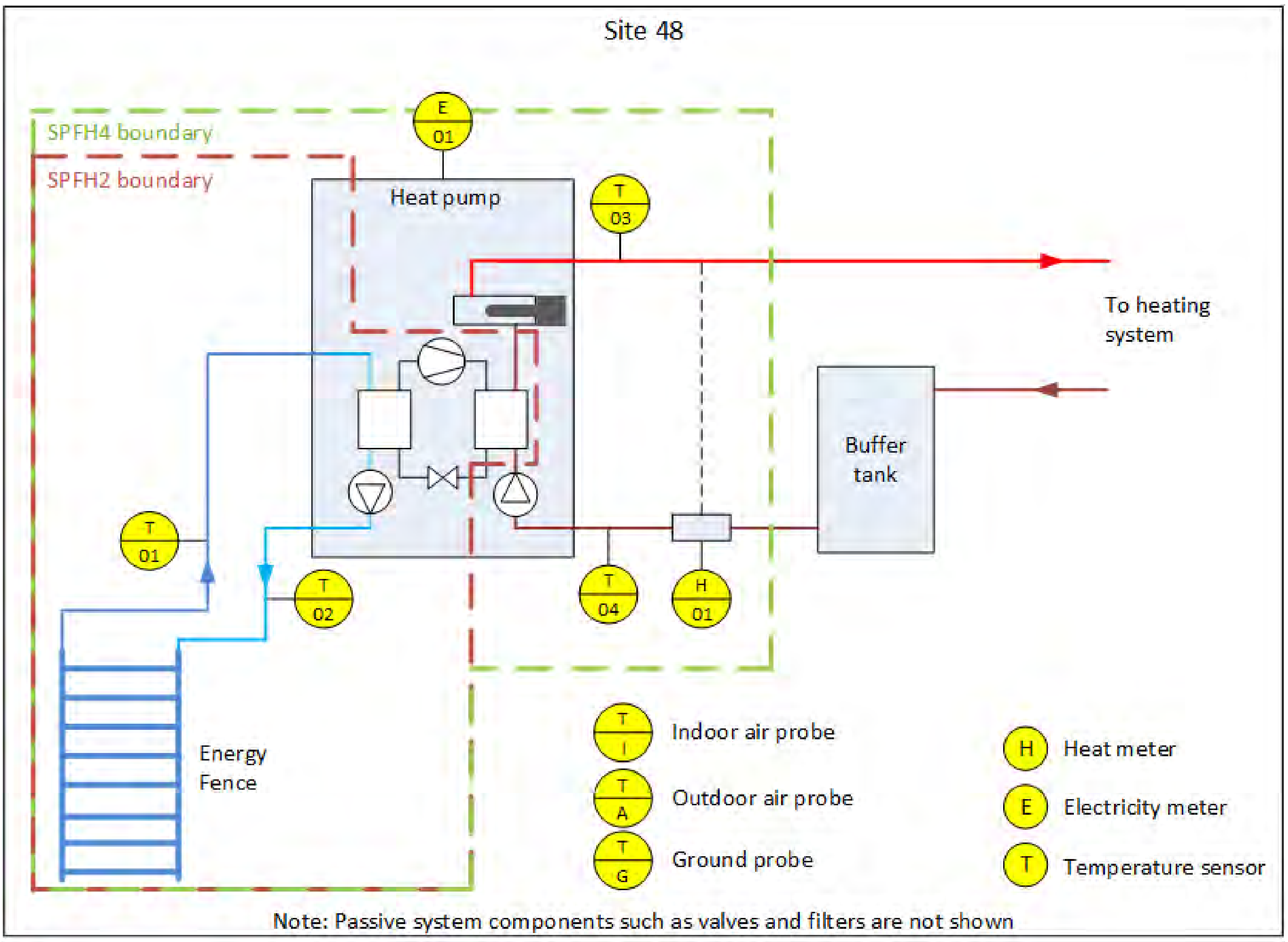
[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses a mechanical rotary-impeller flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is battery-powered. Monitoring was via the pulse interface.

Immersion heater

The heat pump has an internal immersion heater that can be used for auxiliary heat. This heater is supplied via a separate circuit and was not metered, because in normal operation of the heat pump it was always switched off. However, between 25th September and 13th October, the heat pump was found to be faulty and the immersion heater was used to provide some heat to the heating system. This was considered to be abnormal operation and data from this period has been excluded from performance calculations.

Heat pump replacement

There were some problems with the operation of the heat pump during the monitoring period. It is understood that the working fluid needed to be topped up on 2nd February and again on 14th October. The heat pump failed on 12th December and was not used again thereafter. It has subsequently been replaced by an air-source heat pump. It is understood that the decision to use an air-source heat pump was taken mainly because RHI support for the Energy Fence heat collector had been withdrawn.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump including the internal brine pump, but excluding the internal heating circulating pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump]} - \text{[heat added by buffer pump]}}{\text{Electricity used by: [heat pump including brine pump]} - \text{[buffer pump]}}$$

- This calculation required the electrical energy used by the buffer pump inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running.

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer pump was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pump.

$$\mathrm{SPF}_{H4} = \frac{\text{[Heat output of heat pump including immersion heater]}}{\text{[Electricity used by heat pump including internal pumps and immersion heater]}}$$

- The heat added by the SH circulating pump was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pump.

- The heat loss from the buffer tank was not deducted from the total heat output because the buffer tank is inside the heated envelope. No heat was provided by the heat pump when the outdoor air temperature was above 15 °C, so none of the heat loss from the buffer tank has been considered as wasted heat.

The number of 1-minute intervals selected as valid for analysis was 524 459, which represents 99.8% of the 12-month period.

SPF results presented as relative values

Because of the operational problems noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors SPF_{H2} and SPF_{H4} are therefore presented in this case study as “relative” values, whereby each value is shown as an amount above or below a nominal performance.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} behaviour of the system. Periods of abnormal operation as noted above have been excluded. It can be seen that the performance was much lower before the working fluid was recharged on 2nd February.

The higher SPF values between October and December were due to the system having operated with a reduced output temperature.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [6] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

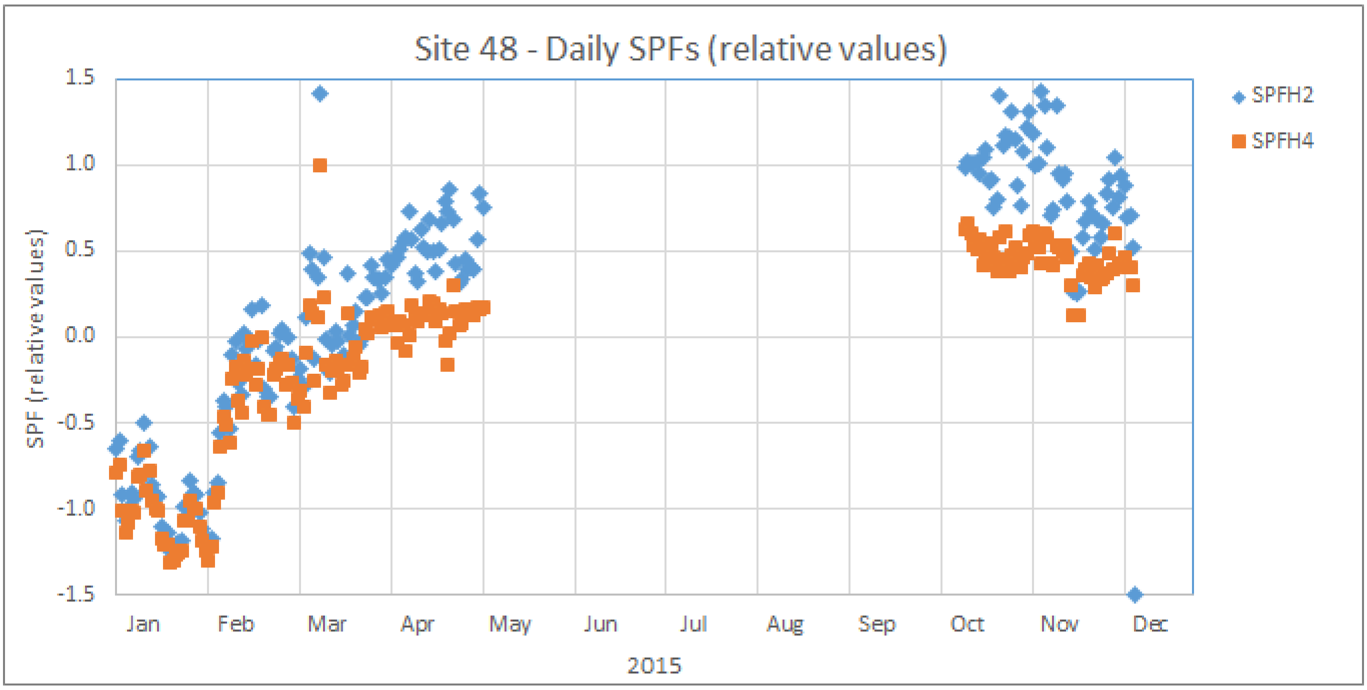

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the sources from which heat is being extracted are the ground and air, and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground/air and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump brine through the heat collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity use by the total heat pump system and the outdoor air temperature are shown for reference. Note that the kWh values have been removed from the graph because of the uncertainty of measurement due to the operational problems.

The low heat output in January was because the heat pump had lost some of its working fluid. It was re-charged on 2nd February.

There was no demand for heat during the summer months. However, it can be seen that the electricity use during the summer was quite high. This was due to the brine and buffer pumps having run regularly during this period, even though the heat pump compressor was not running.

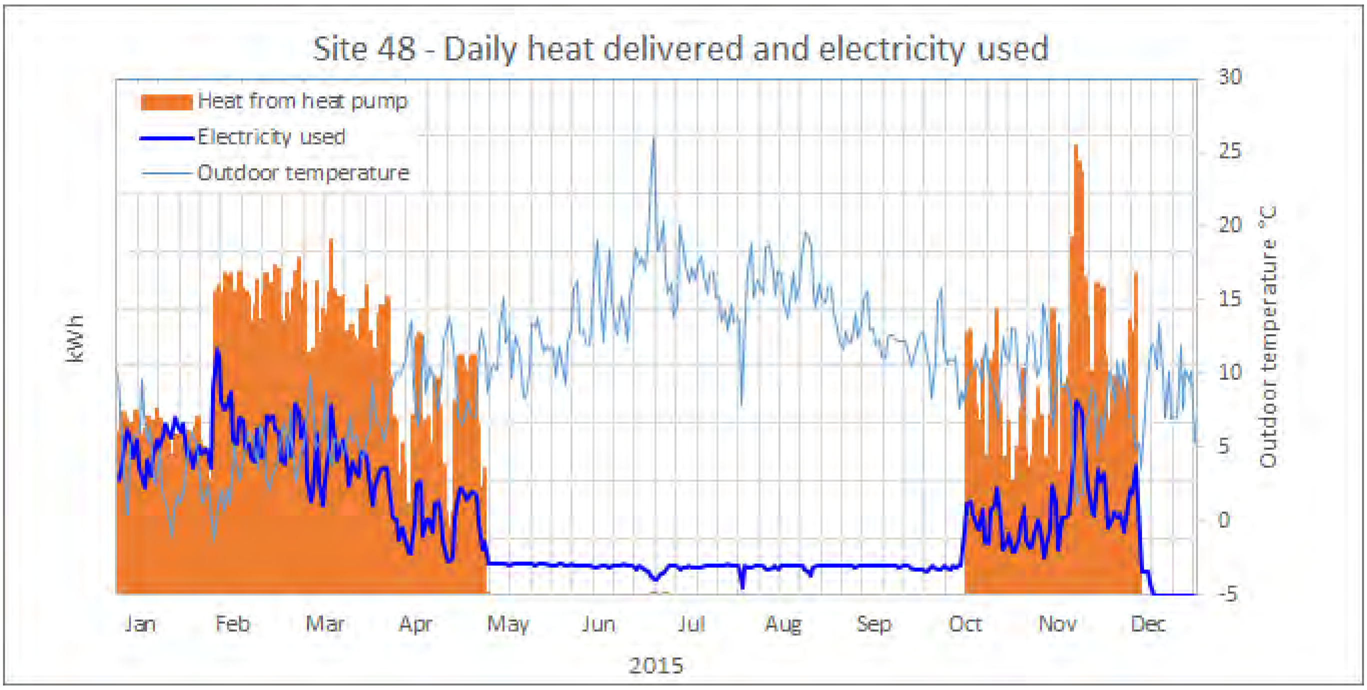

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The estimated energy used by the brine pump and the buffer pump was high, mainly because these pumps continued running unnecessarily during the summer months.

The brine pump accounted for an estimated 17.1% of electricity use, which is above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance.

The buffer pump / heating circulating pump used an estimated 13.7%, which was also above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a negative influence on the system performance.

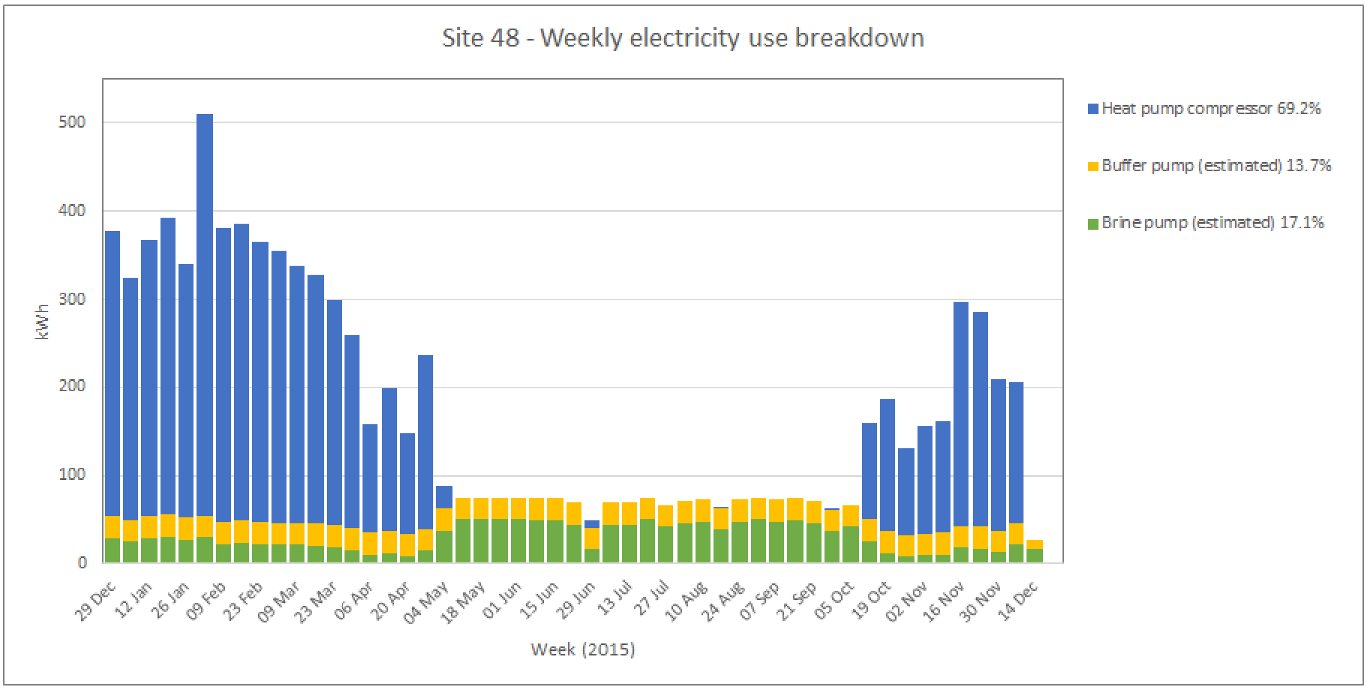

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 3rd February 2015, after the heat pump working fluid had been recharged. The outdoor temperature was between -4 and +4 °C and the ground temperature remote from the Energy Fence was 5.6 °C.

The temperature of the heat pump output was between 31 and 56 °C. The temperature of the brine flow to the heat pump was between -7 and 0 °C while the heat pump was running. It can be seen that the brine temperature tended to follow the outdoor air temperature, showing the effect of the hybrid heat collector.

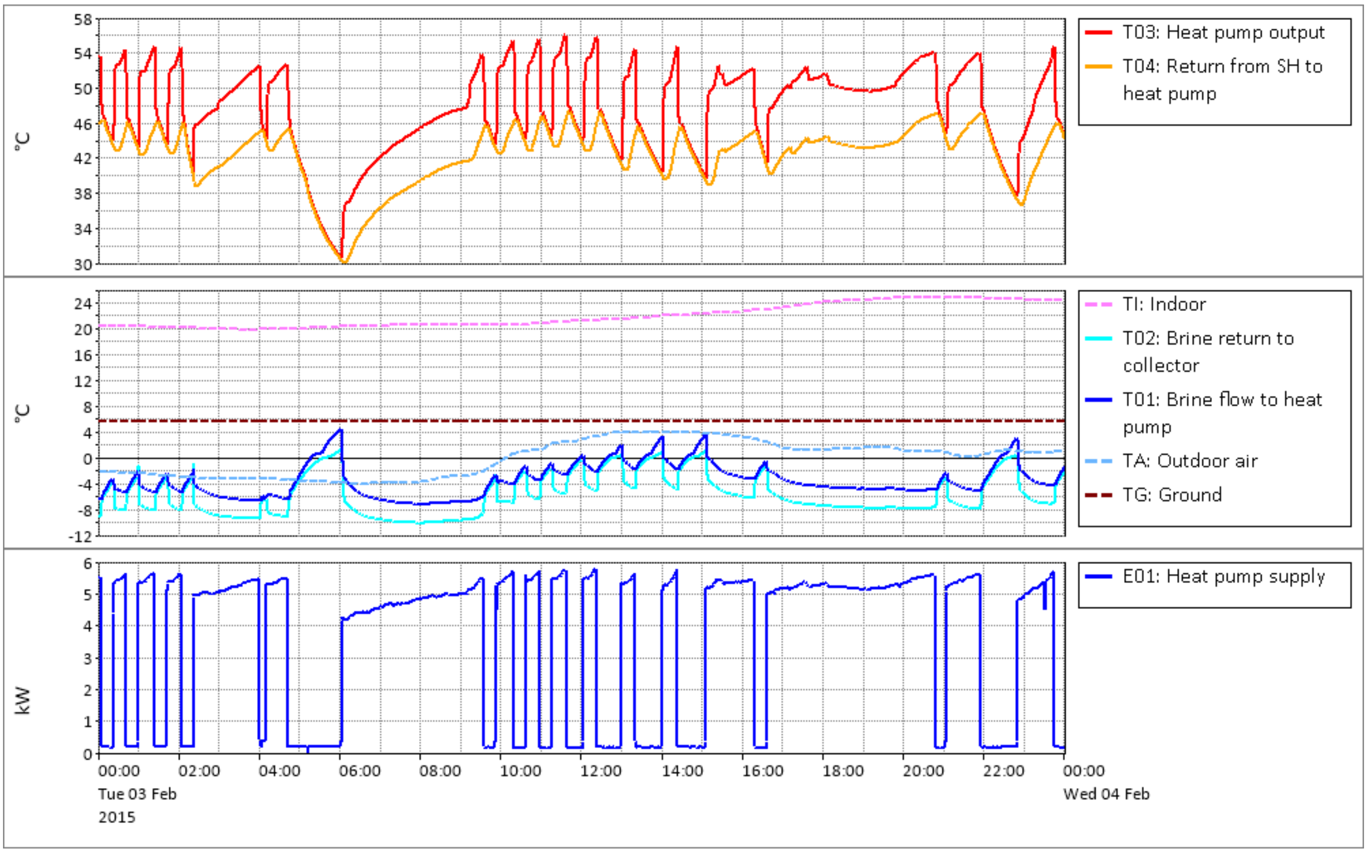

Figure 6 – Operating pattern on 3rd February 2015

Figure 7 shows the operating pattern on 4th May 2015 when the outdoor temperature was between 8 and 17 °C and the ground temperature was 10.8 °C. The heat pump output temperature was briefly up to 61 °C, but more generally in the range 30 to 55 °C.

The temperature of the brine to the heat pump was in the range 4 to 12 °C, falling quite rapidly during each heat pump run.

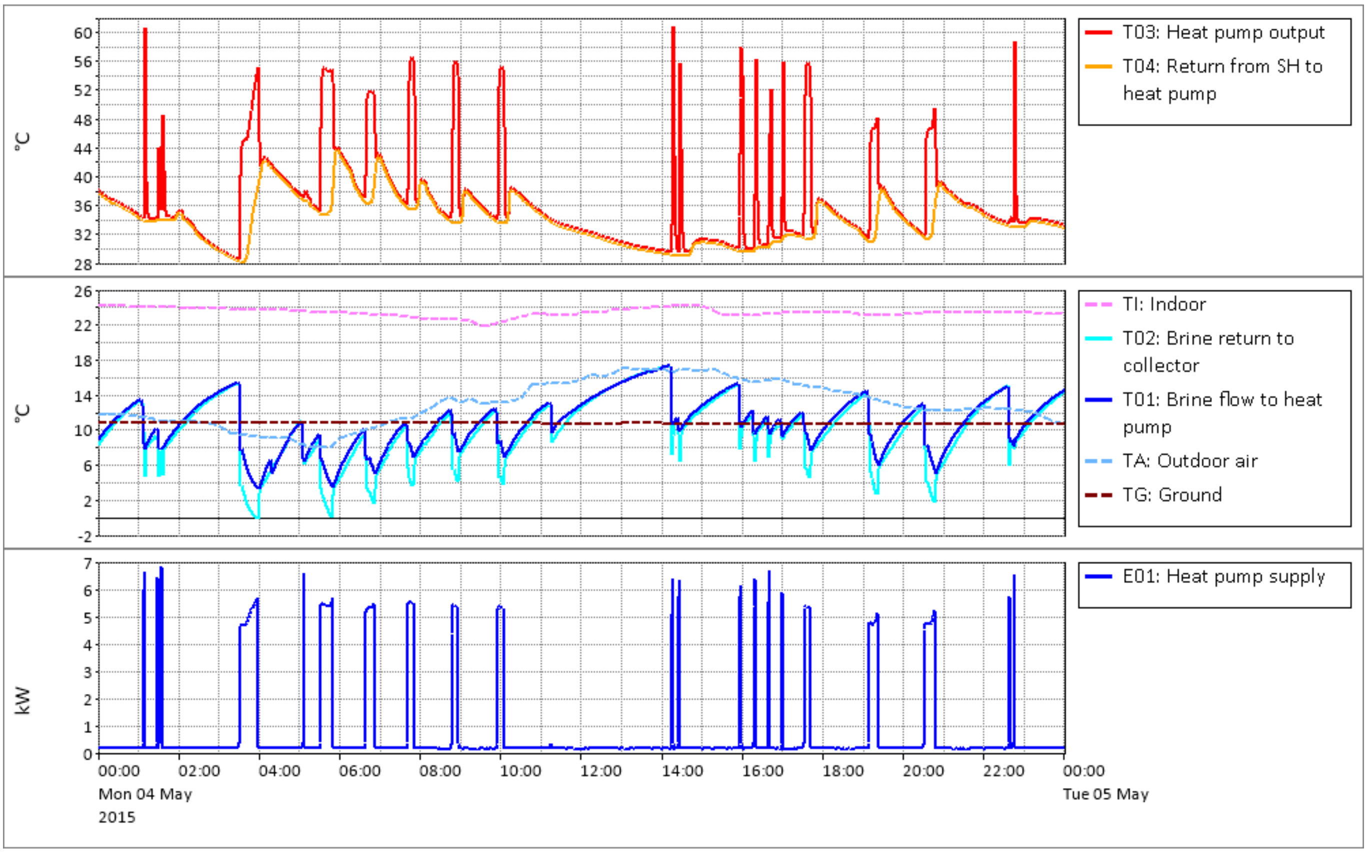

Figure 7 – Operating pattern on 4th May 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[5]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The low heat pump output temperature during January was due to the heat pump running without the full charge of working fluid. The moderate output temperatures between late September and mid-October were due to the immersion heater in the heat pump being used to provide some heat while the heat pump was not working.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

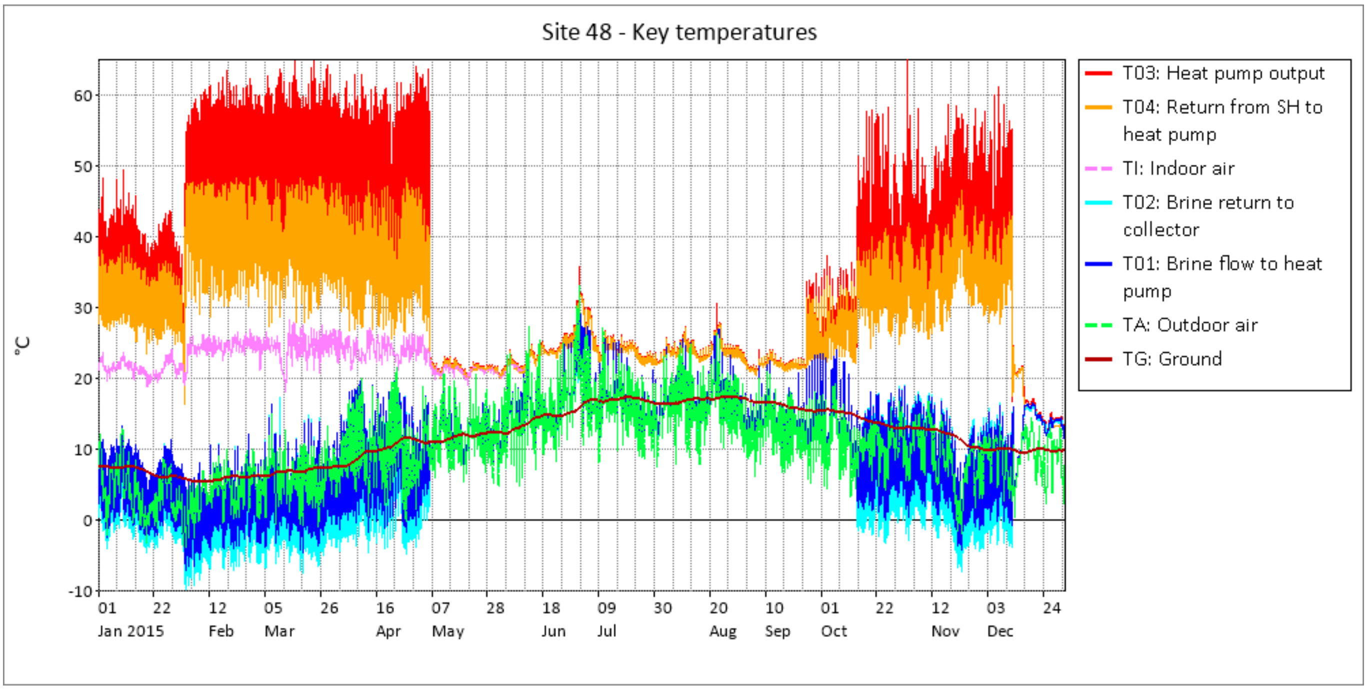

Figure 8 – Key temperatures measured during the period 1st January – 31st December 2015

From February to May the output was generally high – up to 65 °C on some occasions. From mid-October to early December the output temperature was lower than it had been from February to May, and varied with outdoor temperature.

Weather compensation is a performance-enhancing technique whereby the temperature of the output to the space heating emitters is reduced as the outdoor temperature increases (and the heating load therefore decreases).

Figure 9 shows the different weather compensation behaviour during these two periods. The reason for the change in behaviour is not known, but a possible explanation is that a high thermostat setting during the earlier period prevented the weather compensation operating properly.

The improved SPFH4 from October to December can be seen in Figure 3.

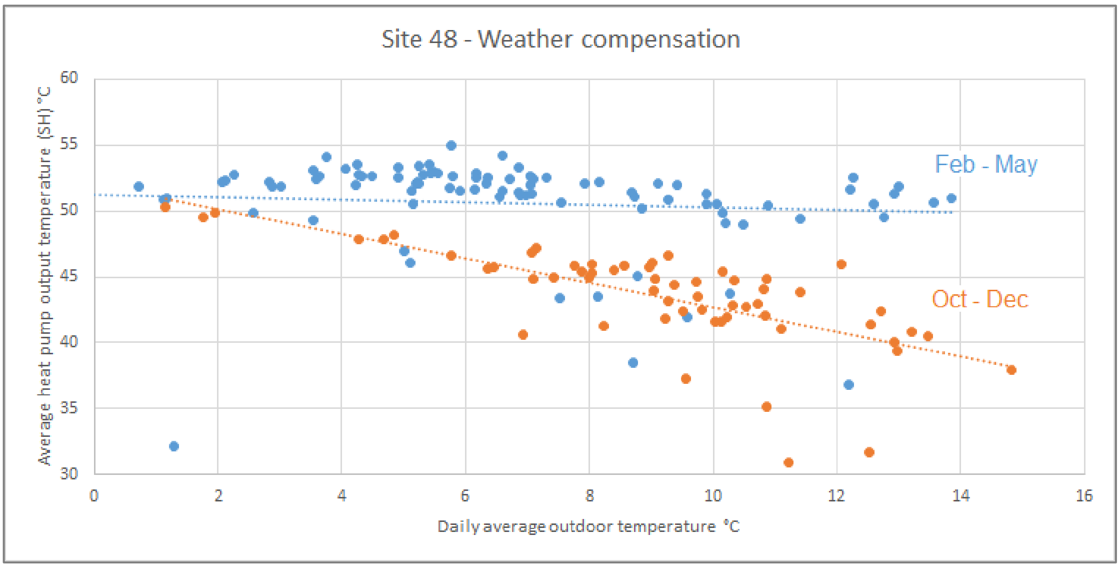

Figure 9 – Weather compensation behaviour

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were generally lower than on most other systems. This would have had a negative influence on system performance.

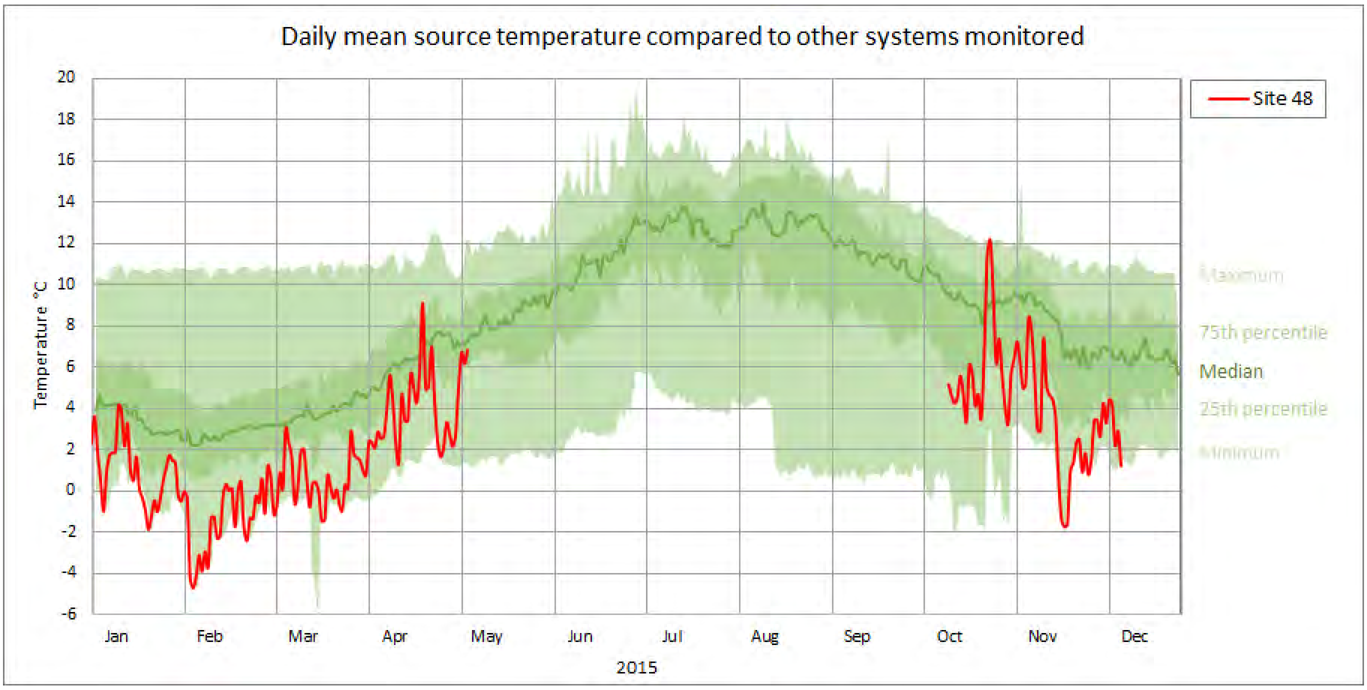

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 48 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system between February and May (after the working fluid was recharged) were above the median value for other systems. This would have had a negative influence on the system performance. Between October and December, the output temperature was more generally close to the median value of other systems. This would have benefited the performance, as reflected in the daily SPFH4 behaviour shown in Figure 3.

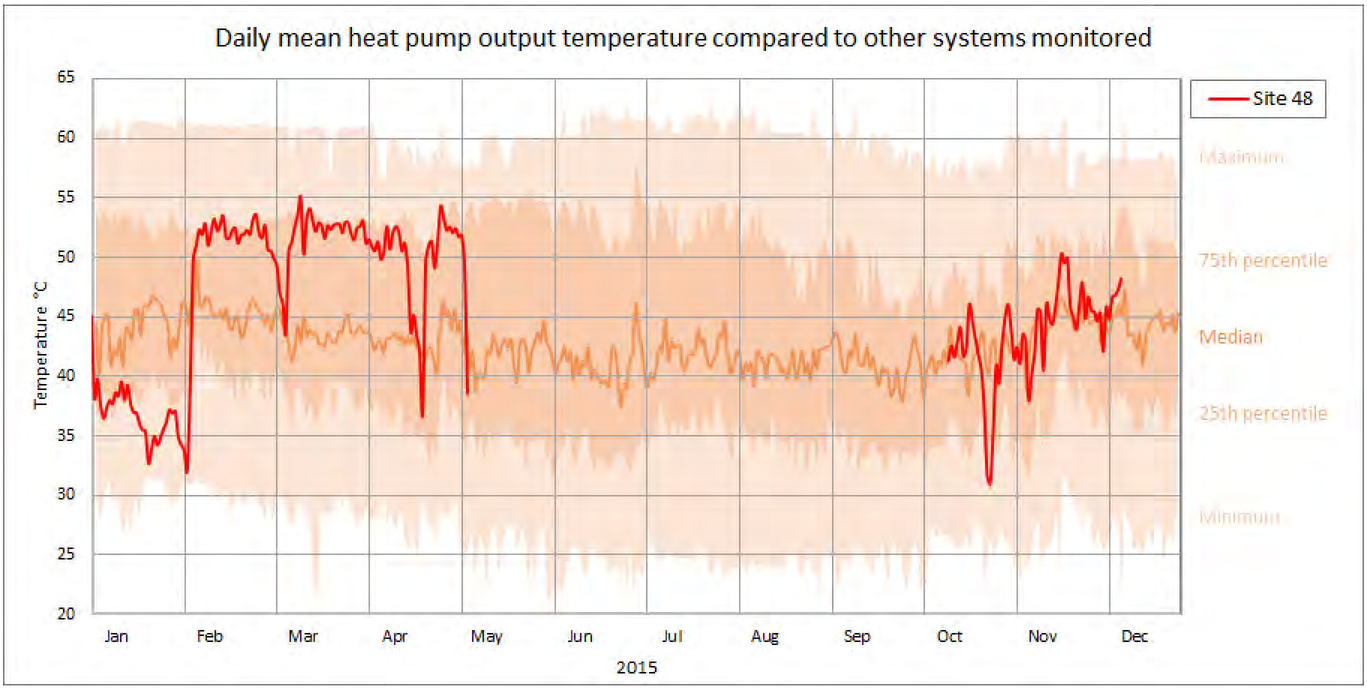

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 48 is shown in red)

Figure 12 shows how the output temperature of this system compares to other heat pump systems that use underfloor heating. The output temperatures on this system (plotted in red) were above average, which would have had a negative influence on system performance.

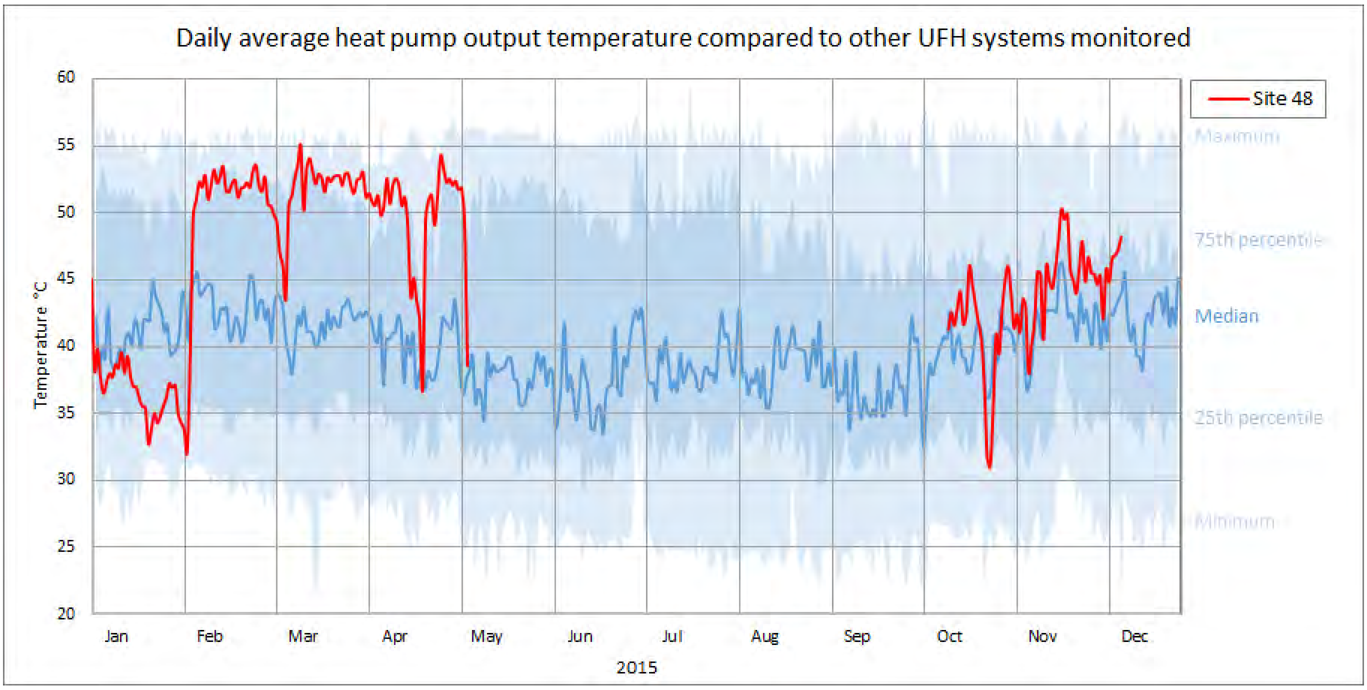

Figure 12 – Daily mean heat pump output temperature compared to those of other systems that use underfloor heating monitored in this project (site 48 is shown in red)

Comments

It was not possible to determine the annual SPF values for this system, because of the operational problems noted above.

Aspects of the system that may have negatively influenced its performance include:

- The heat pump was inadequately charged with working fluid (refrigerant) for part of the monitoring period. This prevented the heat pump working correctly and its performance was impaired.
- The source temperatures were lower than on most other systems monitored: generally in the lower quartile of the range of source temperatures, and lowest of all at times.
- The output temperature was high between February and May following the working fluid recharge in February. It is not known why the controls were set to provide such a high temperature. A possible explanation is that the thermostat had been adjusted to a high setting prior to the recharge and was then inadvertently left at the high setting.
  After October, the output temperatures were more moderate and varied with weather compensation. The period from 14th October to 12th December was probably the only period of normal operation of this system during the year monitored: the heat pump was properly charged with working fluid and the heating controls appear to have been set correctly.
- The brine and buffer pumps ran unnecessarily during the summer period when the heat pump was not in use. This wasted 1600 kWh of electricity at a cost of £235[6]. Switching these pumps off when not needed would have improved the SPFH4 by an estimated 20%.

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[6] Assuming an electricity unit cost of 14.7 p/kWh [5].

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[1] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[2] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[3] D. Hughes, "Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013," DECC, 2016.

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Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 51

Prepared by GRAHAM Energy Management
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This case study provides a brief description of the heat pump installation at Site 51 and performance results from 12 consecutive months of monitoring data.

Site 51 is recreational building in a rural location.

A ground-source heat pump (thermal capacity 38 kW) extracts heat from 10 vertical boreholes beneath a car park and provides heat for radiators and domestic hot water. Auxiliary heat is provided by a gas-fired boiler.

The seasonal heating performance factors measured over a year of operation
(1st January 2015 to 31st December 2015) were:

SPFH2	[Heat delivered by the heat pump] --- [Electricity used by the heat pump (including the brine pump)]	2.69
SPFH4	[Heat delivered by the heat pump] + [heat added by buffer pump & SH circ pumps] + [heat added by DHW immersion heater] – [heat loss from buffer tank] -- Electricity used by: [heat pump (incl brine pump)] + [buffer pump] + [SH circ pumps] + [DHW immersion heater]	2.44

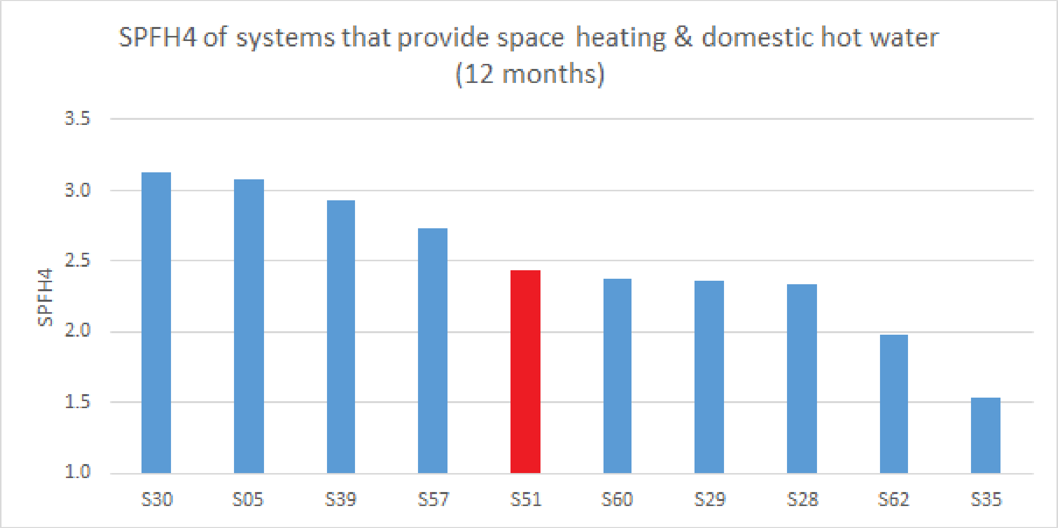


Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of the system that may have negatively influenced its performance include:

- The gas-fired boiler was used much more than should have been necessary.
- The temperature of the output from the heat pump was always high (62 - 63 °C at the end of each run cycle) – irrespective of whether the gas-fired boiler was also running, and irrespective of the outdoor air temperature.
- The domestic hot water system is designed to be heated by water from the space heating buffer tank – an arrangement that does not make best use of the temperature available from the heat pump, and precludes the effective use of weather compensation by always requiring a high heat pump output temperature.

- The domestic hot water immersion heater was used regularly – apparently unnecessarily.
- The temperature of the brine flow to the heat pump was lower than average compared to other systems monitored.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**51**
Survey date	21/03/2014
Monitoring installed	03/07/2014
G/WSHP	GSHP
Building type	Recreational building (golf club house)
Location	Rural
Heat pump capacity kWTH	38
Number of heat pumps	1
Number of compressors	1
Heat source	Vertical boreholes
Heat emitters	Radiators
DHW	Yes
Auxiliary heat	Gas-fired boiler (44 kWTH) 3 kW immersion heater in DHW cylinder
Source pump	Internal to heat pump: 400W
Buffer pump	External to heat pump: 140W max
SH circulating pumps	2 pumps of 245W max
DHW circulating pump	1 pump of 24W
Buffer tank	1000 litre 4-pipe
DHW cylinder	500 litre
Control	Heat pump controller + thermostatic radiator valves
Weather compensation	No
Heat meter type	Vortex
No. of heat meters	1
Heat meter interface	M-Bus
Comments	The gas boiler appears to be operated in bivalent mode (two sources of heat operating in parallel) rather than just as a backup

Table 1 – System details

Site 51 is recreational building in a rural location.

This application entails extracting heat from the ground to provide heat to a brick building that is around 50 years old and is not insulated to modern standards. The building is located in an area with below-average outdoor temperatures – estimated annual mean 9.4 °C (the range for all sites was 8.1 – 12.5 °C, median 10.3 °C). The heat pump has a single output that provides heat simultaneously to both space heating and domestic hot water and runs in (possibly unintentional) bivalent operation with a gas-fired boiler. The design performance of the system would be expected to be below average.

Heat pump and monitoring systems

A ground-source heat pump of 38 kW thermal capacity is installed in a plant room in the basement of the building. Heat is extracted via a brine loop from an estimated 10 vertical boreholes beneath a car park approximately 100 m from the plant room.

The heat emitters for space heating are radiators equipped with thermostatic valves. It is understood that the radiators are those previously installed for use with an oil-fired boiler and have not been re-sized for use with the heat pump.

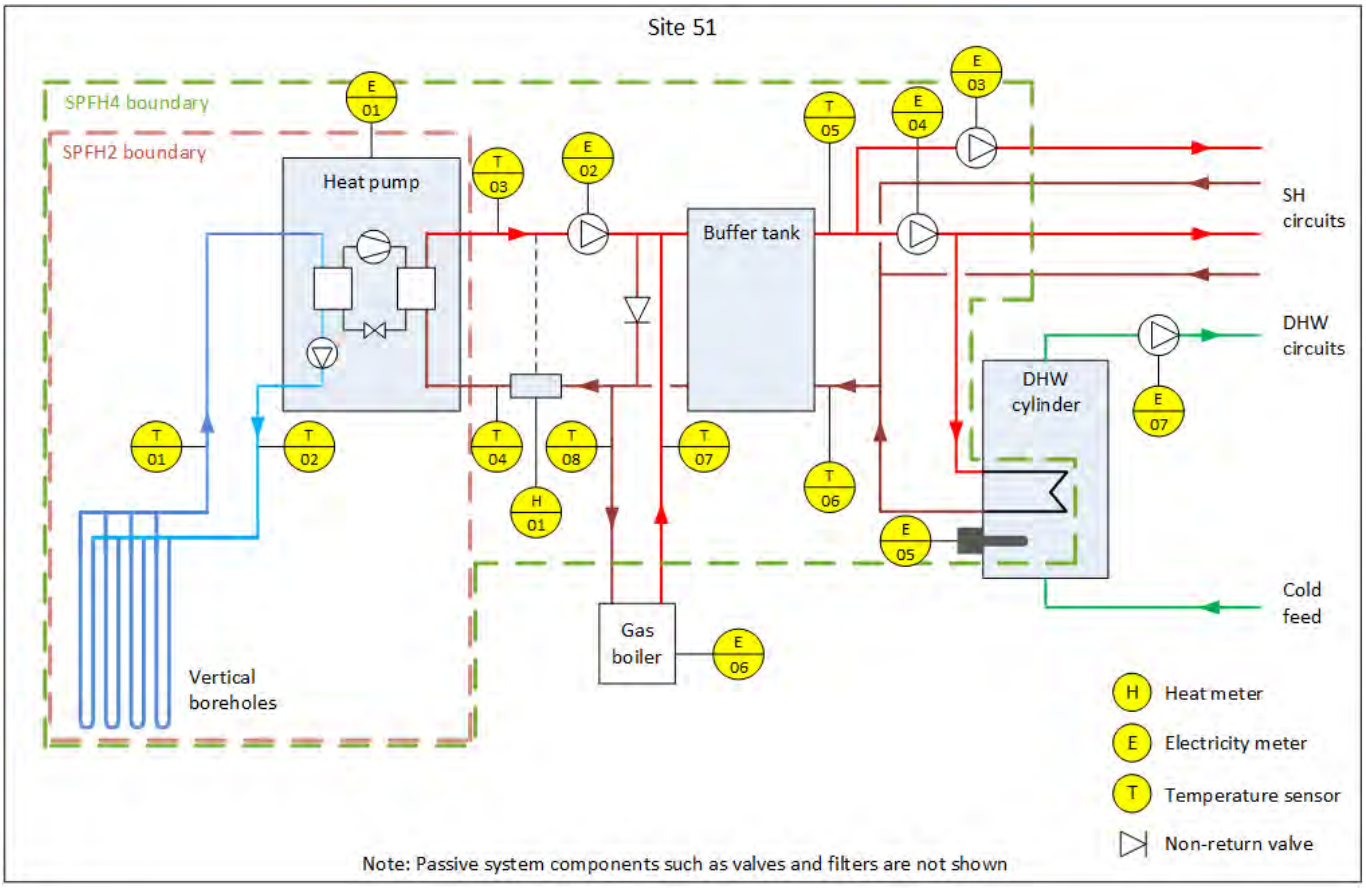
A 1000-litre 4-pipe buffer tank is installed between the heat pump output and the space heating circuits. Hot water from the buffer tank is also pumped through the heating coil of the domestic hot water cylinder. This is an unusual arrangement that is unlikely to lead to the best possible performance of the heat pump system.

Auxiliary heat is provided by a 44 kW_{TH} gas-fired boiler, and by a 3 kW immersion heater in the domestic hot water cylinder.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating and domestic hot water, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

The gas-fired boiler has not been included in the SPF_{H4} boundary as it is understood that bivalent operation is not intended. The boiler is not equipped with either a gas meter or a heat meter, so it is not feasible to accurately determine the heat provided by the boiler.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[1].



Note: Passive system components such as valves and filters are not shown

Figure 2 – System schematic showing the monitoring instrumentation installed

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [3] for further details. Note that these temperature measurements were not used for heat metering.

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses a vortex flow meter installed in the return pipe, with matched temperature sensors installed in pockets in the flow and return pipes. The calculator is mains-powered. Monitoring was via the M-Bus interface.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump including the internal brine pump.
- SPF_{H4} represents the performance of the complete system, including the auxiliary immersion heater (but not the gas-fired boiler) and excluding heat losses from the buffer tank.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of the heat pump]}}{\text{[Electricity used by the heat pump including the internal brine pump]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the buffer pump was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pump.

$$\text{SPF}_{H4} = \frac{\text{[Heat output of heat pump] + [heat added by buffer and SH circulating pumps] – [heat loss from buffer tank] + [heat added by DHW immersion heater]}}{\text{Electricity used by: [heat pump incl. brine pump] + [buffer and SH circulating pumps] + [DHW immersion heater]}}$$

- The heat added by the buffer pump and the heating circulating pumps was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

It was not possible to account for the heat supplied by the gas-fired boiler, as no heat meter or gas meter was installed for the boiler. The electrical input to the boiler and the temperature of the boiler output were monitored, so it is known when the boiler was operating.

The number of 1-minute intervals selected as valid for analysis was 524 494, which represents 99.8% of the 12-month period.

The SPF_{H2} and SPF_{H4} values for this system, measured between 1st January and 31st December 2015, are shown in Table 2:

SPF_{H2}	2.69
SPF_{H4}	2.44

Table 2 – SPF values measured for the period 1st January to 31st December 2015

This means that for each unit of electricity used, this system delivers on average 2.44 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. These figures represent the combined space heating + domestic hot water performance, not including the heat output from the gas-fired boiler. The wide variation in the values in April and May appears to have been due to the gas boiler being used to provide most of the heat (see Figure 6). During most of October, the heat pump was not used at all. The reason for this is not known.

The increased SPF values during late November and December appears to have been due to the much increased use of the heat pump after 3rd November. As shown in Figure 11, the daily mean heat pump output temperature was generally between 60 and 62 °C until 25th November, after which it was lower – generally between 52 and 58

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [6] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

°C. This small reduction in output temperature coupled with the longer heat pump run times would be responsible for the observed increase in performance.

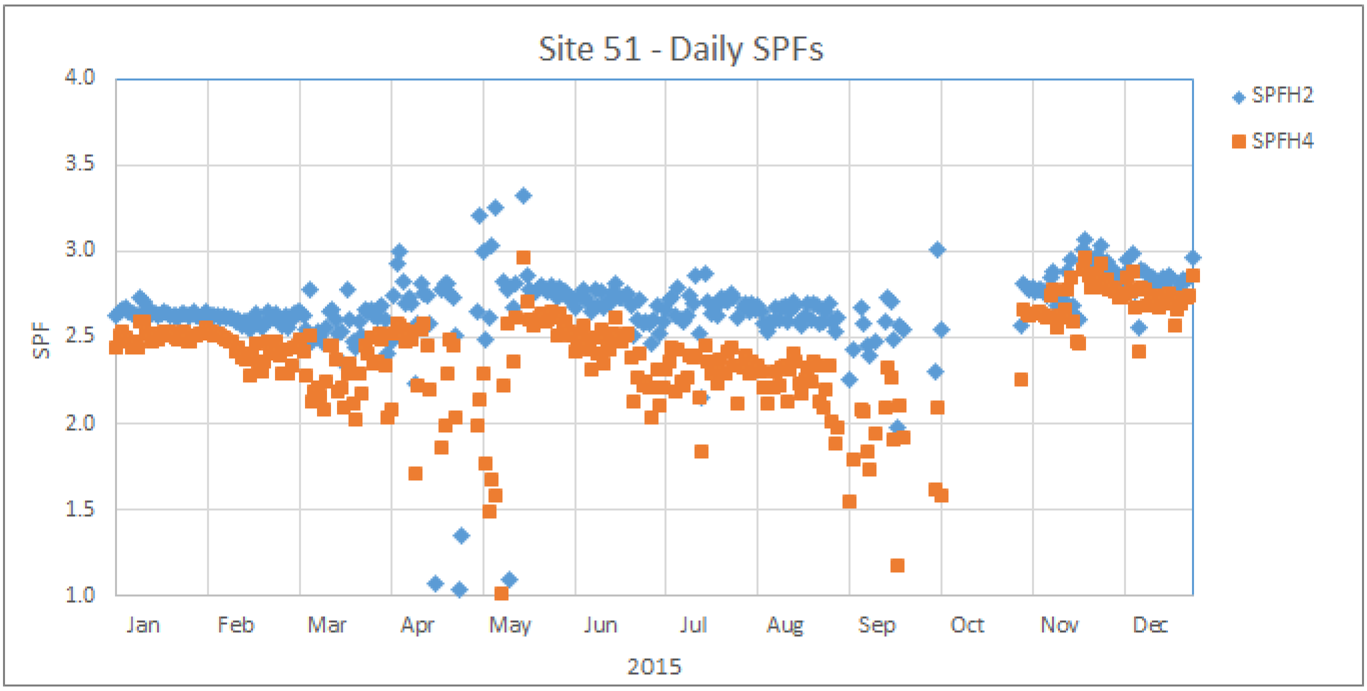

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily (excluding heat from the gas-fired boiler)

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Some heat pump systems incorporate electric immersion heaters or gas-fired boilers to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the energy used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump and from the immersion heater in the domestic hot water cylinder. The output from the gas boiler is not shown (it was not metered). The electricity used by the total heat pump system, and the outdoor air temperature from site 37[4] are shown for reference. The heat delivery was highest during November and December, and it can be seen in Figure 3 that the daily SPF values were also higher during this period.

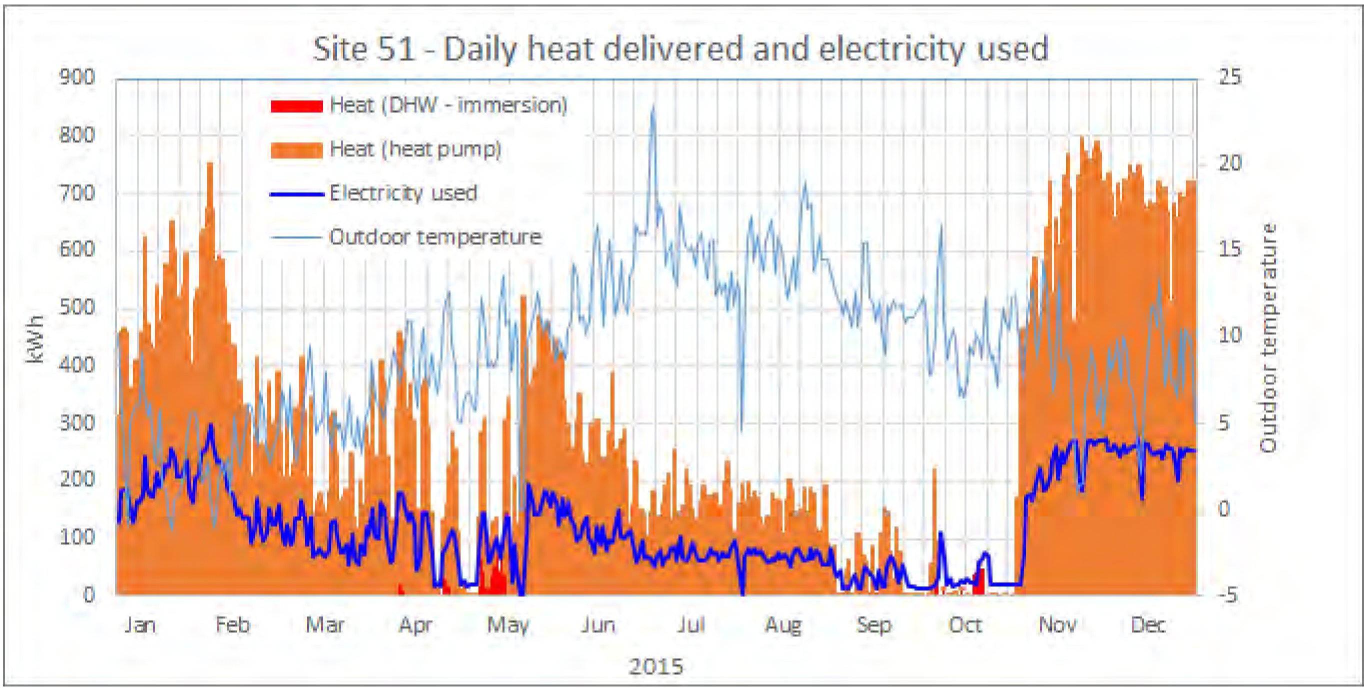

Figure 4 – Daily heat delivered and electricity used by the total heat pump system (excluding heat from the gas-fired boiler)

Breakdown of heat delivered

It was not possible to determine a breakdown of the heat delivery to space heating and domestic hot water on this system.

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[4] The outdoor temperature was not recorded at this site. The temperatures at site 37 are believed to be broadly similar to those at this site.

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The heat pump electricity use was highest during November and December, corresponding to the period of maximum heat delivery as shown in Figure 4. It is not known why the heat pump use was lower in January and February, when the outdoor temperature was lower. (The gas boiler was used much more at the start of the year than at the end of the year – see Figure 6.)

The domestic hot water immersion heater is controlled by a timeswitch with a manual override. Its use on several occasions is unexplained. The heat pump and/or gas-fired boiler should have been able to meet the domestic hot water demand, as they are considerably more powerful than the immersion heater.

The buffer pump and the heating circulating pumps accounted for 7.7% of the electricity used by the total heat pump system, which was below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance.

It was not possible to separately estimate the electricity used by the brine pump. It runs at the same time as the compressor, so it was not possible to determine the power drawn by the brine pump from analysis of the electricity metering data. The rating data for the pump is not available.

The immersion heater in the domestic hot water cylinder accounted for 2.8% of the total electricity. It is not known why this heater was used at all, considering the availability of the gas-fired boiler.

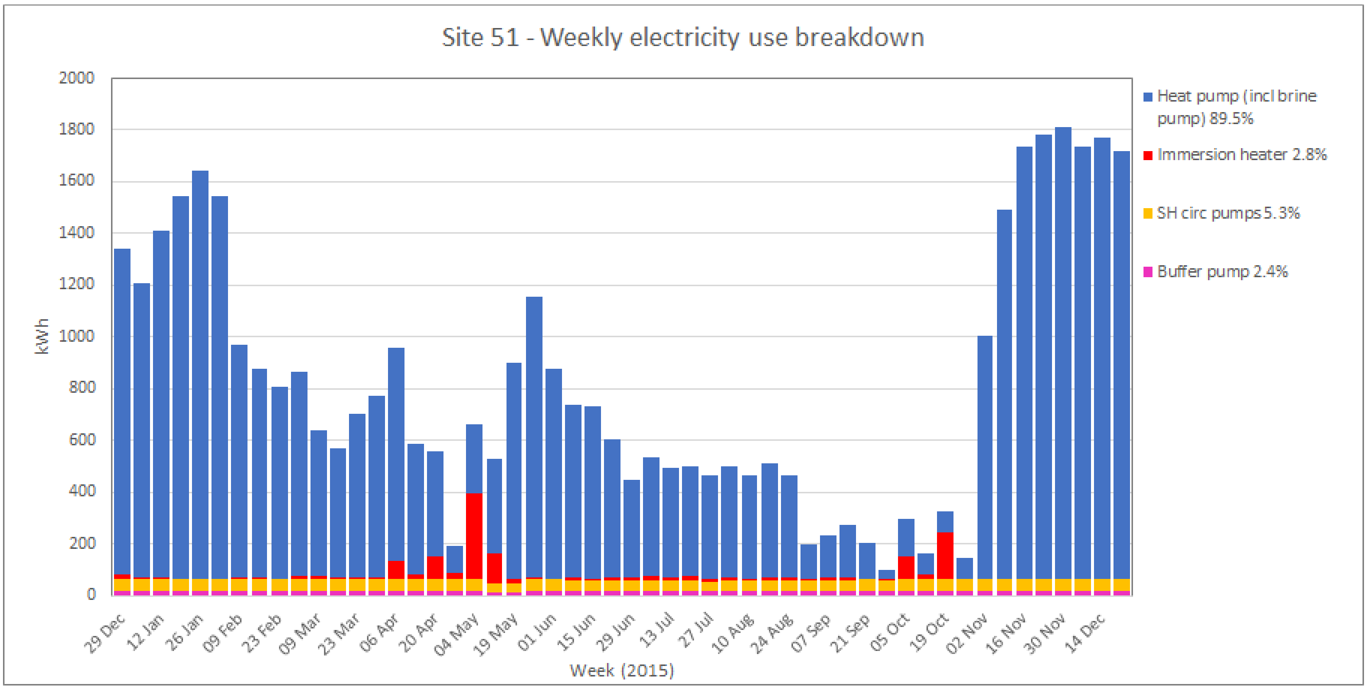

Figure 5 – Weekly electricity use breakdown

Gas-fired boiler operation and estimate of SPF_{H4} for bivalent operation

A gas-fired boiler is installed to provide additional heat. This boiler was understood to be used only for auxiliary heat and for backup. However, it appears to have been used in parallel with the heat pump (bivalent operation) for much of the time.

It is possible to make an approximate estimate of the heat provided by the boiler, using measurements of the boiler flow and return temperatures T07 and T08. Inspection of the data recorded from these sensors showed that the temperature difference [T07 - T08] varied as the boiler output was modulated with a maximum value of 16 °C, which was assumed to correspond to the maximum rated boiler output of 44 kWTH.

Assuming a constant water flow rate[5] through the boiler, the boiler output in kWTH can thus be calculated as:

$$H_{GasBoiler} = [T07 - T08] * 44.0 / 16.0$$

Figure 6 shows the resulting estimated daily heat output of the heat pump and the boiler.

After 3rd November the heat pump was in much greater use, with the gas-fired boiler being used only occasionally. The reason for this is not known, but it seems likely that the boiler had been used more than necessary as a result of inappropriate control strategy or settings.

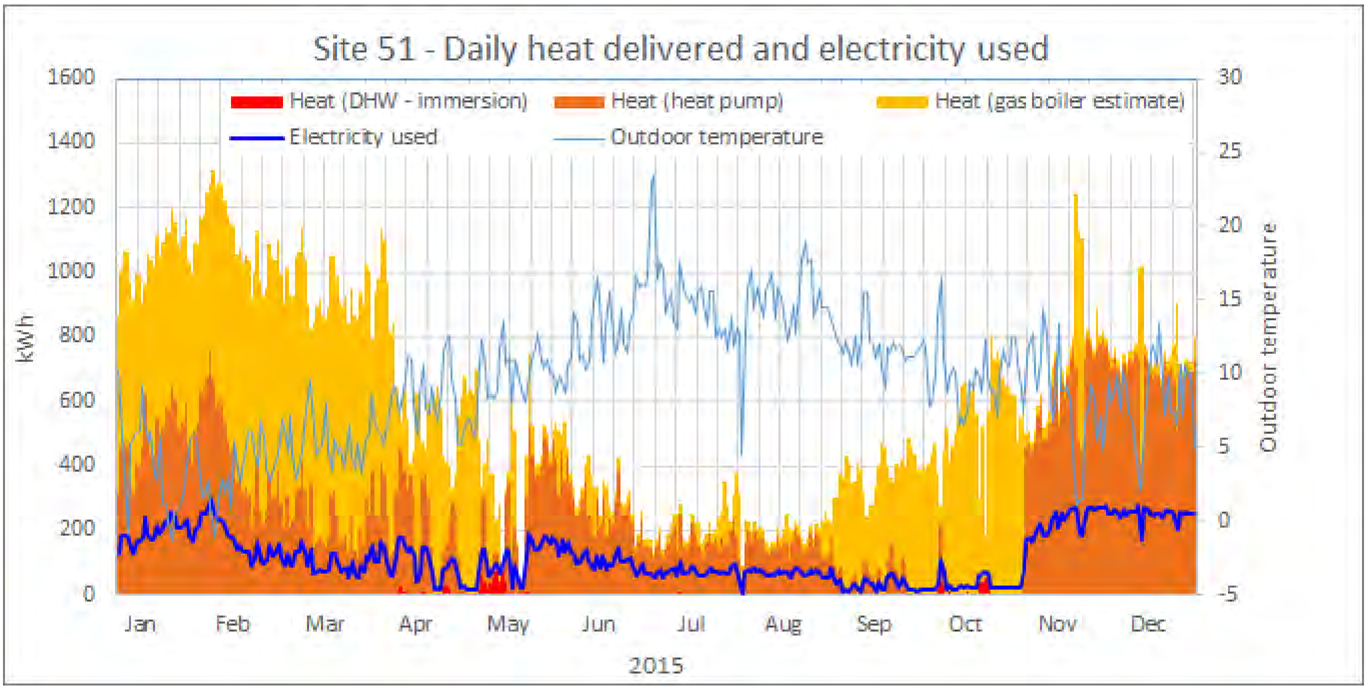

Figure 6 – Daily heat delivered and electricity used by the total heat pump system (including the estimated heat output of the gas-fired boiler)

An estimate of the SPFH4 for bivalent operation of the system can be made using the following equation:

$$\text{SPF}_{H4} = \frac{\begin{array}{c}\text{[Heat output of heat pump] + [heat added by buffer and heating circ pumps]} \\ \text{– [heat loss from buffer tank] + [heat added by DHW immersion heater] + [heat from gas boiler]}\end{array}}{\begin{array}{c}\text{Electricity used by: [heat pump incl brine pump] + [buffer and heating circulating pumps]} \\ \text{+ [DHW immersion heater] + [energy value of gas used by boiler]}\end{array}}$$

Assuming a boiler efficiency[6] of 81% to determine the energy value of the gas supply, the estimated bivalent-mode SPFH4 is 1.20.

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

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[5] The flow rate through the boiler was not measured.

[6] The assumed boiler efficiency is the same as that used for estimating CO_2 and fuel bill savings in the Final Report [5].

Figure 7 shows the operating pattern on a typical winter day on 5th January 2015 when the outdoor temperature was estimated between 1 and 8 °C. The heat pump cycled on and off, running for 25 to 90 minutes at intervals of an hour or more. However, the gas-fired boiler was running all day, providing a steady output temperature of 60 °C to mix with the output from the heat pump to the buffer tank. The output from the heat pump reached 63 °C. This behaviour does not suggest best use of the heat pump. It might have been expected that it would run longer (or continuously) with a lower output temperature to maximise the renewable heat generation, and that the gas-fired boiler would be used if needed to boost the output. The reason for the system operating in this way is unknown, but it suggests that the control strategy needs to be revised.

The temperature of the brine flow to the heat pump was between 2.5 and 5.5 °C.

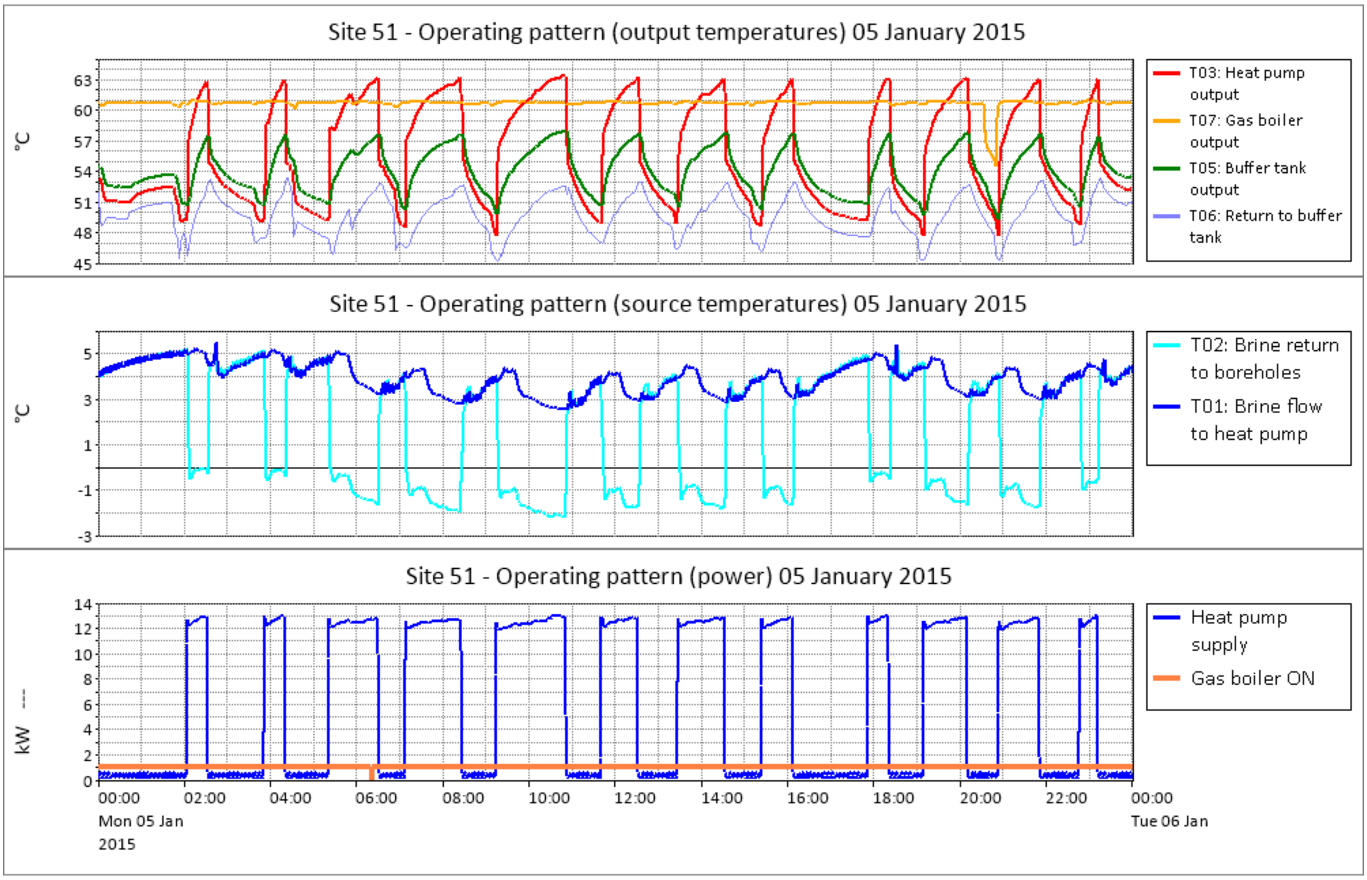

Figure 7 – Operating pattern on 5th January 2015

Figure 8 shows the operating pattern during a day on 5th August 2015 when the outdoor temperature was estimated between 11 and 21 °C and the space heating load would have been minimal. The gas-fired boiler was not in use. It is notable that the heat pump output temperature was still up to 62 °C, which indicates that weather compensation was either not enabled or had no effect. Again, this appears to have been the result of poor control strategy.

The heat pump runs were for approximately 15 - 20 minutes each, at intervals of an hour or more. This was well within the cycling guidelines determined from previous research [2].

The brine temperature while the heat pump was running was between 8 and 9 °C.

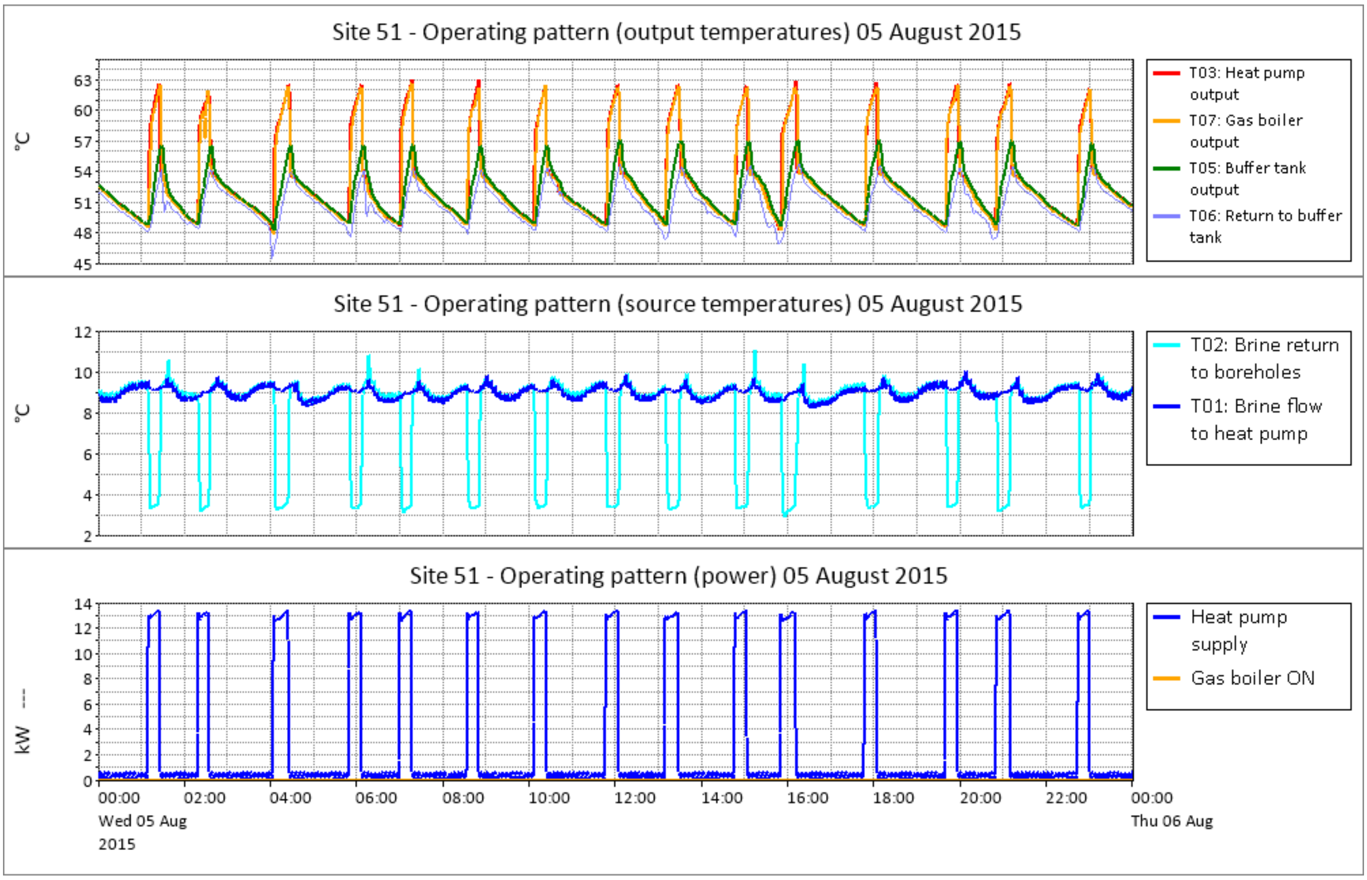

Figure 8 – Operating pattern on 5th August 2015

Source and sink temperatures

Figure 9 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[7]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The consistently high heat pump output temperature throughout the year is further indication that weather compensation was not functioning.

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[7] Temperatures of the heat pump system were recorded at 2-minute intervals.

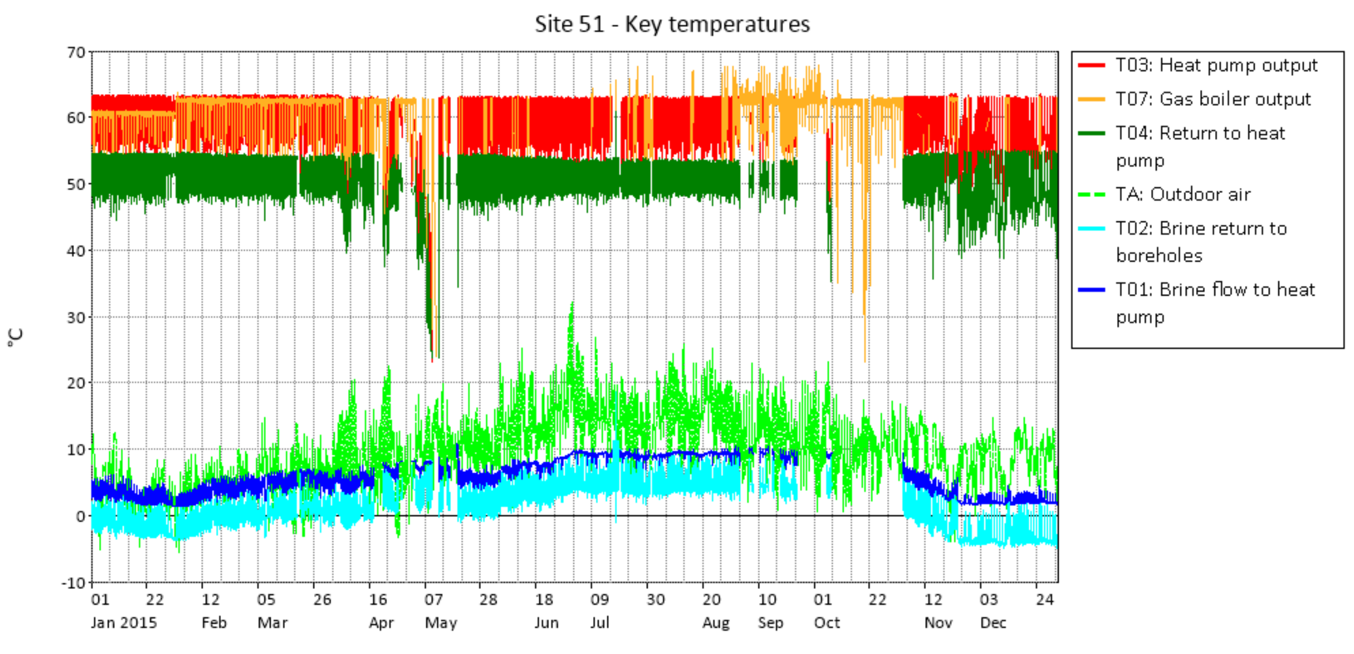

Figure 9 – Key temperatures measured during the period 1st January – 31st December 2015

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were average during the early part of the year, but were at the low end of the range toward the end of the year when the heat pump was in greater use. The lower brine temperatures would have had a negative influence on system performance, because of the increased temperature lift required of the heat pump.

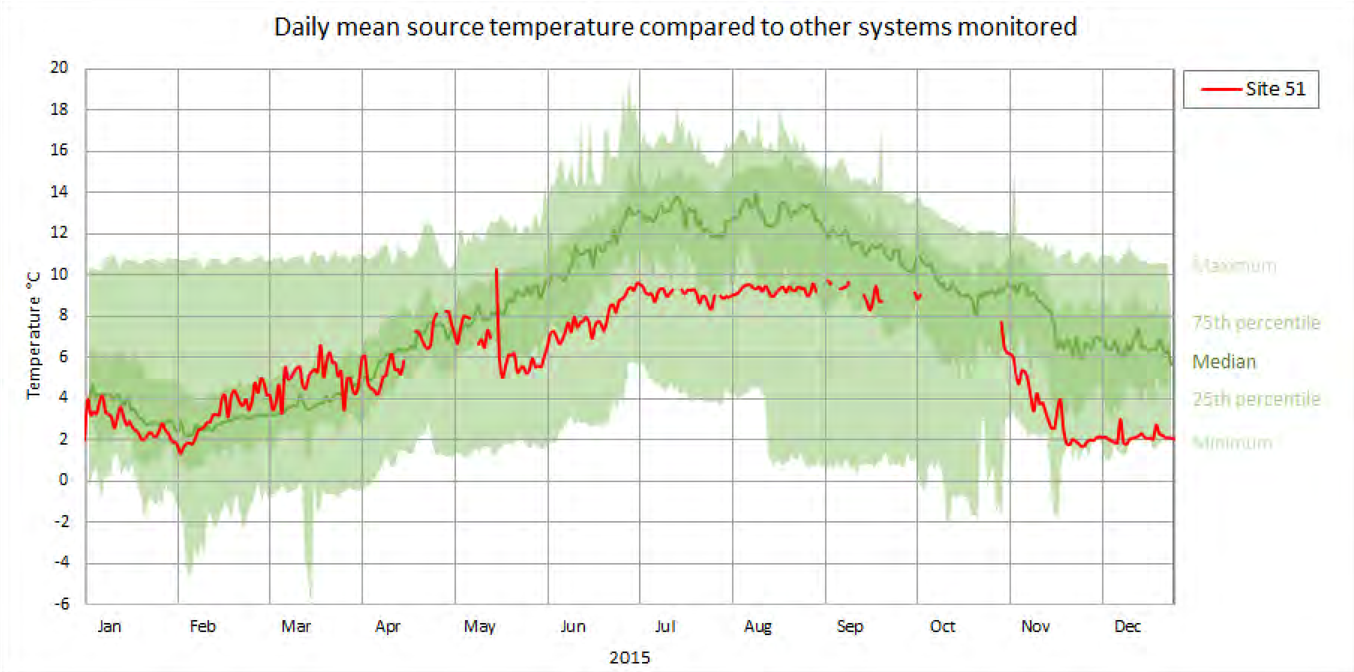

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 51 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were at the upper end of the values observed on other installations. This would have had a significant negative influence on the system performance.

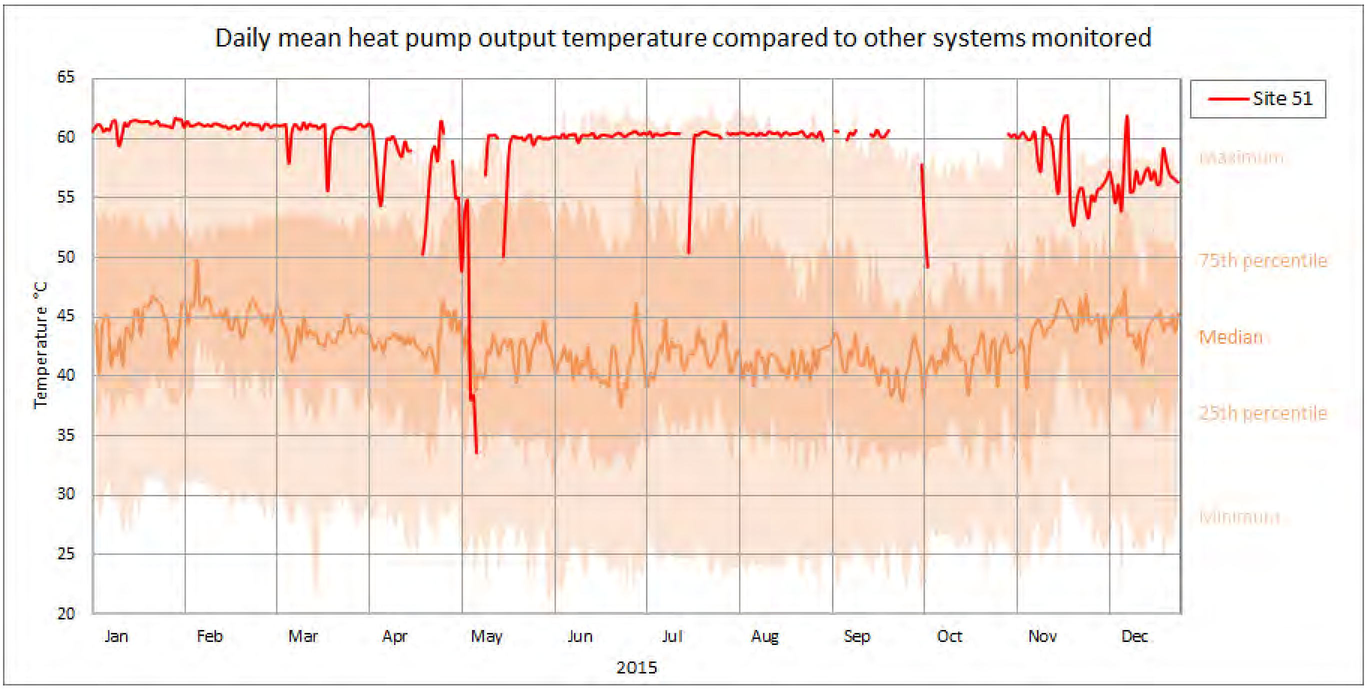

Figure 11 – Daily mean heat pump output temperature compared to those of other systems monitored in this project (site 51 is shown in red)

Comments

The performance figures presented for this system do not take account of the unmetered heat supplied by the gas-fired boiler. The boiler was operated much of the time in parallel with the heat pump for reasons that are unknown, and it seems from the recorded data that parallel operation of the heat pump and boiler was probably not usually needed. During the relatively cold period of November and December, the heat pump provided most of the heat output, so it would appear that it is capable of meeting the heat demand under most conditions.

This performance of this system (SPFH4 = 2.44) was average compared to other systems providing both space heating and domestic hot water that were monitored in this project (SPFH4 range: 1.54 to 3.13, median value 2.41).

Aspects of the system that may have negatively influenced its performance include:

- The gas-fired boiler was used much more than should have been necessary. The heat pump should be used whenever possible to maximise the renewable heat provided. The control strategy or settings should be adjusted to make better use of the heat pump.
- The temperature of the output from the heat pump was always high (62 - 63 °C at the end of each run cycle) – irrespective of whether the gas-fired boiler was also running, and irrespective of the outdoor air temperature. During mild weather, the radiators presumably could operate at a lower temperature than during the coldest periods. No advantage of this is being taken to reduce the heat pump output temperature (i.e. weather compensation). It may be worth investigating whether there is an opportunity to reduce the output temperature during mild weather, and to check that the weather compensation function of the control system is correctly configured.
- It is not known why the domestic hot water system is designed to be heated by water from the buffer tank – an arrangement that does not make best use of the temperature available from the heat pump,

and one that may preclude the effective use of weather compensation by always requiring a high heat pump output temperature.

- The domestic hot water immersion heater was used regularly. It is unclear why this was necessary, as the heat pump or the gas-fired boiler could have provided the heat at lower cost.
- The temperature of the brine flow to the heat pump was lower than average compared to other systems monitored (during the period at the end of the year when the heat pump was being used more than it had been previously).

An estimate of the bivalent-mode performance was made by estimating the heat output of the boiler using temperature data. The estimated SPF_{H4} for bivalent operation during the period monitored was 1.20.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.,” EN 14511.

[5] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps – Final Report,” BEIS, 2018.

[6] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 53

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 53 and performance results from 12 consecutive months of monitoring data.

Site 53 is an office / warehouse building, located on a small suburban industrial estate.

A water-source heat pump (thermal capacity 30 kW) extracts heat from a river that flows past the building, and provides heat to an underfloor heating system. The system is reversible to provide cooling when required, although this capability is rarely used.

The seasonal heating performance factors measured over a year of operation
(1st April 2015 to 31st March 2016) were:

SPF_{H2}	[Heat delivered by the heat pump] – [heat added by internal buffer pumps] --- [Electricity used by the heat pump excluding internal buffer pumps + source & brine pumps]	2.62
SPF_{H4}	[Heat delivered by the heat pump] + [auxiliary heat] + [heat added by SH circ pumps] --- [Electricity used by the total heat pump system]	2.25

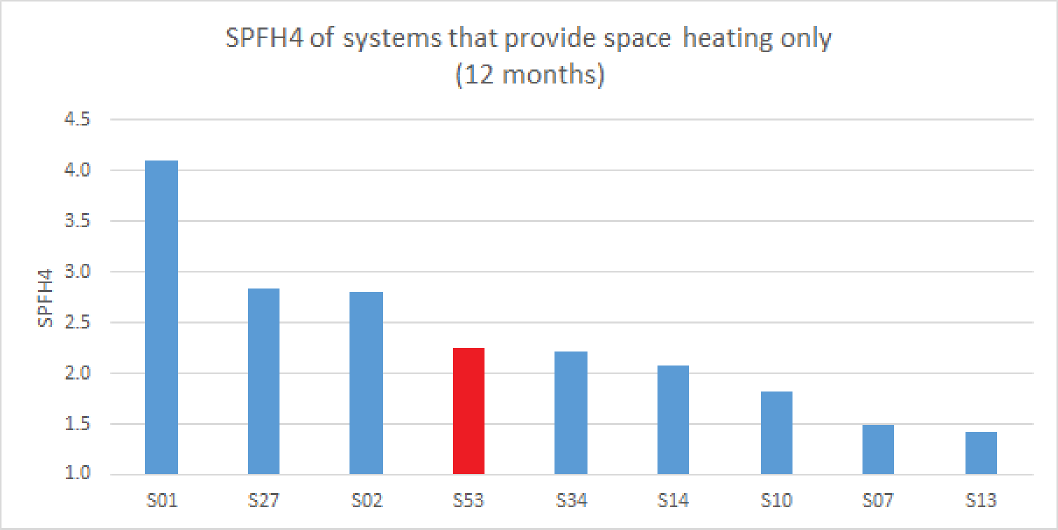

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating only

Aspects of this system that positively influenced its performance are:

- The temperature of the brine at the inlet to the heat pump was above average compared to other systems in the monitored sample for part of the monitoring period.
- The temperature of the heat pump output was below average compared to other systems in the monitored sample, and below average compared to other underfloor heating systems.

Aspects of the system that may have negatively influenced its performance include:

- The electricity used by the open-loop river water pump was very high: 13.8% of the electricity used by the total heat pump system. The river water and brine pumps together accounted for 16.0% of total electricity which is considerably above the average electricity used by source pumps on other systems monitored (range 2.3% - 29.8%, median 7.6%).

- The indoor air temperature was not well controlled, leading to the heat pump operating at times when it should not have been needed.
- The reversing valves would have introduced some pumping and heat losses into the system and would have increased the capital cost of the system – apparently unnecessarily, as the cooling arrangements reportedly do not work adequately and are now not used.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	53
Survey date	22/01/2015
Monitoring installed	19/03/2015
G/WSHP	WSHP
Building type	Offices and warehouse
Location	Suburban
Heat pump capacity kW$_{TH}$	30
Number of heat pumps	1
Number of compressors	2 (2 vapour-compression circuits)
Heat source	River water
Heat emitters	Underfloor heating pipes
DHW	No
Auxiliary heat	Immersion heater 13 kW max
Source pumps	1) Underwater pump in the river: 1 kW 2) Internal to heat pump (for brine loop): 2 pumps of 145 W
Buffer pumps	Internal to heat pump: 2 pumps of 70 W
SH circulating pumps	1 pump of 40 W max (variable-speed) 2 pumps of 45 W max (variable-speed)
Buffer tank	500 litre 4-pipe
Control	Heat pump controller + wireless programmer & room thermostats
Weather compensation	Yes
Heat meter type	Vortex
No. of heat meters	1
Heat meter interface	M-Bus
Comments	The system is equipped with reversing valves to provide cooling during warm weather

Table 1 – System details

Site 53 is a single-storey office and warehouse building, constructed in 2013 on a small suburban industrial estate.

The application entails extracting heat from river water to provide space heating via underfloor pipes in a modern well-insulated building incorporating offices and a warehouse in a location with outdoor temperatures slightly above the median for all sites monitored. (The mean outdoor temperature for site 53 was 10.7 °C. The range for all sites was 8.1 – 12.6 °C, median 10.5 °C.) The design performance of the system in heating mode would be expected to be high.

Heat pump and monitoring systems

A heat pump with two vapour-compression circuits and a total thermal capacity of 30 kW is installed in a corner of the warehouse, adjacent to the office area. Water is pumped from a river that runs past the building though a plate heat exchanger that transfers heat to brine and thence to the heat pump evaporator. The water is discharged back to the river in an open-loop pumping arrangement, with the discharge above the river water surface.

Heat is provided to space heating via underfloor heating pipes in the offices and fan-coil heaters in the warehouse.

The system can be reversed to provide cooling via the underfloor pipes. This arrangement is understood not to work very well, and was not used during the monitoring period.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

A 500-litre 4-pipe buffer tank is installed between the heat pump output and the heating circuits. This buffer tank is within the heated envelope, so the heat losses from it were not deducted from the system heat output.

Auxiliary heat can be provided by a 13 kW immersion heater. This was not used during the monitoring period.

Electricity meters (denoted by the circular "E" symbols) were installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") were monitored at key points in the system using surface-mounted probes[1]. The outdoor air temperature was also monitored.

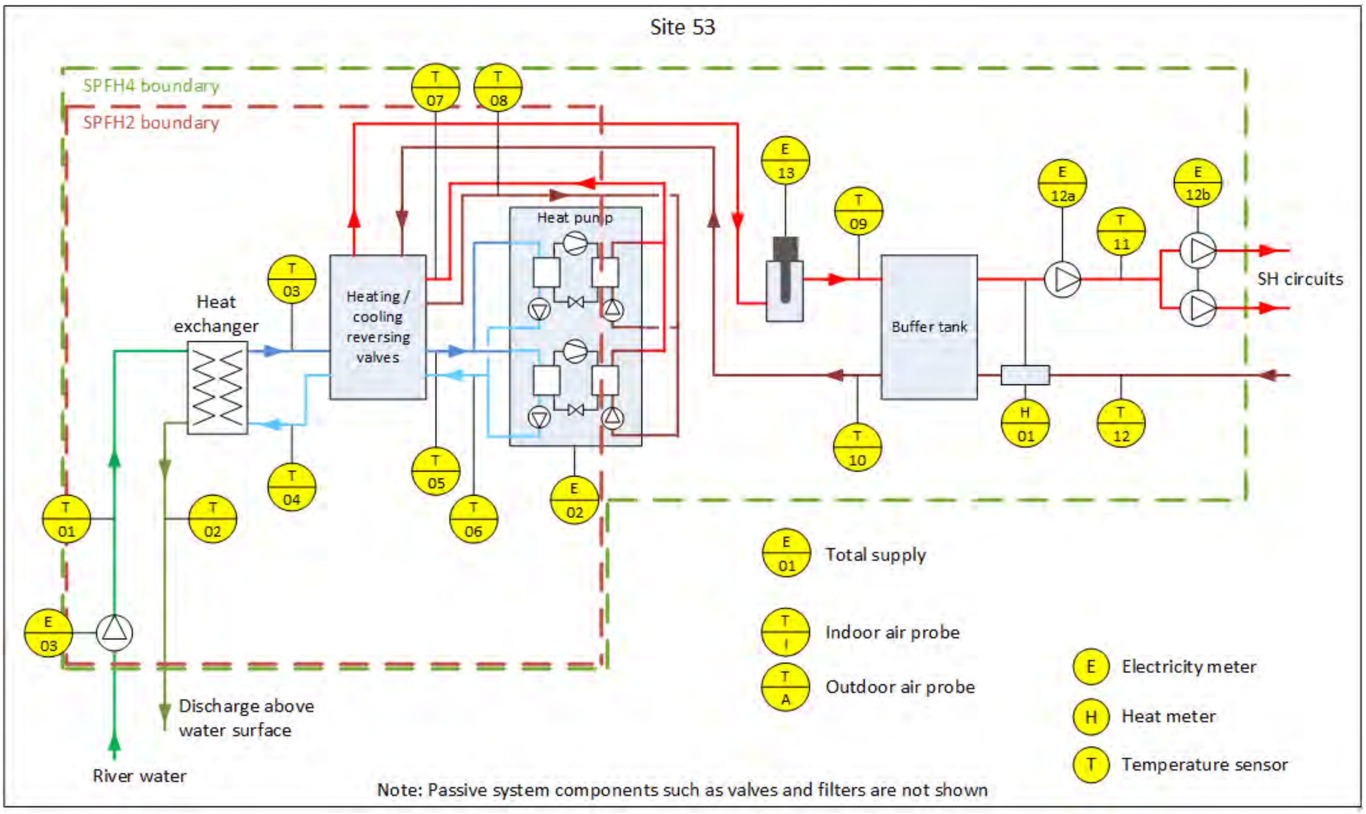

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the system. The heat meter on this system is installed between the buffer tank and the heating circuits. It uses a vortex flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is mains-powered. Monitoring was via the M-Bus interface.

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [1] for further details. Note that these temperature measurements were not used for heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump and brine pumps.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters (if used), excluding periods when the system was operating in cooling mode.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat measured by the heat meter] + [heat loss from buffer tank]} - \text{[heat added by buffer pumps]}}{\text{Electricity used by: [heat pump excluding the buffer pumps] + [river water pump]}}$$

- This calculation required the electrical energy used by the buffer pumps inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pumps, calculated for intervals that the power on the heat pump supply circuit phase supplying the pumps was above a minimum value.

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.

$$SPF_{H4} = \frac{\text{[Heat measured by the heat meter] + [heat loss from buffer tank] + [heat added by SH circulating pumps]}}{\text{[Electricity used by the total heat pump system]}}$$

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The immersion heater has not been shown in the SPF equations as it was not used during the monitoring period.

The number of 1-minute intervals selected as valid for analysis was 525 914, which represents 99.8% of the 12-month period.

The average SPF_{H2} and SPF_{H4} values for this system, measured between 1st April 2015 and 31st March 2016, are shown in Table 2.

SPF_{H2}	2.62
SPF_{H4}	2.25

Table 2 – SPF values measured for the period 1st April 2015 to 31st March 2016

This means that for each unit of electricity used, this system delivers on average 2.25 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. The gap in the data in November was due to a problem with the monitoring system[4].

There was a wide variation in the SPF values from day to day. This is explained by the daily variation in heat demand while the electricity used by the auxiliary pumps remained fairly constant.

It is also notable that during periods of zero heat demand the measured SPF values were below 1.0. These unusually low values are explained by the auxiliary pumps continuing to run although not required because the heat pump was not running. The total energy used during these periods was small, so the effect on the overall annual SPF values was small. However, such energy wastage is undesirable.

The high SPF values for a few days after the restart at the beginning of January were due to the heat pump output temperature being lower than normal while the building warmed up to normal operating temperature.

There is considerable scatter in the SPF values. This appears to have been due to the indoor thermostat(s) having been adjusted from time to time, resulting in large variations in heat demand and heat pump output temperature.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [4] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[4] No data was received from the electricity monitoring system between 7th - 22nd and 23rd – 26th November because of a data communication failure.

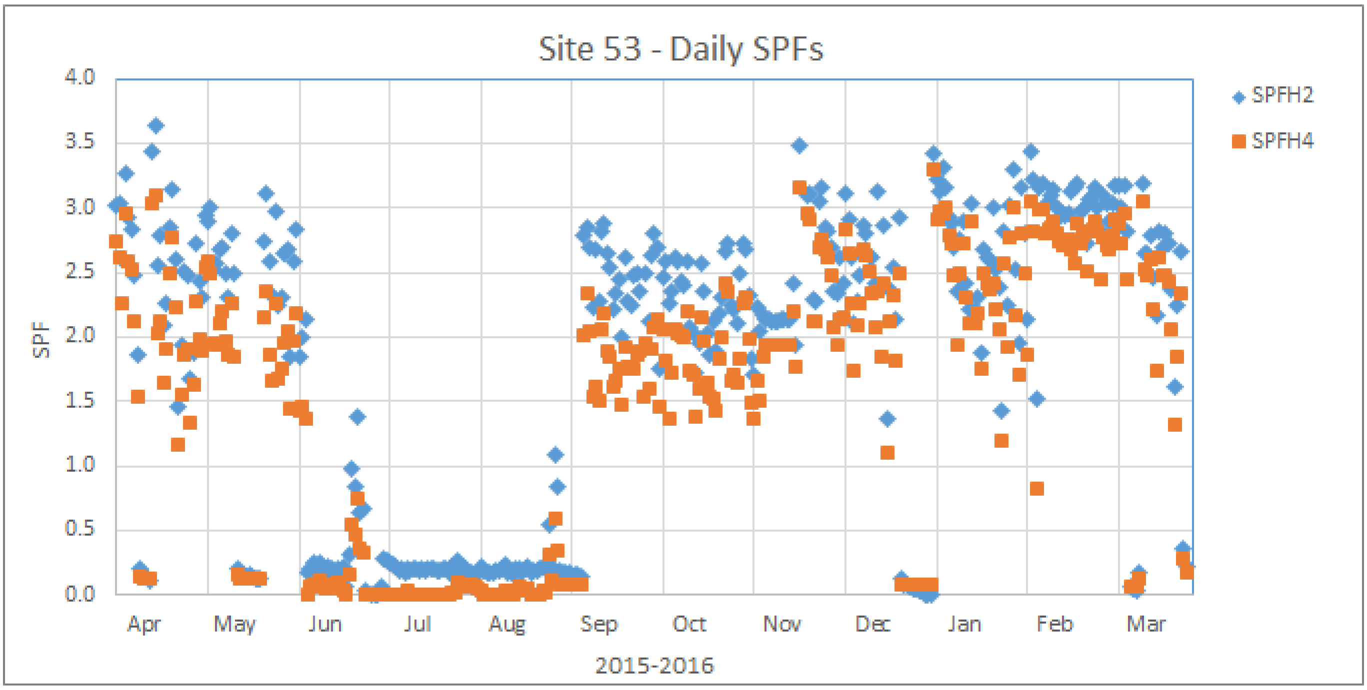

Figure 3 – Seasonal performance factors SPF$_{H2}$ and SPF$_{H4}$ calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the river water and the sink is the space being heated.

Heat extraction from the source to the heat pump is via an open-loop circuit from the river, through a water-to-brine heat exchanger, and through a brine circuit to the heat pump. The brine will always be colder than the source, because a temperature difference between the river water and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the water from the source, the brine through the heat exchanger, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. Additional pumping power is also needed on this system to pump the brine and the hot water through the reversing valves. These pumps use electricity, which can be a significant part of the total electricity used by the system.

An electric immersion heater is installed to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions. This heater was not used during the period monitored.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required for the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump system. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The heat output generally varied with the outdoor temperature. The high output in early January was due to the system re-heating the building after the shutdown over the Christmas/New Year break.

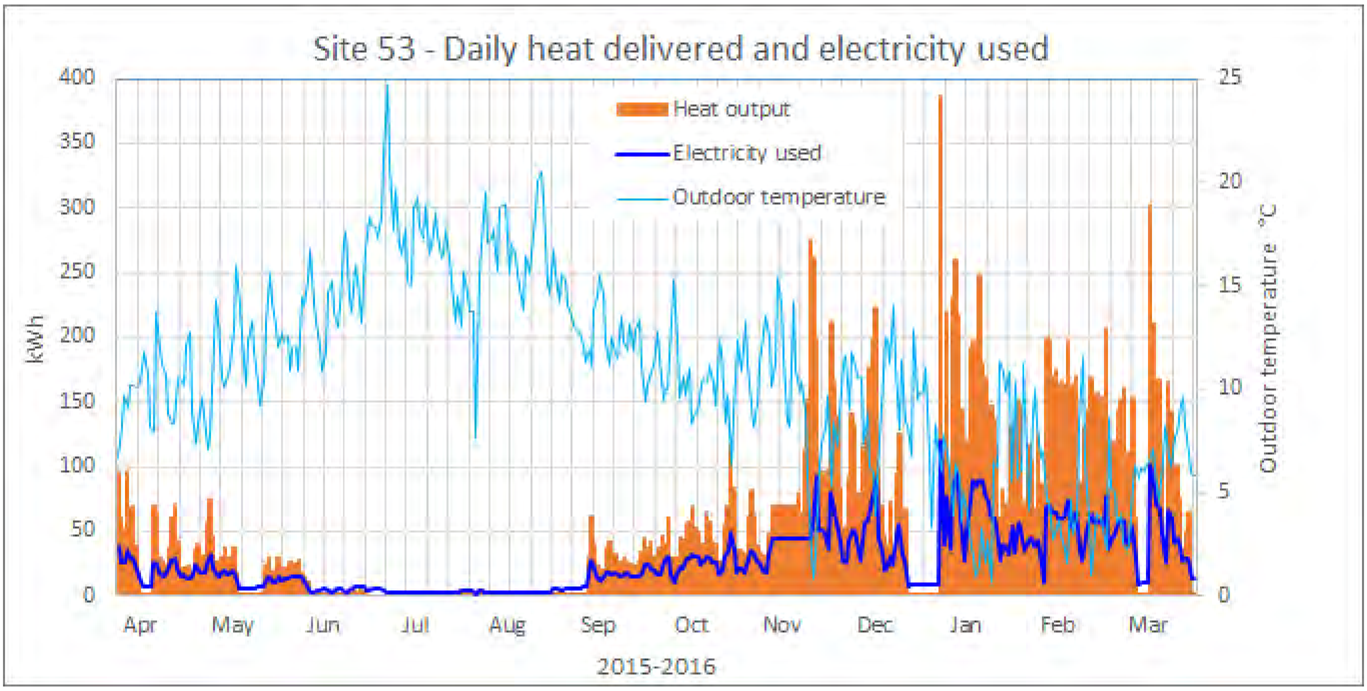

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The electricity used by the brine and buffer pumps in the heat pump was estimated as described above.

The river water pump accounted for 13.8% of total electricity use. This high figure is explained by the nature of the open loop water circuit, where the pump has to lift the water from the river to the heat exchanger in the plant room (approximately 3 m vertical lift), rather than just circulate it through a closed loop.

The brine circulating pumps used an estimated 2.2% of the total electricity.

The river water and brine pumps together accounted for 16.0% of total electricity which is considerably above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance.

The buffer pumps and the heating circulating pumps together used an estimated 10.0% of the electricity, which was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a negative influence on the system performance.

The electricity used by the heat pump during the summer months when there was no heating demand was due to an internal single-phase load of 94 W – presumably the controls.

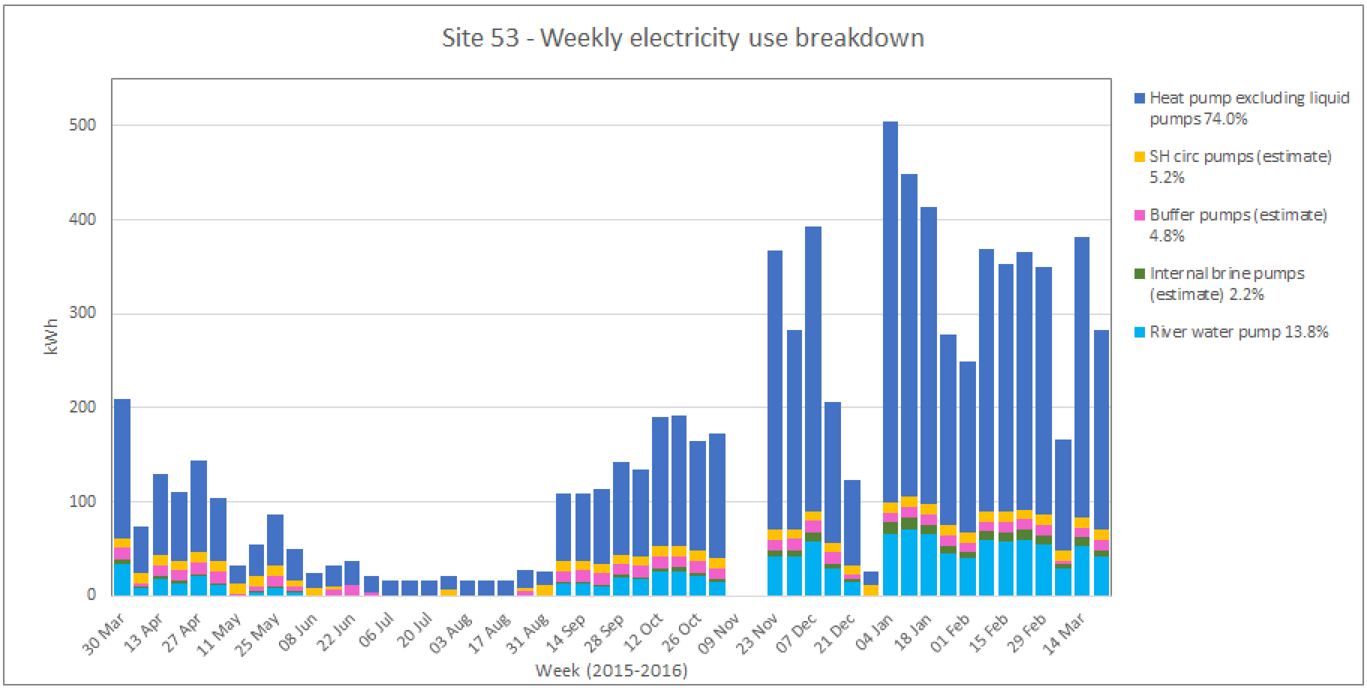

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operational behaviour over a 3-day winter period, 14th – 16th February 2016. The outdoor temperature was between -4 and +6 °C. The indoor temperature was between 21 and 23 °C.

The demand for heat, as shown by the thermal power curve ("Heat output to SH" red line in the bottom section), appeared to be fairly constant (although cycling as the heat pump cycled on and off) throughout the Sunday when the premises were not occupied.

There was no heat output from midnight on Sunday until 08:00 on Monday. As there was no significant change in outdoor temperature during this period, the change in demand was presumably a consequence of the control programme.

From 08:00 on the Monday, the heat pump ran continuously for 4 hours, with both compressors being used for short periods of 4 – 11 minutes. Thereafter, it cycled on/off for the rest of the day, using only one compressor. The minimum run time was 20 minutes, and the cycling behaviour was comfortably within the guidelines recommended by previous research [2].

The outdoor temperature dropped to -4 °C during the night, and the heat demand increased, with the heat pump using both compressors at times, until 10:30 on the Tuesday. The heat pump then did not run again until 14:40.

The outdoor temperature rose fairly quickly to 6 °C at 15:00 on Tuesday. The indoor temperature increased to 23 °C at the same time: this may have been due to some overshoot in the control system or to solar gain. It is not known why the heat pump was operating when the indoor temperature was above 22 °C. This indicates a possible problem with the control strategy.

The pattern of operation at the end of Tuesday was similar to that on the Sunday.

It is not known why there was a demand for heat all day on the Sunday or during the night.

The effect of weather compensation can be seen: the heat pump output temperature was generally higher when the outdoor temperature was lower.

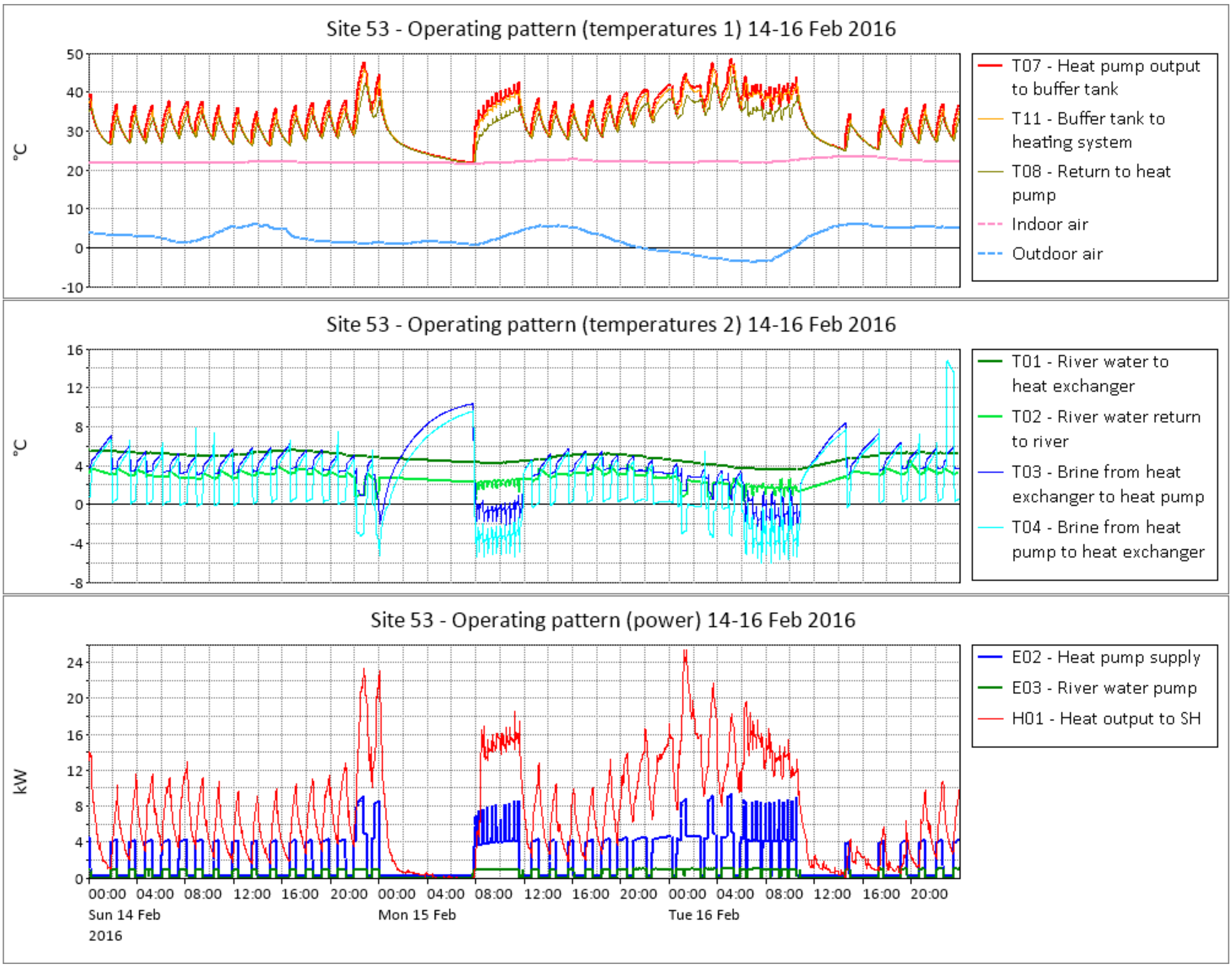

Figure 6 – Operating pattern 14th - 16th February 2016

Figure 7 shows the operating pattern during a day on 8th September 2015 when the outdoor temperature was between 7 and 13 °C. The indoor temperature was between 21 and 23 °C.

The heat pump ran every 2 to 4 hours, with the run time varying from 15 to 30 minutes. This is good part-load behaviour and is well within the cycling guidelines determined from previous research [2].

The river water pump ran whenever one or both heat pump compressors were running.

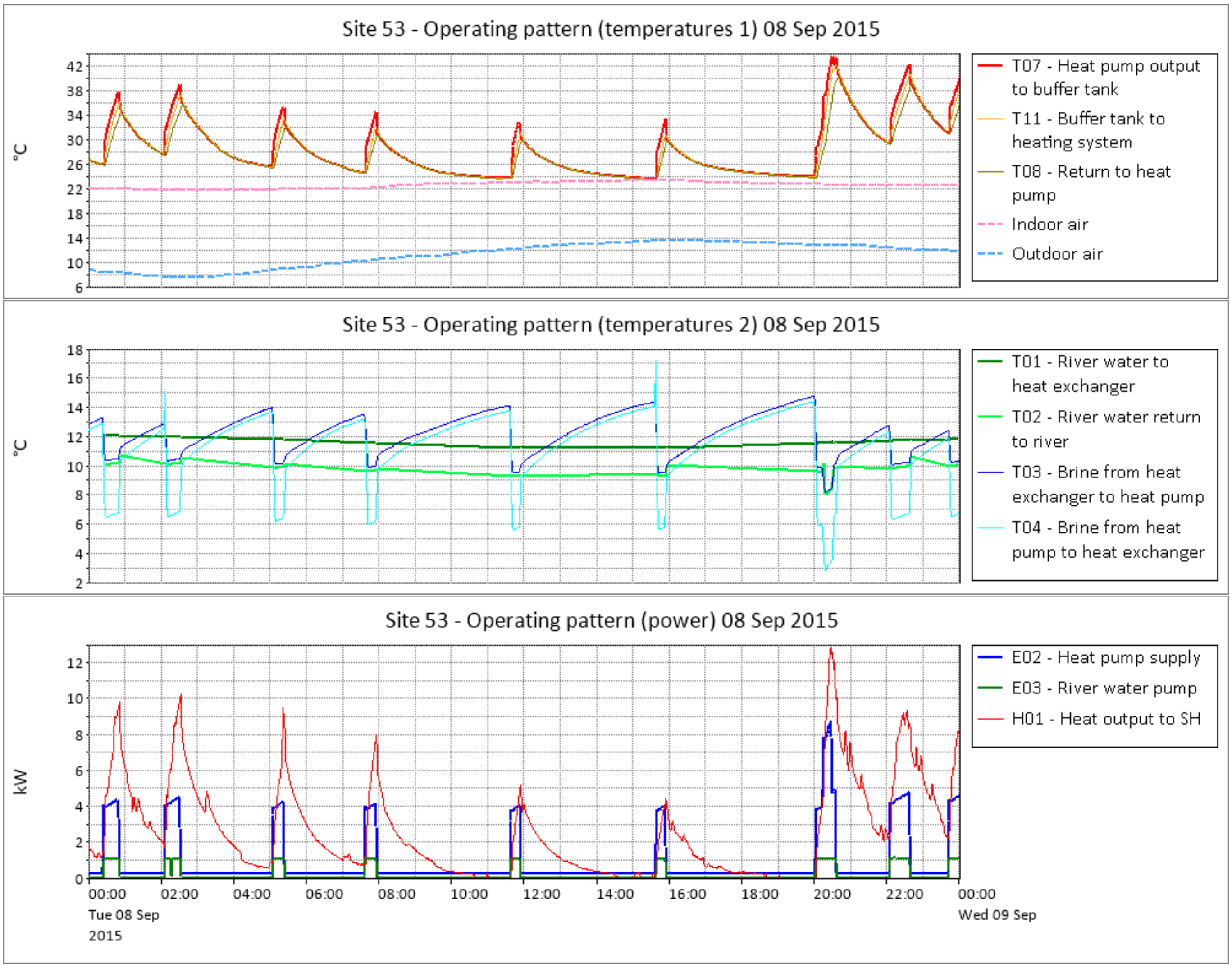

Figure 7 –Operating pattern on 8th September 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, river water, brine and the outputs from the heat pump, plotted over the year[5]. The river water, brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The river water temperature varied during the year between 7 and 14 °C. The temperature of the brine to the heat pump was between -7 and +13 °C.

The temperature difference between the river water and the brine to the heat pump was between 3 and 4 °C while the heat pump was running.

The heat pump output temperature varied between 23 and 56 °C. The temperature from the buffer tank to the heating circuits varied between 22 and 55 °C.

The temperature loss through the buffer tank was generally between 1 and 2.5 °C.

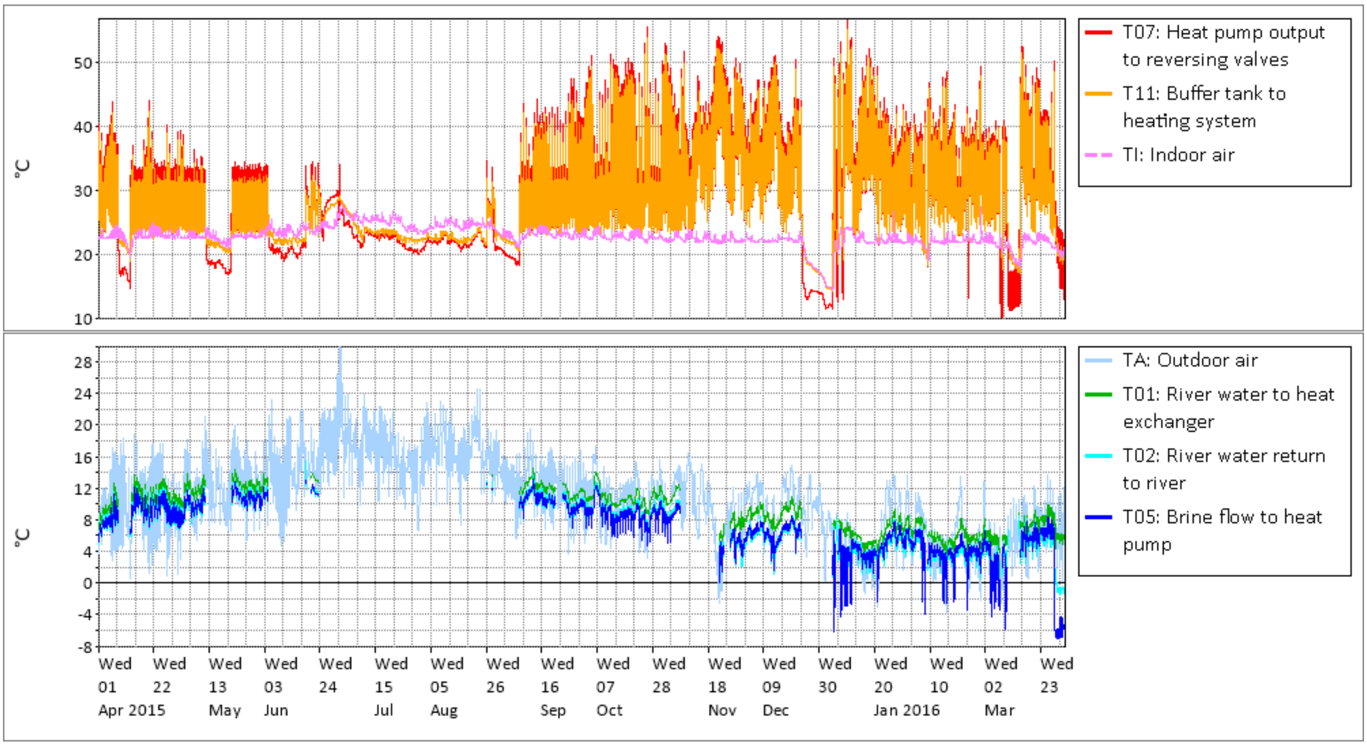

Figure 8 – Key temperatures measured during the period 1st April 2015 – 31st March 2016

Freezing in the river water circuit

At the end of March there was an incident of freezing in the river water circuit. Figure 9 shows the brine temperature dropping below 0 °C on 28th March and the river water return temperature dropping to -1.2 °C on the 29th March. The heat pump continued to run approximately twice every hour for very short intervals of around 2 minutes, but there was almost no heat output. This situation persisted until 31st March when the problem was discovered. It is not known why this problem occurred. It is understood that the plate heat exchanger was not damaged in this incident, although it was clearly an undesirable occurrence and illustrates what can happen if there is no protection against freezing in water-source heat pumps.

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[5] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes.

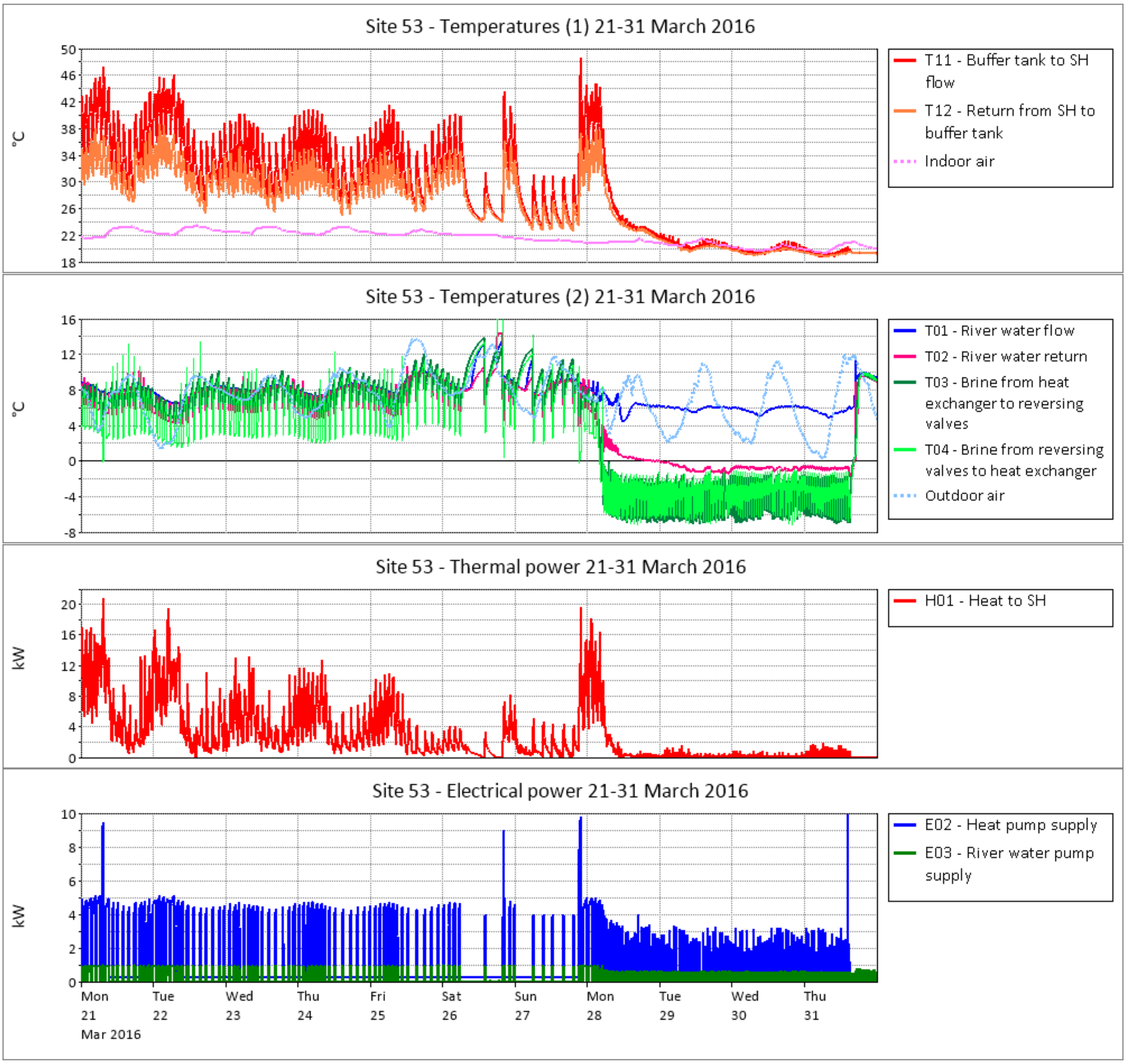

Figure 9 – River water circuit freezing incident 28th – 31st March 2016

Figure 10 shows the daily mean brine flow temperature compared to the source temperatures (at the heat pump) of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were above average during the first three months of the monitoring period, and approximately average after August. The above-average temperatures would have had a positive influence on system performance.

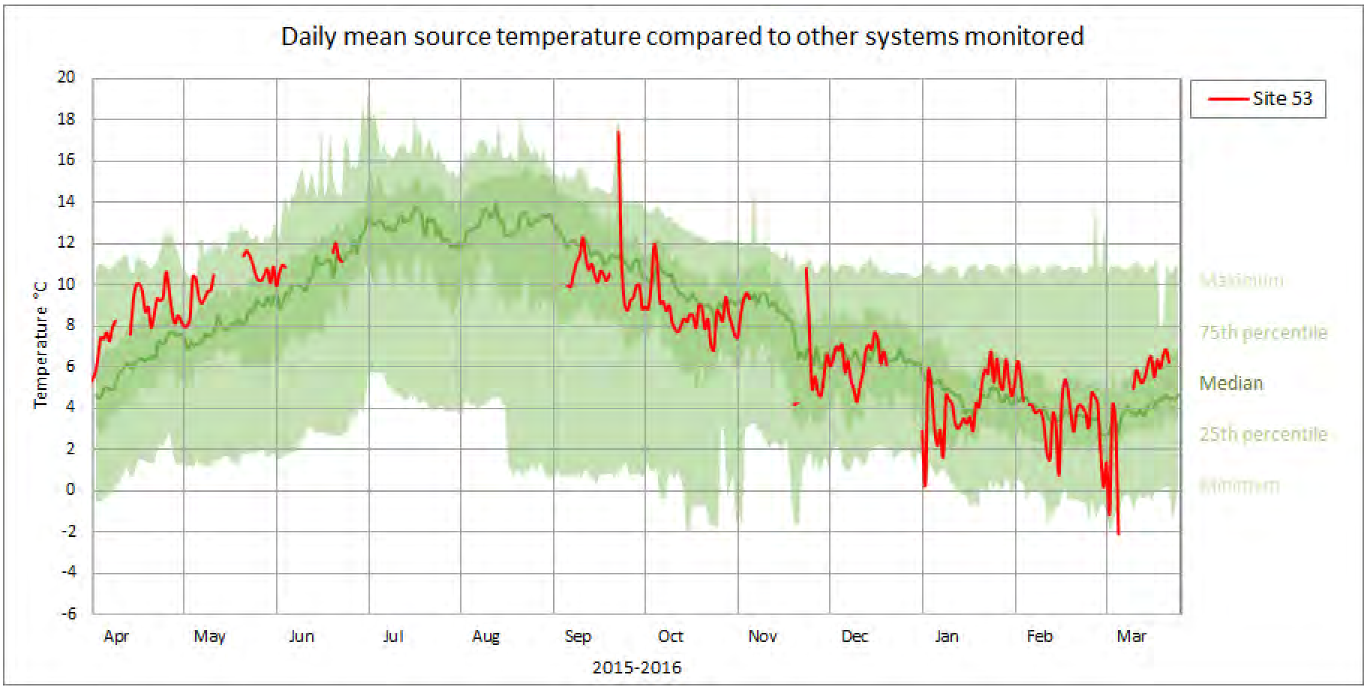

Figure 10 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 53 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were below average compared to other systems. This would have had a positive influence on the system performance.

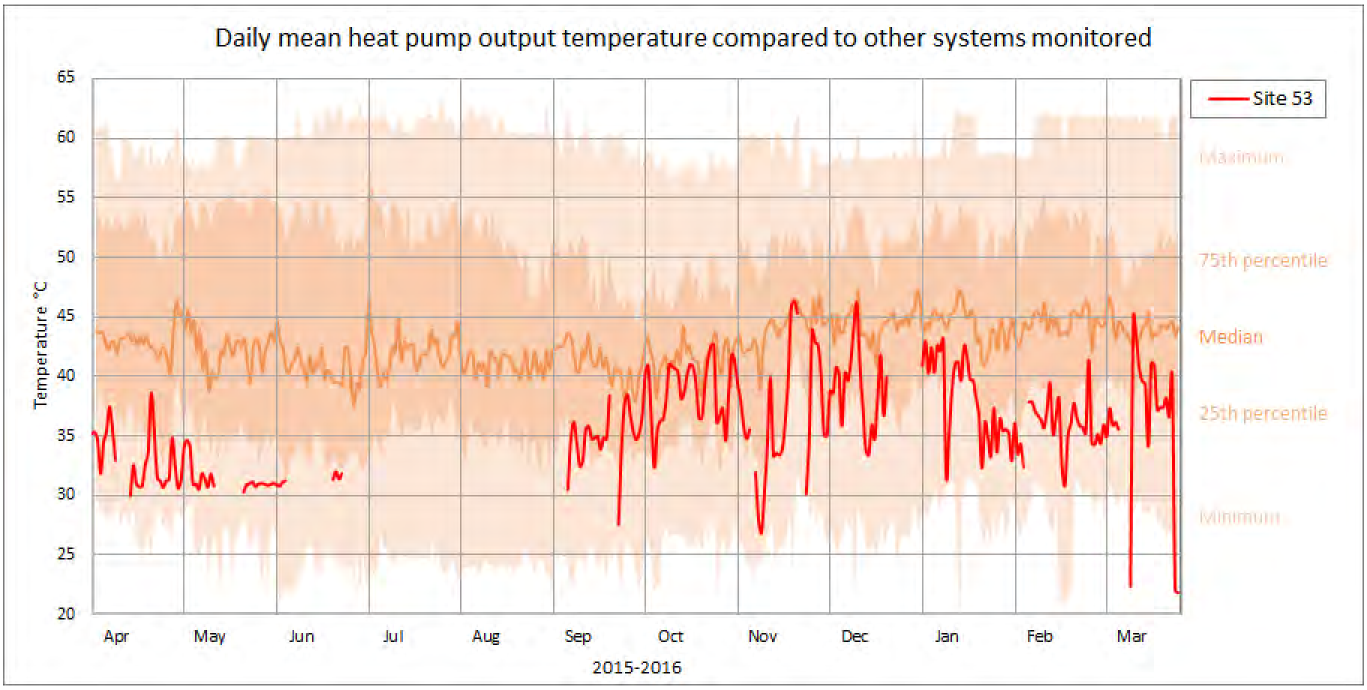

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 53 is shown in red)

Figure 12 shows the daily average temperature of the flow to the underfloor heating. The temperatures on this system were below average compared to other underfloor heating systems monitored. This would have had a positive influence on system performance.

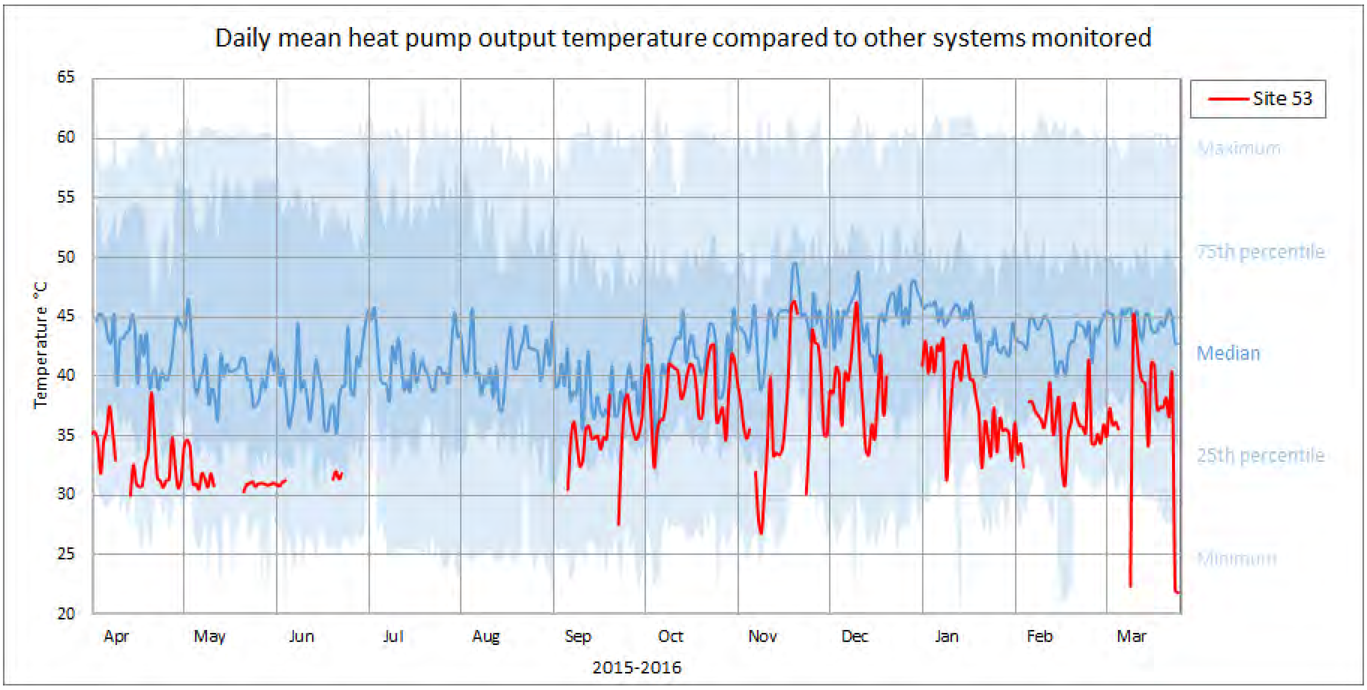

Figure 12 – Daily average temperature of the flow to the underfloor heating circuits compared to other underfloor heating systems monitored (site 53 is shown in red)

Comments

The overall performance of this system (SPFH4 = 2.25) was average compared to other systems providing space heating only that were monitored in this project (SPFH4 range: 1.42 to 4.10, median value 2.23).

Aspects of this system that positively influenced its performance are:

- The temperature of the brine at the inlet to the heat pump was above average compared to other systems in the monitored sample for part of the monitoring period.
- The temperature of the heat pump output was below average compared to other systems in the monitored sample, and below average compared to other underfloor heating systems.

Aspects of the system that may have negatively influenced its performance include:

- The electricity used by the river water pump was very high: 13.8% of the electricity used by the total heat pump system.
- The river water and brine pumps together accounted for 16.0% of total electricity which is considerably above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The buffer pumps and the heating circulating pumps together used an estimated 10.0% of the electricity, which was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). The control settings should be altered so that these pumps do not run during periods when there is no demand for heat.
- The indoor air temperature was not well controlled, leading to the heat pump operating at times when it should not have been needed.
- The reversing valves would have introduced some pumping and heat losses into the system and would have increased the capital cost of the system – apparently unnecessarily, as the cooling arrangements reportedly do not work adequately and are now not used.

It is unclear why there is demand for heating during weekends and nights when the premises are unoccupied. It is also unclear why the indoor temperature varies considerably. The control strategy should be reviewed to ensure better control of the indoor temperature, with set-back during times when the building is unoccupied. This will reduce the overall heat pump output temperature and yield improved performance and energy savings.

It would also be very desirable to review the mechanism in place to prevent freezing of the river water at the heat exchanger.

Bibliography

[1] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[2] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[3] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.," EN 14511.

[4] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.," EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 56

Prepared by GRAHAM Energy Management
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January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 56 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 56 is a retail shop in a rural location.

A ground-source heat pump (thermal capacity 33 kW) extracts heat from horizontal ground loops, and provides space heating via underfloor heating pipes and domestic hot water.

Seasonal performance factors are not presented because characteristics of the heat meter, previously installed for the Renewable Heat Incentive and used to monitor this system, have led to unacceptably high uncertainties of measurement of the heat delivered.

Aspects of this system that positively influenced its performance are:

- The electricity used by the buffer pump and the space heating circulating pump (4.9% of the total electricity) was below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).
- The temperature of the brine flow to the heat pump was above average compared to other systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the heat pump output was above average compared to other systems monitored.
- Weather compensation was not used.
- The heat output during the summer did not reduce as would usually be expected. This may have been due to faulty or incorrectly configured controls.
- The desuperheater of the heat pump is not used to provide heat for domestic hot water.

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[1] The heat meter installation on this system uses strap-on temperature sensors. This technique is known [1] to be prone to unacceptably large measurement errors and the performance values could therefore not reliably be determined.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
Desuperheater	A heat exchanger that removes heat from superheated gas discharged from a compressor. This provides a small amount of heat at a temperature which is higher than that of the main condensation process
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**56**
Survey date	24/01/2015
Monitoring installed	21/03/2015
G/WSHP	GSHP
Building type	Retail shop
Location	Rural
Heat pump capacity kW$_{TH}$	32.8
Number of heat pumps	1
Number of compressors	1
Heat source	Horizontal ground loops: total 1200 m
Heat emitters	Underfloor heating pipes
DHW	Yes
Auxiliary heat	Immersion heaters in buffer tank: 2 x 6 kW Immersion heater in DHW cylinder: 1 x 3 kW
Source pump	Internal to heat pump: 1 pump of 1.25 kW
Buffer pump	Internal to heat pump: 1 pump of 180 W
SH circulating pumps	1 pump of 260 W max
DHW circulating pump	1 pump of 50 W max
Buffer tank	700 litre 4-pipe
DHW cylinder	300 litre
Control	Heat pump controller + programmable thermostat
Weather compensation	No
Heat meter type	Ultrasonic
No. of heat meters	1
Heat meter interface	Pulse (10 kWh / pulse)
Comments	

Table 1 – System details

Site 56 is a retail shop located within a larger single-story retail facility in a rural location.

The application entails extracting heat from the ground to provide space heating and domestic hot water to the shop. The outdoor temperature at the site was average compared to other sites monitored. (The mean outdoor temperature at the site was 10.6 °C. The range for all sites was 8.1 – 12.6 °C, median 10.5 °C.) The design performance of the system would be expected to be above average.

Heat pump and monitoring systems

A ground-source heat pump of 32.8 kW thermal capacity is installed in a room adjacent to an office area.

The heat source is 1200 m of horizontal ground loops at a depth of approximately 1.2 m. The manifold of the ground array is approximately 200 m from the heat pump.

Heat is provided to space heating via a 700 litre 4-pipe buffer tank to underfloor heating pipes and to domestic hot water via a 300 litre indirect cylinder.

The heat pump is equipped with pipe connections to a desuperheater, intended for providing high temperatures for domestic hot water. These connections have not been used.

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Auxiliary heat can be provided by two 6 kW immersion heaters in the buffer tank and a 3 kW immersion heater in the domestic hot water cylinder.

The system is controlled by the heat pump controller in conjunction with a wireless programmable thermostat.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures (“T”) are monitored at key points in the system using surface-mounted probes[2]. The ground, outdoor air and indoor air temperatures are also monitored.

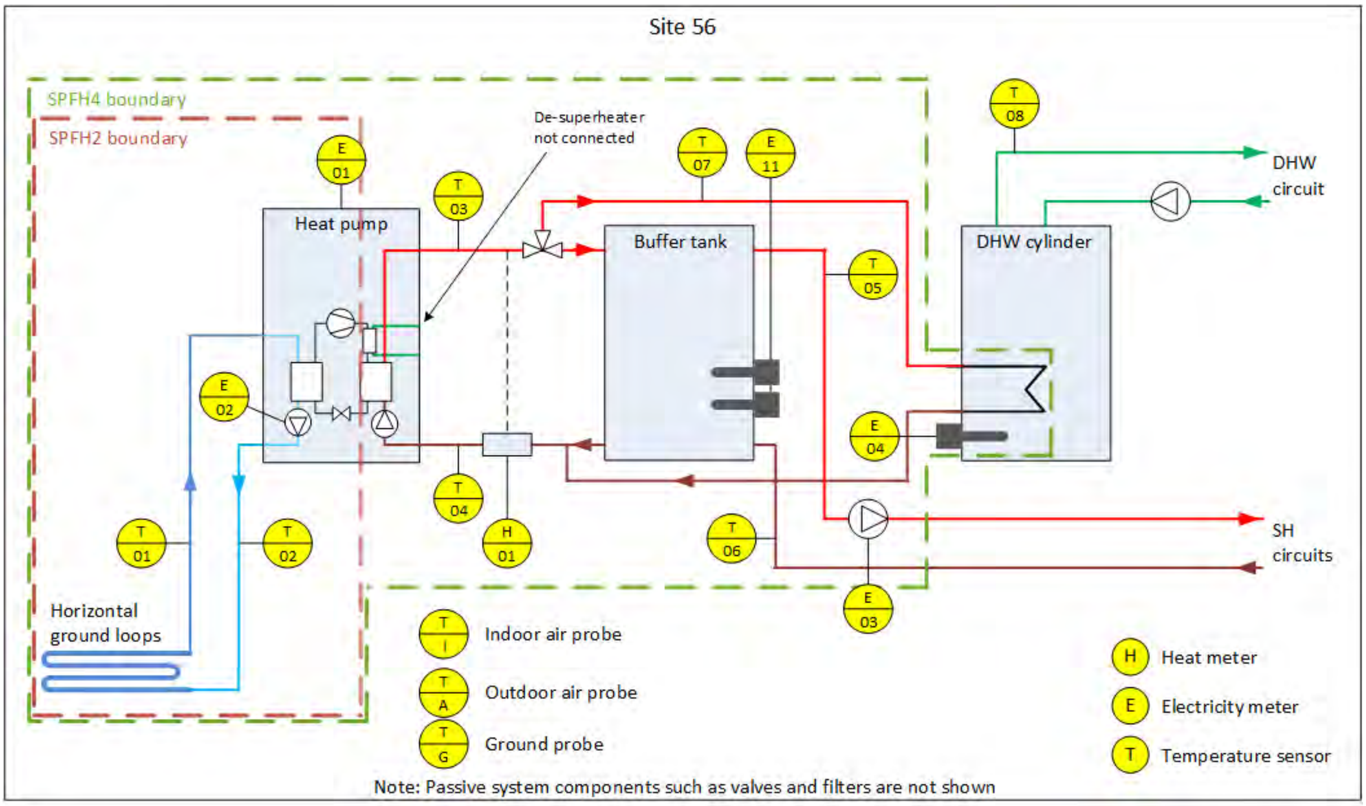

Figure 1 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was installed with the temperature probes strapped to the pipes and covered by a layer of pipe insulation. This arrangement is not as recommended by the heat meter manufacturer and is known [1] to cause potentially large errors in the heat measurement. It was not possible to determine the system performance with any reliable degree of accuracy because of this uncertainty. The flow meter is an ultrasonic type, installed in the return pipe between the heat pump and the buffer tank. The calculator is battery-powered. Monitoring was via the pulse interface.

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[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [5] for further details. Note that these temperature measurements were not used for heat metering.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters (if used).

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [2].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump]} - \text{[heat added by buffer pump]}}{\text{Electricity used by: [heat pump including the brine pump but excluding the buffer pump]}}$$

- This calculation required the electrical energy used by the buffer pump inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pump, calculated for intervals that the heat pump was running.

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

- The heat added by the circulating pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pumps.

$$\text{SPFH4} = \frac{\text{[Heat output of heat pump]} - \text{[heat loss from buffer tank]} + \text{[heat added by SH circ pump]} + \text{[heat added by immersion heaters]}}{\text{Electricity used by: [heat pump]} + \text{[brine pump]} + \text{[SH circulating pump]} + \text{[immersion heaters]}}$$

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 525 864, which represents 99.8% of the 12-month period

SPF results presented as relative values

Because of the heat metering issues noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors SPFH2 and SPFH4 are therefore presented in this case study as "relative" values, whereby each value is shown as an amount above or below a nominal performance.

Figure 2 shows the weekly[5] SPFH2 and SPFH4 behaviour of the system[6]. The SPF values reduced over the monitoring period. The explanation for this appears to be that the indoor temperature set-point was reduced (as seen in Figure 8) causing the daily heat demand to reduce, but without any reduction in the heat pump output temperature or in the electricity used by the auxiliary pumps.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [6] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

[5] The relatively high value of the pulse output (10 kWh / pulse) from the heat meter does not facilitate presentation of daily SPF values, because the small number of pulses recorded each day leads to significant scatter in the daily heat measurement.

[6] The actual values are not shown because of the high uncertainty of measurement of the heat metering on this system. Relative values are shown to give some indication of the scale of the behaviour.

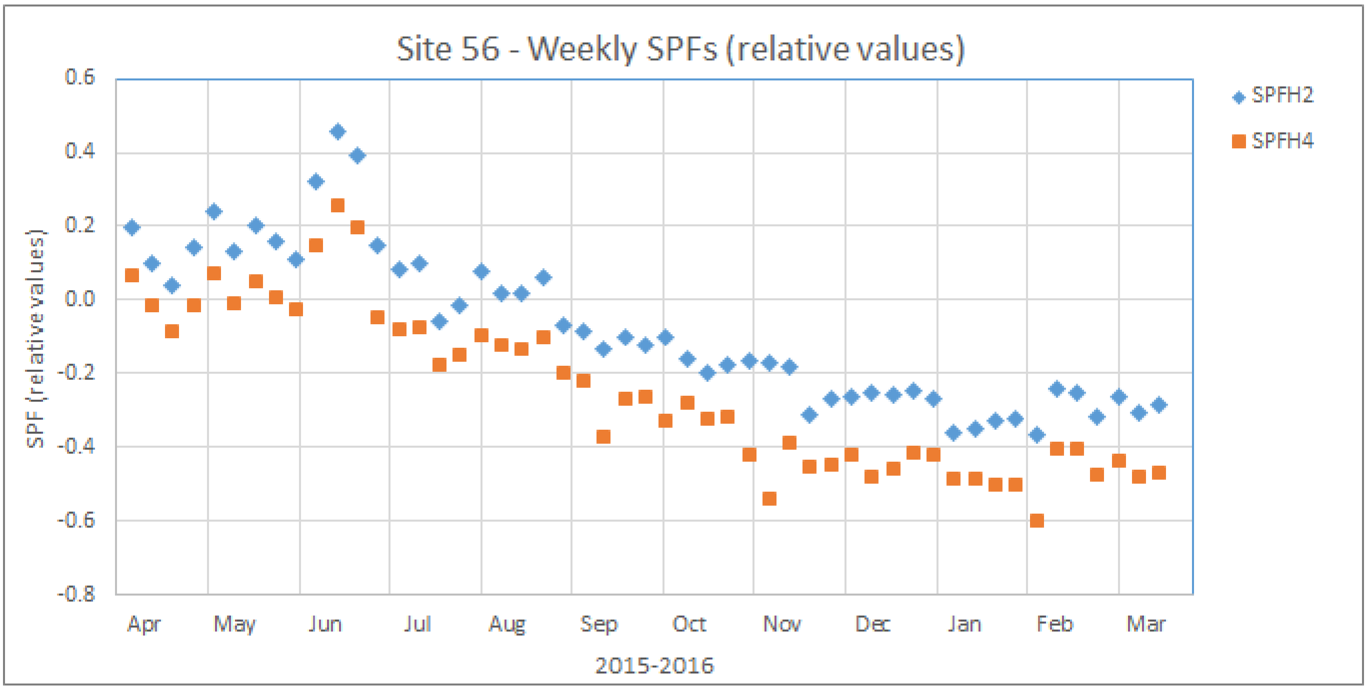

Figure 2 – Seasonal performance factors SPFH2 and SPFH4 calculated weekly

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the “temperature lift”. In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated and the domestic hot water.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Electric immersion heaters are installed in the heating buffer tanks and in the domestic hot water cylinder, to provide auxiliary heat at times when the heat pump is unable to provide the heat required by the load – usually during very cold conditions.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [3] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required by the building depends on various factors, particularly the outdoor temperature.

Figure 3 shows the weekly heat output from the heat pump. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. Note that the kWh values have been removed from the graph because of the high uncertainty of measurement of the heat meters.

The immersion heaters were not used during the monitoring period.

Due to the location of the heat meter, the proportion of the total heat that was provided to domestic hot water could not be measured on this system.

The weekly heat output measurement during the first few weeks was much higher than during later weeks when the outdoor temperature was similar or lower. This appears to have been due to the indoor temperature set-point having been reduced.

It is also notable that the heat output did not diminish significantly during the summer when the space heating load should have been very low. This was possibly due to an inadequate control strategy – which should be investigated.

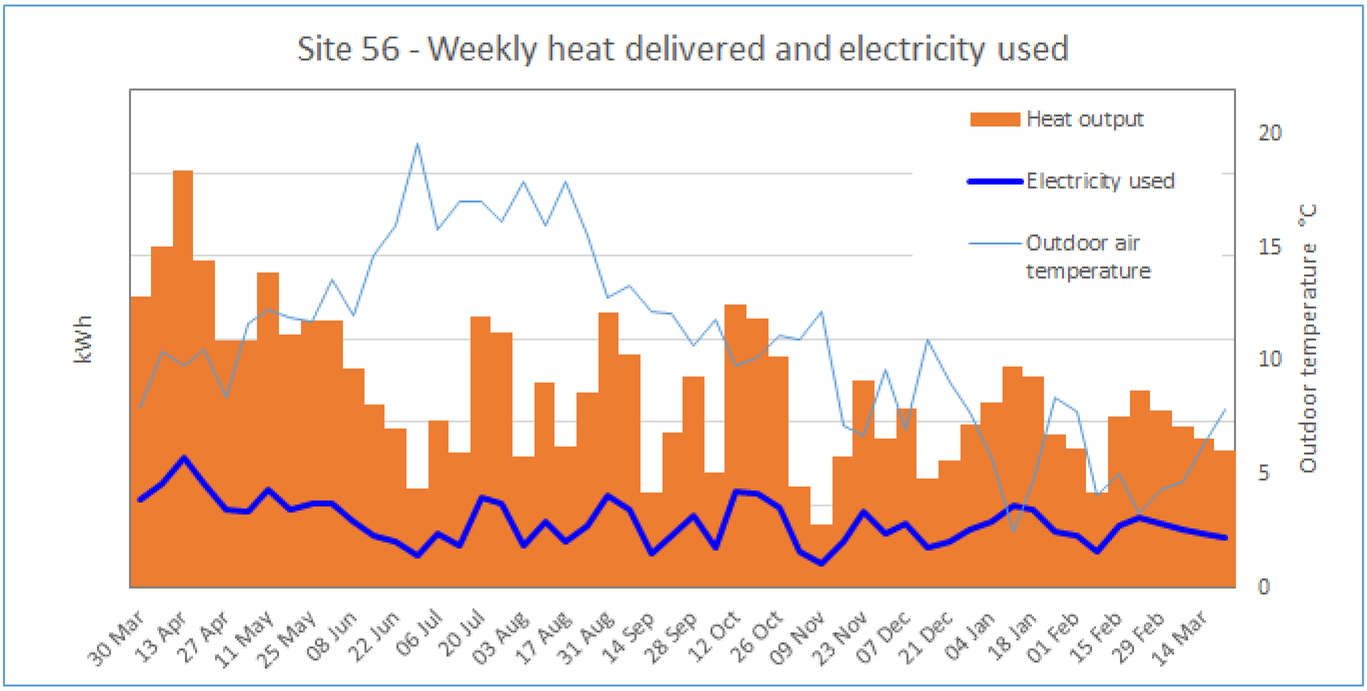

Figure 3 – Weekly heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

It was not possible to determine a breakdown of the heat delivery to space heating and domestic hot water on this system.

Breakdown of electricity use

Figure 4 shows the weekly breakdown of electricity use. The electricity used by the buffer pump in the heat pump was estimated from the pump rating data and analysis of the detailed data recorded by the electricity monitor. The brine pump was metered separately.

It can be seen that the electricity used during the first few weeks was higher than at any time later in the year. This corresponds with the higher heat output shown in Figure 3.

The brine circulating pump used 7.6% of the electricity used by the total heat pump system, which was average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

The buffer pump and the space heating circulating pump together used 4.9% of the electricity, which was below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance.

However, the space heating circulating pump was used throughout the warm summer period when heating would not usually be needed. This was probably due to incorrect control settings and would have had a negative influence on overall performance.

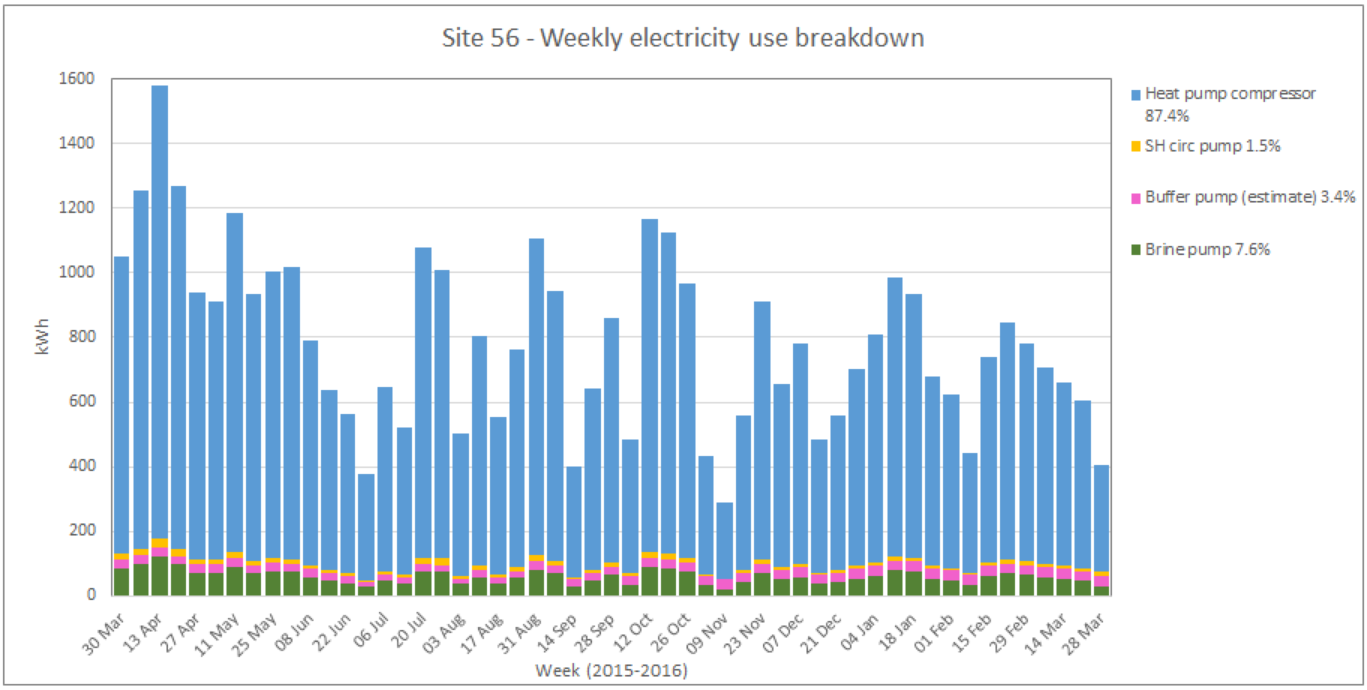

Figure 4 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 5 shows the operating pattern over two days 8th – 9th January 2016 when the outdoor temperature was between 2 and 9 °C. The heat pump operated for a long run of around 12 hours each day, and for several short runs of between 3 and 10 minutes. The very short runs are undesirable for both performance and equipment lifetime reasons. The possible cause of these is examined in the next section.

The heat pump output temperature varied between 47 and 50 °C for most of each day, with peaks of up to 60 °C. The temperature of the brine flow to the heat pump was between 5 and 8 °C while the heat pump was running. The ground temperature[7] was 7.4 °C at the start of the first day, and 6.7 °C at the end of the second day.

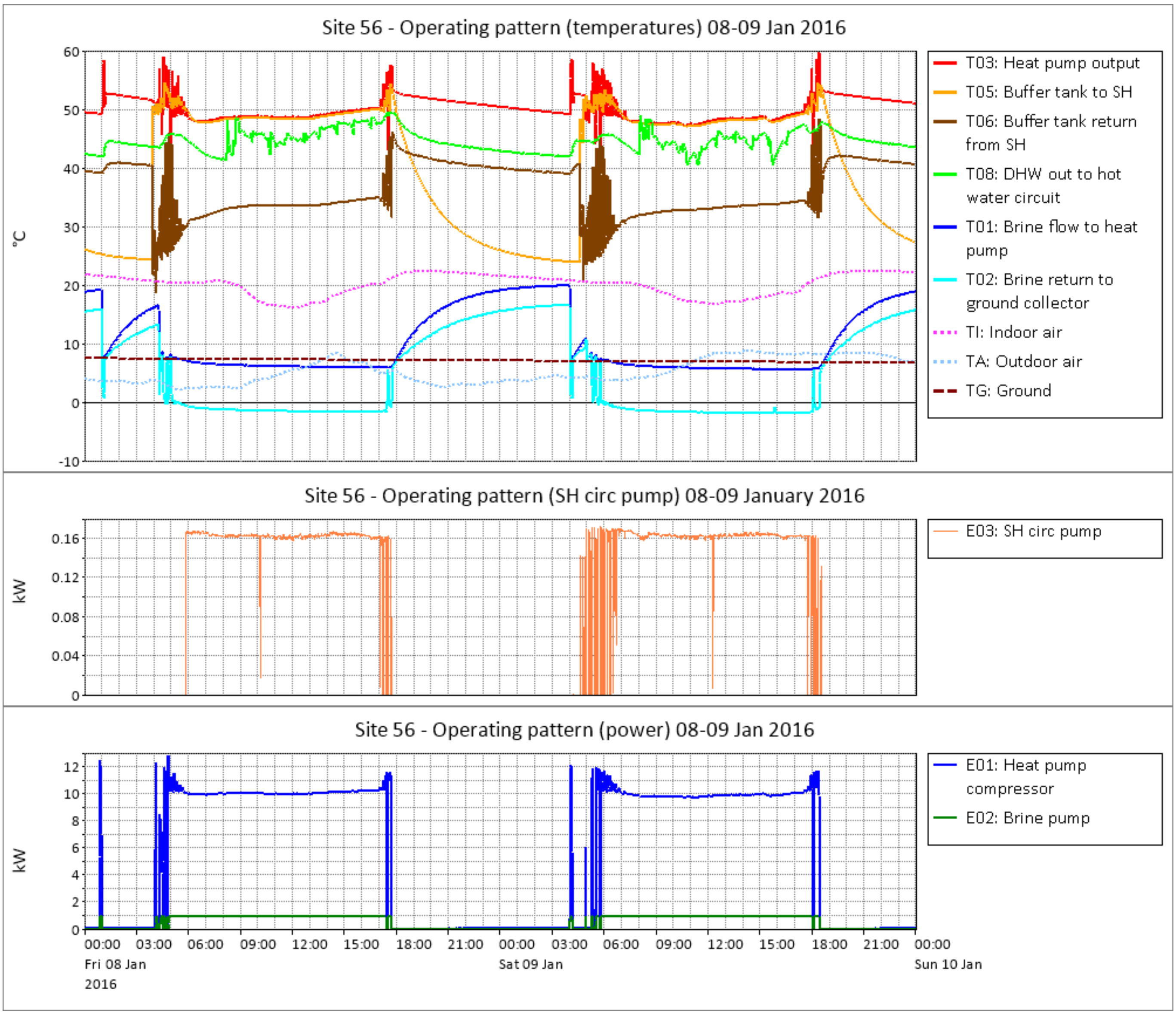

Figure 5 – Operating pattern 8th – 9th January 2016

Figure 6 shows the behaviour during a 6-hour period on 9th January 2016, at the beginning of the daily heating cycle.

The heat pump ran for 10 minutes at 04:00 to top up the domestic hot water. The maximum output temperature was 58 °C.

The space heating circulating pump started running at 04:36 – initially for a series of short runs of 3 – 9 minutes. After 06:44 it ran continuously until 17:45. The first two short runs apparently circulated heat from the buffer tank. The heat pump started during the third run of the circulating pump and ran for three progressively longer runs of 3, 6 and 12 minutes, before starting its continuous run at 05:50. The heat pump output temperature

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[7] The ground temperature was measured 1 m below the surface at a location remote from the ground collector.

during the initial short runs was high (up to 58 °C) compared to the maximum of 50 °C during the continuous 12-hour run.

The temperature oscillations are believed to be caused by the use of a smart thermostat (programmable controller) that is intended for use with a boiler. It appears that this controller imposes on/off cycles that are not appropriate for a heat pump system. Use of a different type of controller to avoid the short cycles and the unnecessarily high output temperatures should have a positive influence on the overall performance and the life of the heat pump.

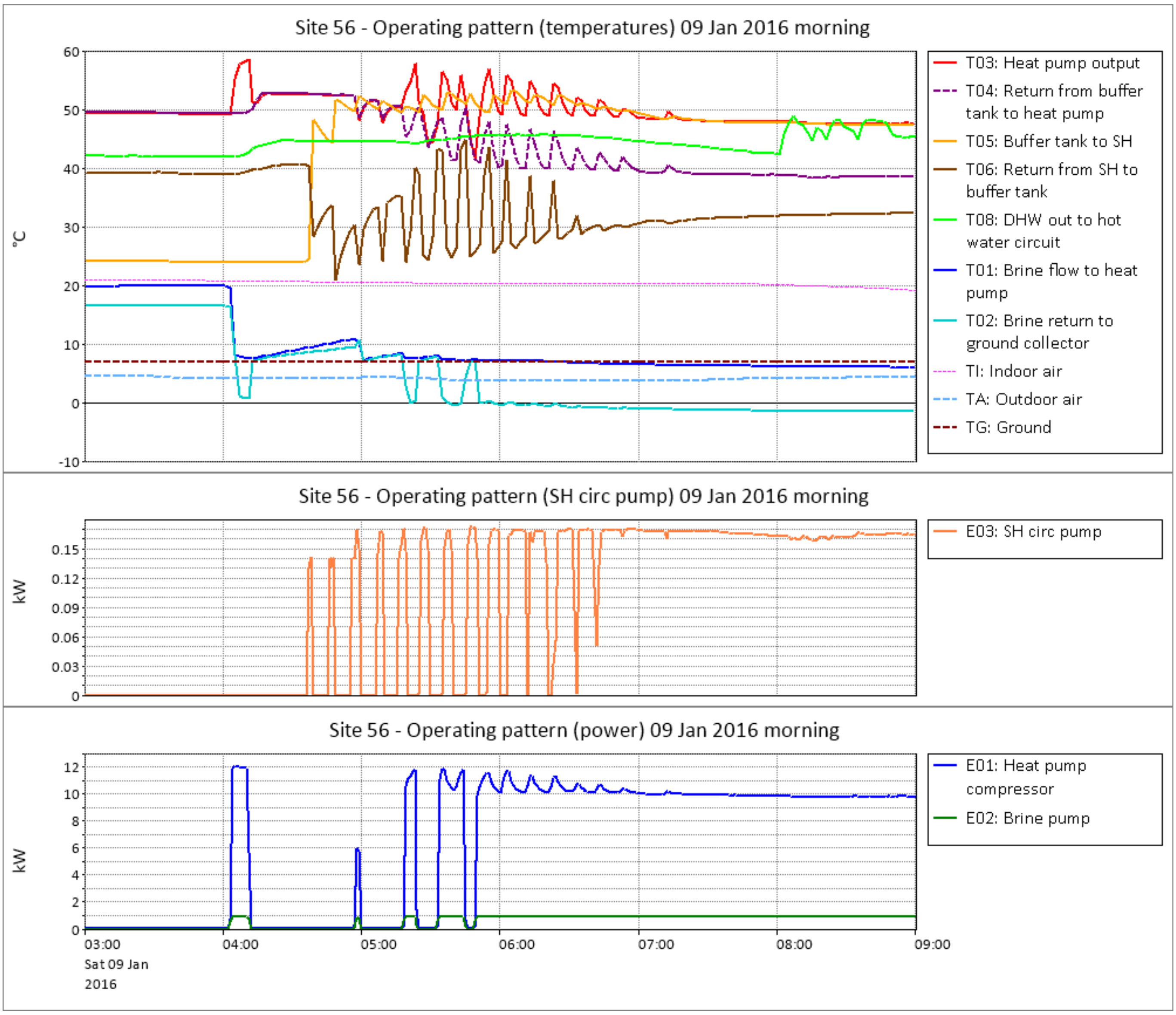

Figure 6 – Detail of operation on the morning of 9th January 2016

Figure 7 shows the operating pattern on 29th June 2015 when the outdoor temperature was between 12 and 23 °C. The indoor temperature was between 21 and 27 °C.

There was demand for space heating in the morning. The space heating circulating pump operated from 00:30 to 09:30 and the heat pump ran from 01:30 to 08:00. The maximum heat pump output temperature during this period was 53 °C. The temperature of the brine flow to the heat pump was 14 °C at the start of the run and 11.5 °C at the end.

The heat pump ran again for 30 minutes at 10:30 and for 8 minutes at 15:15 to provide heat to domestic hot water. The maximum output temperature during these runs was 60 °C.

Figure 7 –Operating pattern on 29th June 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the ground, outdoor air, brine, output from the heat pump, and flow and return from the buffer tank to space heating, plotted over the year[8]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running. There was no data from the indoor temperature sensor after 16th January.

The heat pump output temperature varied between 38 and 60 °C, the higher temperature being reached on most days throughout the year, evidently for domestic hot water production.

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[8] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor and indoor temperatures were recorded every 15 minutes and the ground temperature every hour.

The output from the buffer tank to the space heating circuit was between 20 and 56 °C. There is no indication of weather compensation being used. These temperatures are high for an underfloor heating system and would have had a negative influence on the system performance.

The temperature of the brine flow to the heat pump generally followed the ground temperature to within ± 1.5 °C. The lowest brine temperature was 3.1 °C on 22nd January.

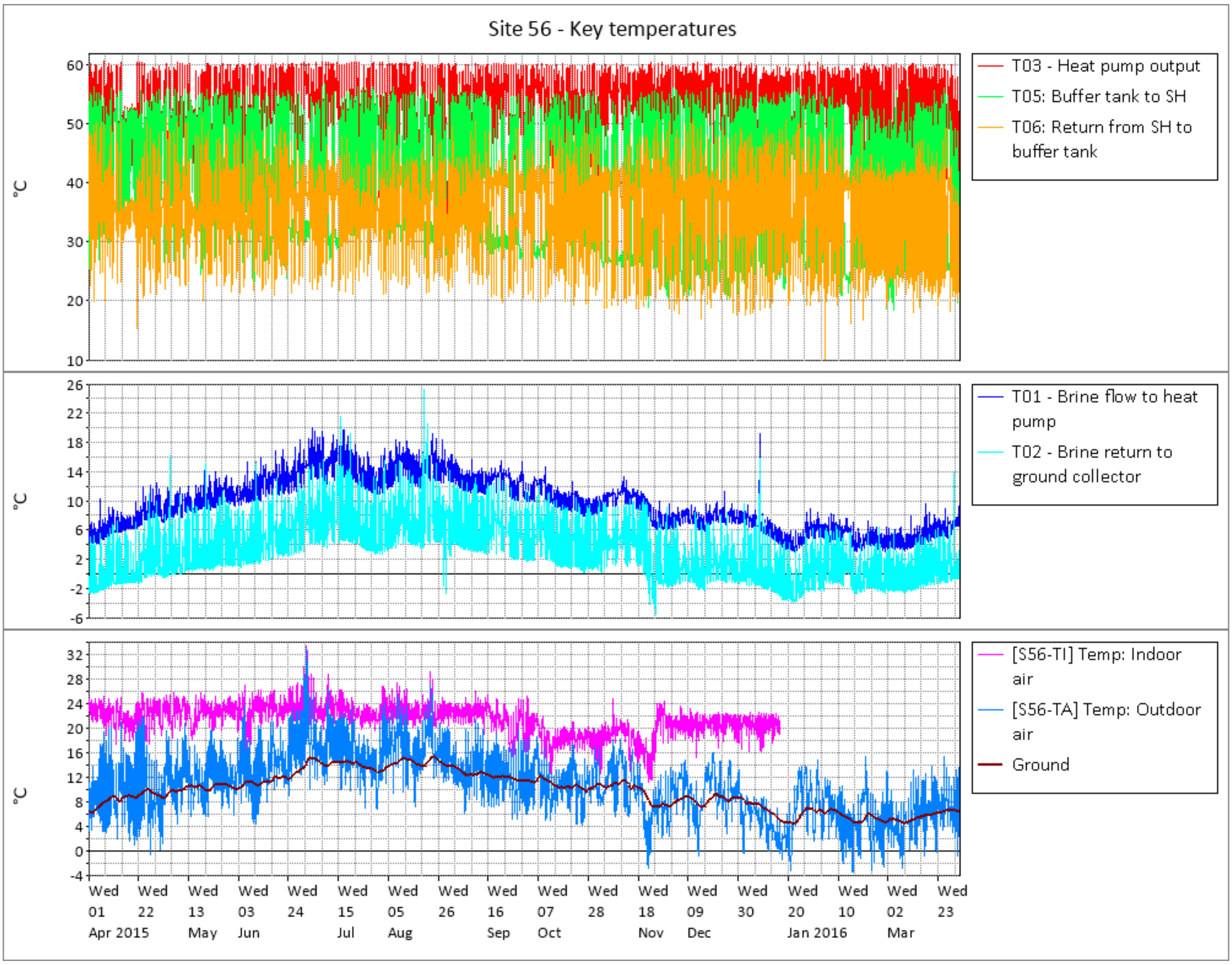

Figure 8 – Key temperatures measured during the period 1st April 2015 – 31st March 2016

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures (at the heat pump) of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were above average compared to other systems. This would have had a positive influence on system performance.

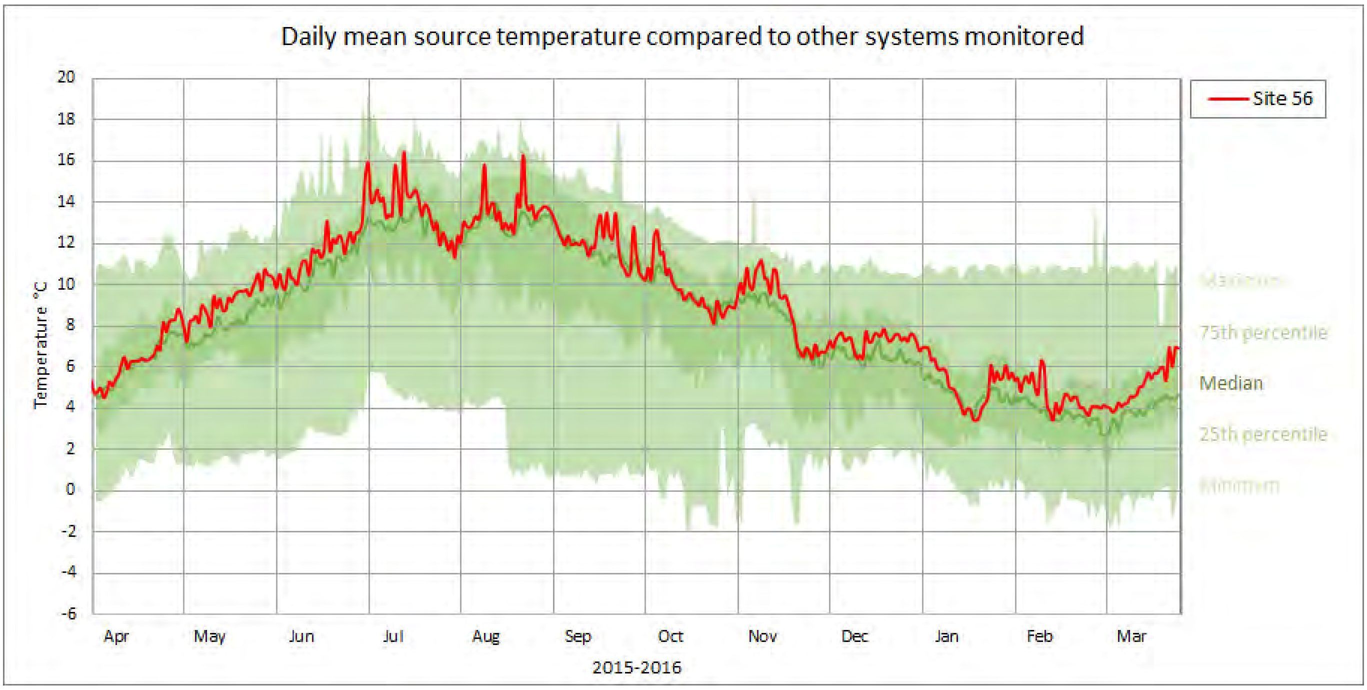

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 56 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The low temperature difference on this system indicates good collector performance.

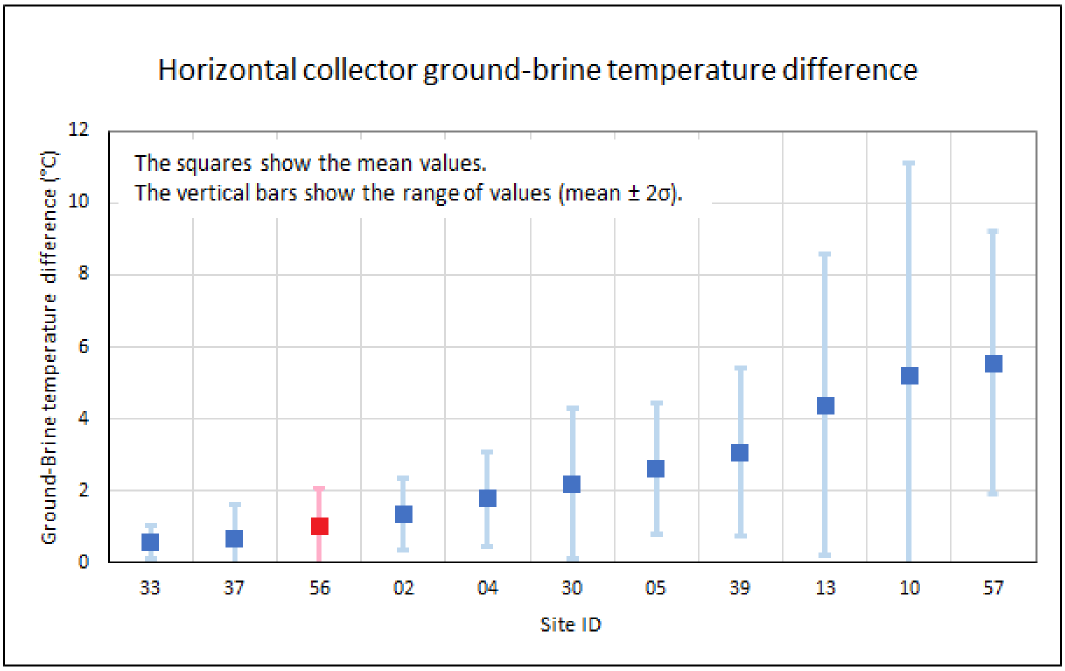

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 56 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were above average compared to other systems. This would have had a negative influence on the system performance.

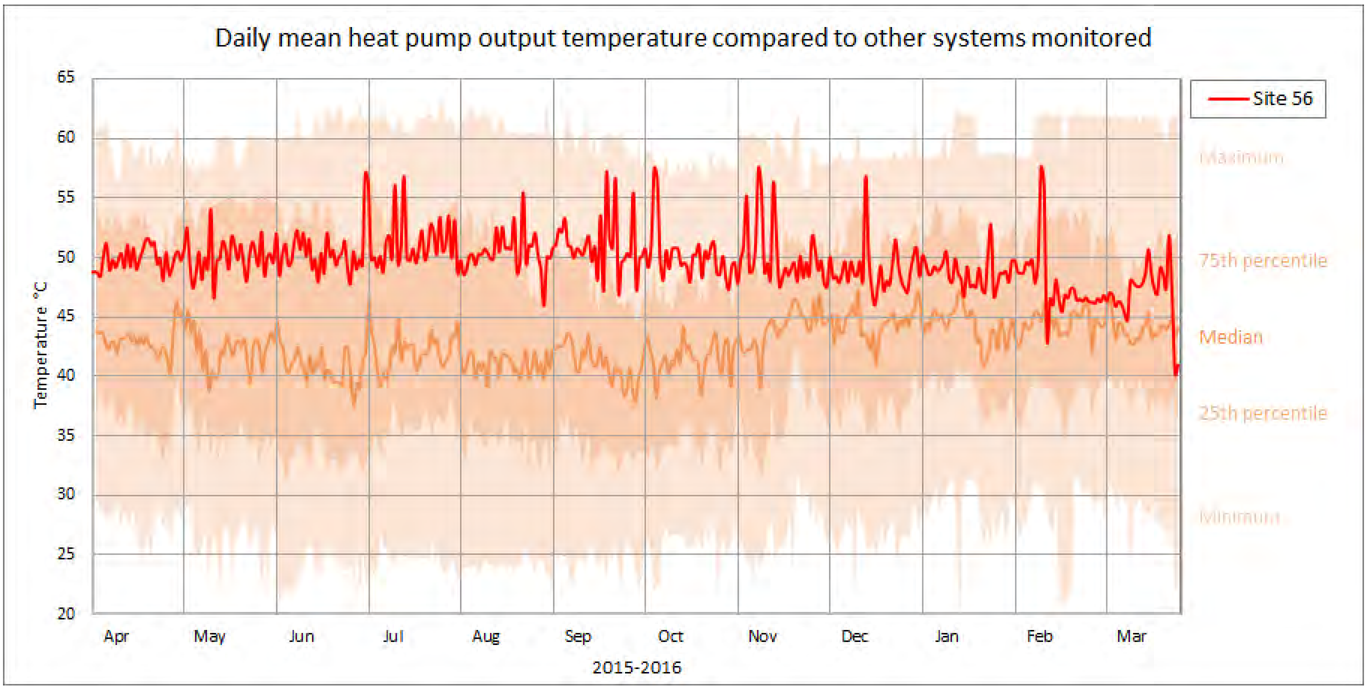

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 56 is shown in red)

Figure 12 shows the daily mean temperature of the flow to the underfloor heating pipes compared to other systems using underfloor heating monitored in this project. The temperatures on this system were above average compared to other systems. This would have had a negative influence on the system performance.

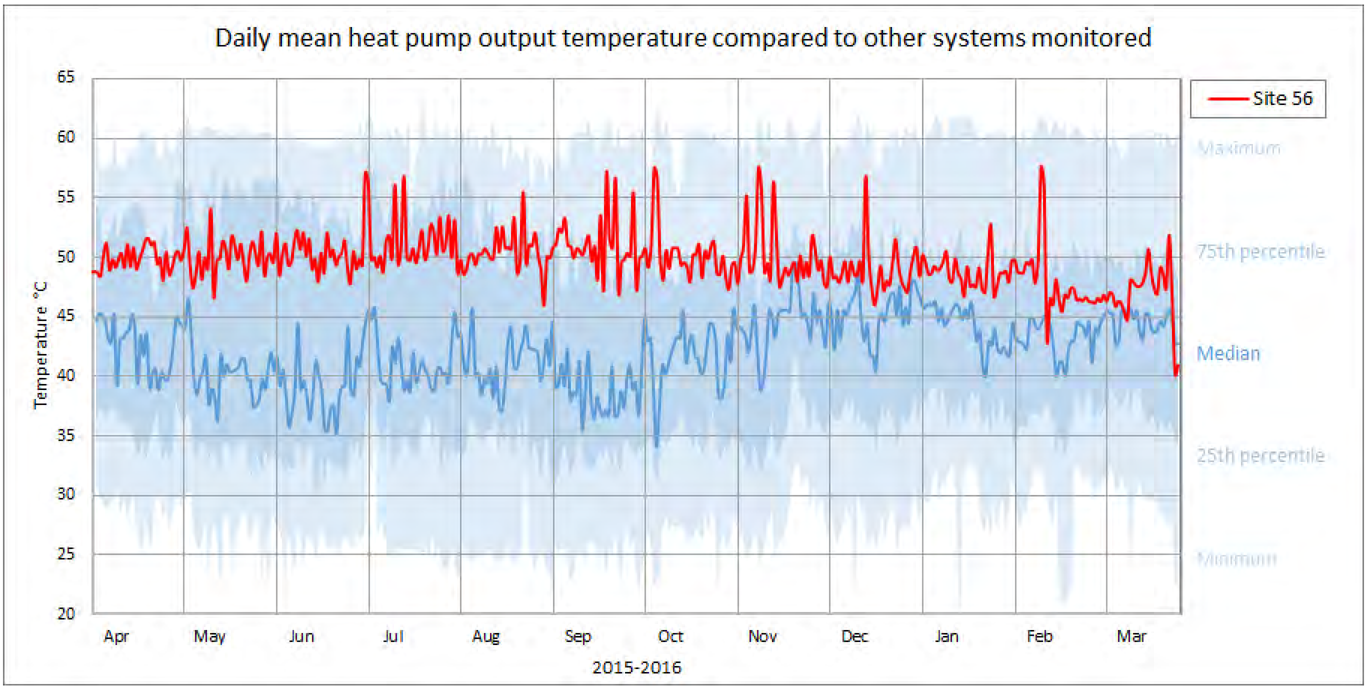

Figure 12 – Daily mean temperature of flow to underfloor heating compared to other systems using underfloor heating monitored in this project (site 56 is shown in red)

Comments

The performance of this system could not be determined with reliable accuracy because of known issues with the heat metering arrangement installed.

Aspects of this system that positively influenced its performance are:

- The electricity used by the buffer pump and the space heating circulating pump (4.9% of the total electricity) was below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).
- The temperature of the brine flow to the heat pump was above average compared to other systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the heat pump output was above average compared to other systems monitored.
- Weather compensation was not used. If this can be implemented, the overall performance of the system should improve.
- The heat output during the summer did not reduce as would usually be expected. This may have been due to faulty or incorrectly configured controls. Avoidance of unnecessary space heating during the summer will yield significant savings in annual electricity use.
- It is not known why the desuperheater of the heat pump is not used. The manufacturer’s installation manual shows an example of how the desuperheater (referred to as “hot gas”) can be used for heating domestic hot water. This arrangement would allow the output to space heating to be at a lower temperature, with a consequent improvement in the overall system performance.
- It was observed that the heat pump tends to run for a number of short cycles during initial operation of the heating system each day. Short cycling is known [3] to be undesirable as it impairs performance and causes excessive wear and tear on the equipment. The control system should be altered to prevent this happening.
- Underfloor heating may not be the most appropriate type of heat emitter for a retail shop. Fan-coil heaters might give better overall system performance because they can be more easily controlled to provide heat only during the times needed.

Bibliography

[1] D. Butler, A. Abela and C. Martin, “Heat meter accuracy testing (URN: 15D/446),” DECC, 2015.

[2] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[3] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[4] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.,” EN 14511.

[5] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps - Interim Report. URN 16D/013.,” DECC, 2016.

[6] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 57

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 57 and performance results from 12 consecutive months of monitoring data.

Site 57 is a detached house used as offices. It is in a rural location.

A ground-source, high temperature heat pump (thermal capacity 40 kW) extracts heat from horizontal ground loops, and provides space heating via underfloor heating pipes and domestic hot water.

The seasonal heating performance factors measured over a year of operation
(1st April 2015 to 31st March 2016) were:

SPFH2	[Heat delivered by the heat pump] – [heat added by internal buffer pumps] --- [Electricity used by the heat pump (excluding buffer pumps) + brine pump]	2.88
SPFH4	[Heat delivered by the heat pump] – [heat loss from buffer tank] + [heat added by SH circ pump] --- [Electricity used by heat pump (incl aux heater & internal pumps) + brine pump + SH circ pump]	2.73

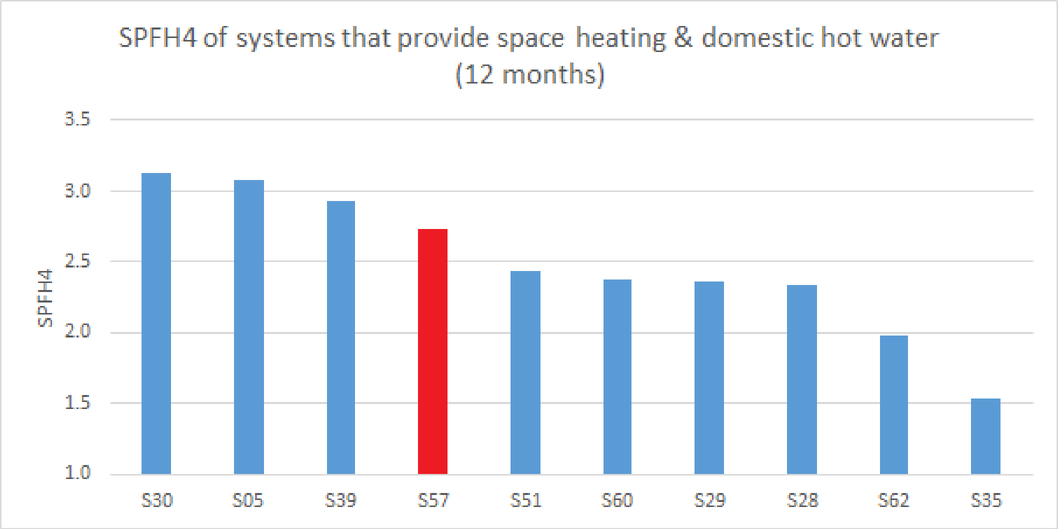

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influence its performance are:

- No auxiliary heat was used.
- Weather compensation was used.
- The electricity used by the buffer pump and the space heating circulating pump (5.6% of the electricity) was below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the brine flow to the heat pump was below average compared to other systems monitored.

- The electricity used by the brine pump (9.9% of the total electricity) was above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The temperature of the heat pump output was above average compared to other systems monitored.
- Only an estimated 2.6% of the heat pump output was used for domestic hot water. It would probably be better to install point-of-use water heaters and use the heat pump only for space heating. This would potentially allow it to operate with lower output temperatures and fewer annual run hours, with resultant improvement in system performance and a reduction in overall electricity use.
- This is a high-temperature heat pump system (maximum output temperature 65 °C) that does not use auxiliary immersion heaters. As would be expected, the performance was lower than that of other systems operating with lower output temperatures, but better than systems that use immersion heaters to achieve high temperatures. (If the system did not provide domestic hot water, a high-temperature heat pump would not be needed.)

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**57**
Survey date	23/01/2015
Monitoring installed	21/03/2015
G/WSHP	GSHP
Building type	Detached 3-storey house used as offices
Location	Rural
Heat pump capacity kWTH	40
Number of heat pumps	1
Number of compressors	2
Heat source	Horizontal ground loops: 6 x 250 m at a depth of 1 – 1.2 m
Heat emitters	Radiators with thermostatic valves. Some new oversized radiators were installed for use with the heat pump. Others were previously used with an oil-fired boiler.
DHW	Yes
Auxiliary heat	None
Source pump	External to heat pump: 1 pump of 890 W max
Buffer pumps	Internal in heat pump: 2 pumps of 90 W
SH circulating pumps	External to heat pump: 1 pump of 180 W max (variable speed)
DHW circulating pump	None
Buffer tank	100 litre 3-pipe
DHW cylinder	300 litre
Control	Heat pump controller + room thermostat + thermostatic radiator valves
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	2
Heat meter interface	Pulse (1 kWh / pulse)
Comments	

Table 1 – System details

Site 57 is a large, red brick, detached, 3-storey house in a rural location. It is used as offices and is understood to be occupied only during normal business hours.

This application entails extracting heat from the ground to provide space heating and domestic hot water to a brick building that is at least 50 years old and is not insulated to modern standards. The outdoor temperature at the site was average compared to other sites monitored. (The mean outdoor temperature at the site was 10.6 °C. The range for all sites was 8.1 – 12.6 °C, median 10.5 °C.) The high-temperature heat pump provides domestic hot water without using auxiliary immersion heaters. The design performance of the system would be expected to be below average.

Heat pump and monitoring systems

A ground-source heat pump of 40 kW thermal capacity is installed in the basement of the house. The heat pump comprises two vapour compression circuits. One of these is capable of providing high-temperature (up to 65 °C) heat to domestic hot water or space heating; the other is used for space heating only.

The heat source is 6 x 250 m horizontal ground loops in the garden of the house, at a depth of approximately 1.2 m.

Heat is provided for space heating via a 100-litre buffer tank to radiators fitted with thermostatic valves. The buffer tank is unusual in having three connections: the flow from the heat pump, the supply to the heating circuit, and a connection to the return pipe. The tank is fitted with a fourth tapping which is unused. It is not known why this arrangement was adopted, but it could be expected that the buffer tank would have some of the characteristics of a 4-pipe buffer tank.

Domestic hot water is provided via a 300-litre thermal accumulator.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

There is no auxiliary heater installed on this system.

The system is controlled by the heat pump controller in conjunction with a room thermostat located in the ground floor hallway and thermostatic valves on each radiator.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures (“T”) are monitored at key points in the system using surface-mounted probes[1]. The ground, outdoor air and indoor air temperatures are also monitored.

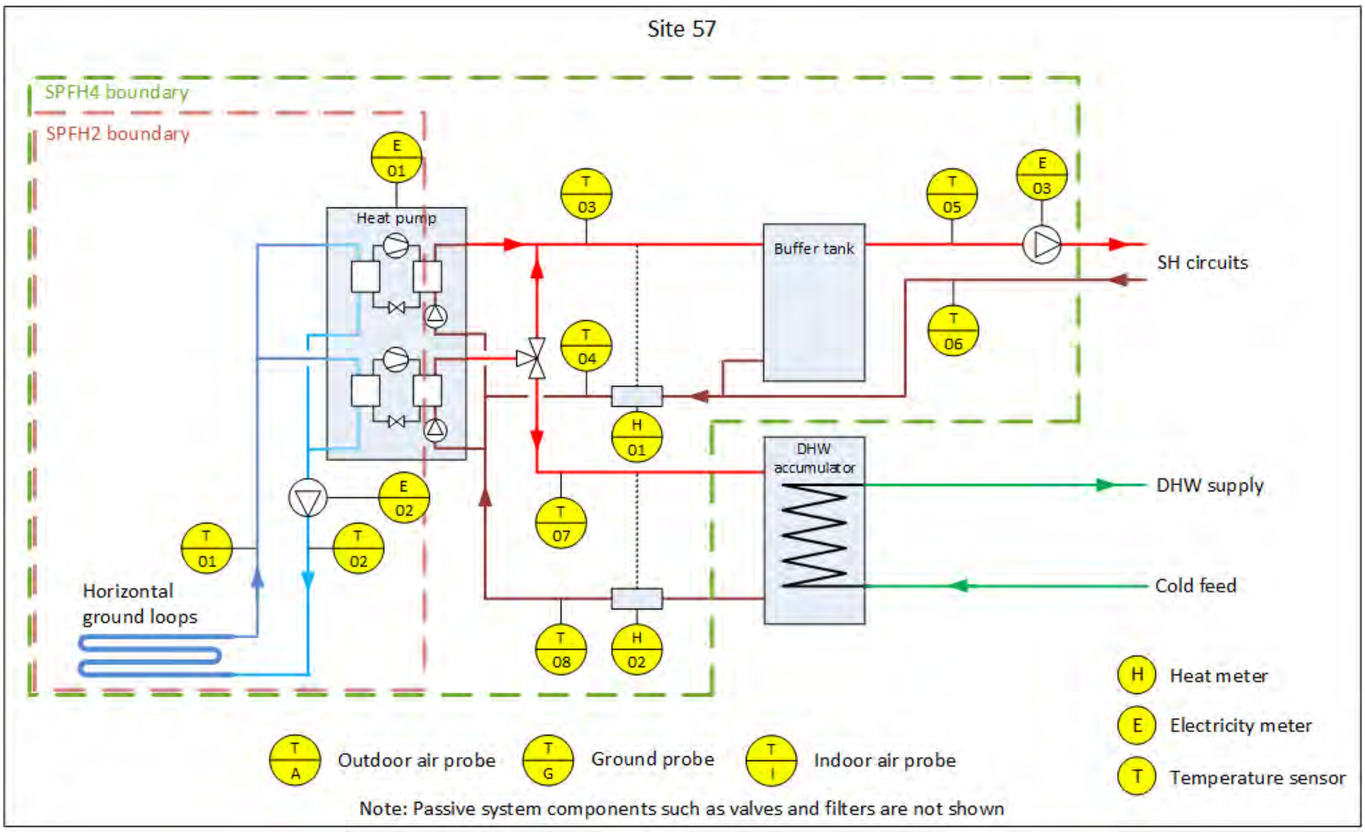

Figure 2 – System schematic showing the monitoring instrumentation installed

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[1] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pump. The heat meters on this system are installed between the heat pump and the buffer tank and between the heat pump and the domestic hot water accumulator. Ultrasonic flow meters are installed in the return pipes, with matched pairs of temperature sensors installed in fittings with the probes in pockets in the flow and return pipes. The calculators are battery-powered. Monitoring was via the pulse interfaces.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[2] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump to SH \& DHW] – [heat added by internal buffer pumps]}}{\text{Electricity used by: [heat pump excluding buffer pumps] + [brine pump]}}$$

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[2] Structured Query Language: a programming language used for managing data held in a relational database management system.

- This calculation required the electrical energy used by the buffer pumps inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pumps, calculated for intervals that the associated heat pump compressor was running.

- The heat added by the circulating pumps was estimated as 30% (the assumed pump efficiency[3]) of the electrical energy supplied to the pumps.

$$SPF_{H4} = \frac{\text{[Heat output of heat pump to SH \& DHW]} - \text{[heat loss from buffer tank]} + \text{[heat added by SH circ pump]}}{\text{Electricity used by: [heat pump]} + \text{[brine pump]} + \text{[SH circulating pump]}}$$

- The heat added by the SH circulating pump was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pump.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 525 858, which represents 99.8% of the 12-month period.

The SPF_{H2} and SPF_{H4} values for this system, measured between 1st April 2015 and 31st March 2016, are shown in Table 2.

SPF_{H2}	2.88
SPF_{H4}	2.73

Table 2 – SPF values measured for the period 1st April 2015 to 31st March 2016

This means that for each unit of electricity used, this system delivers on average 2.73 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the system. The SPF_{H2} values were higher during warmer weather in the summer months. The SPF_{H4} values also generally increased with warmer weather. The lower values during June, July and August were a consequence of the very low space heating load factor resulting in reduced system efficiency. The total heat delivered to space heating during the summer was very small, so the overall effect of the low SPF_{H4} values is minimal.

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[3] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

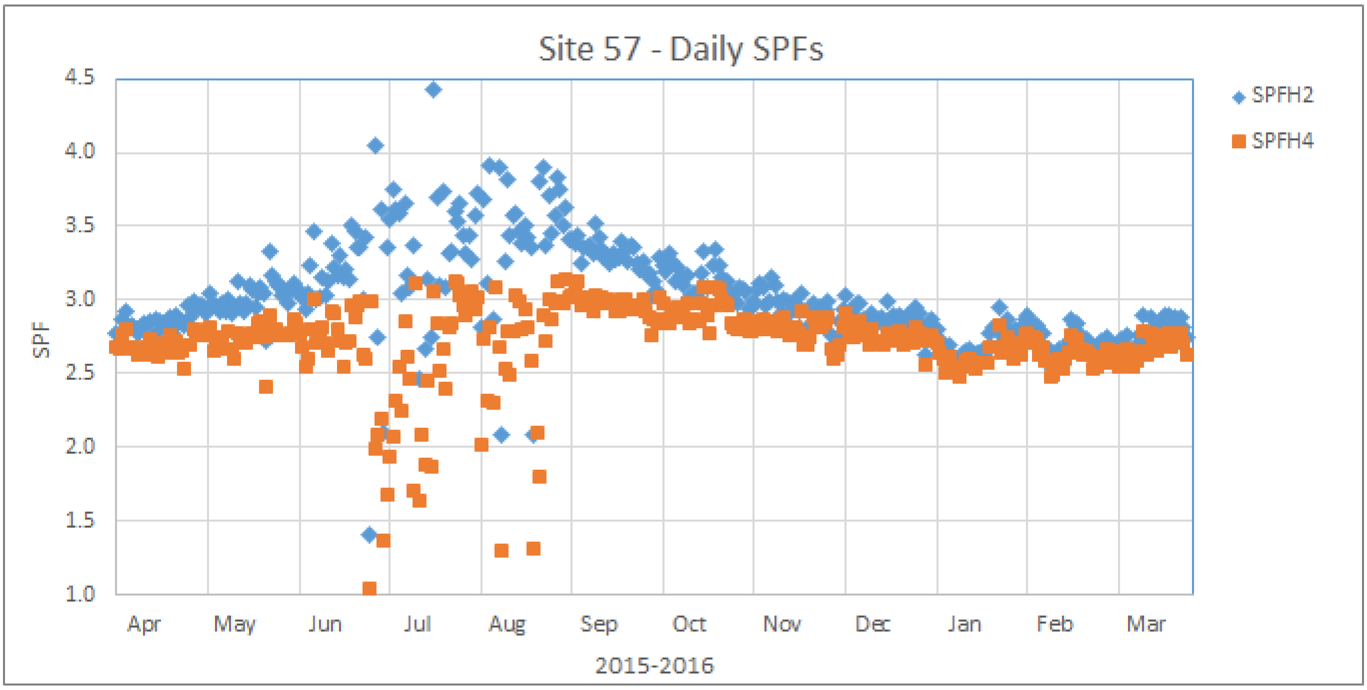

Figure 3 – Seasonal performance factors SPF_{H2} and SPF_{H4} calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated and the domestic hot water.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required for the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference.

The heat provided to space heating varied with the outdoor air temperature.

The heat provided to domestic hot water was approximately constant throughout the year.

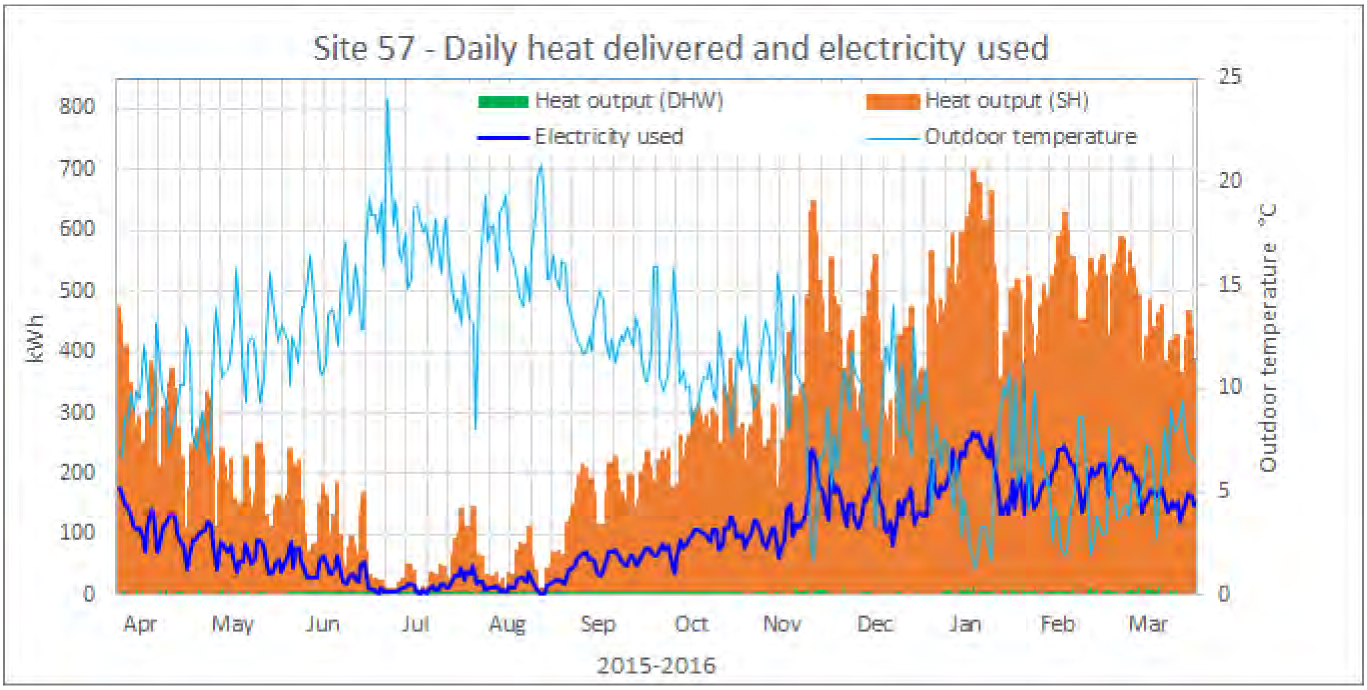

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

Table 3 shows the breakdown of the heat output from the heat pump to space heating and to domestic hot water during the period from 1st April 2015 to 31st March 2016.

	%
Heat output from heat pump to space heating	97.4%
Heat output from heat pump to domestic hot water	2.6%

Table 3 – Breakdown of heat delivered to space heating and domestic hot water

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. As it was not possible to meter directly, the electricity used by the buffer pumps in the heat pump was estimated from the pump rating data and analysis of the detailed data recorded by the heat pump electricity monitor (E01).

The brine pump accounted for 9.8% of the electricity used by the total heat pump system, which was above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance.

The buffer pumps and the space heating circulating pump together used an estimated 5.6% of the electricity, which was below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a positive influence on the system performance.

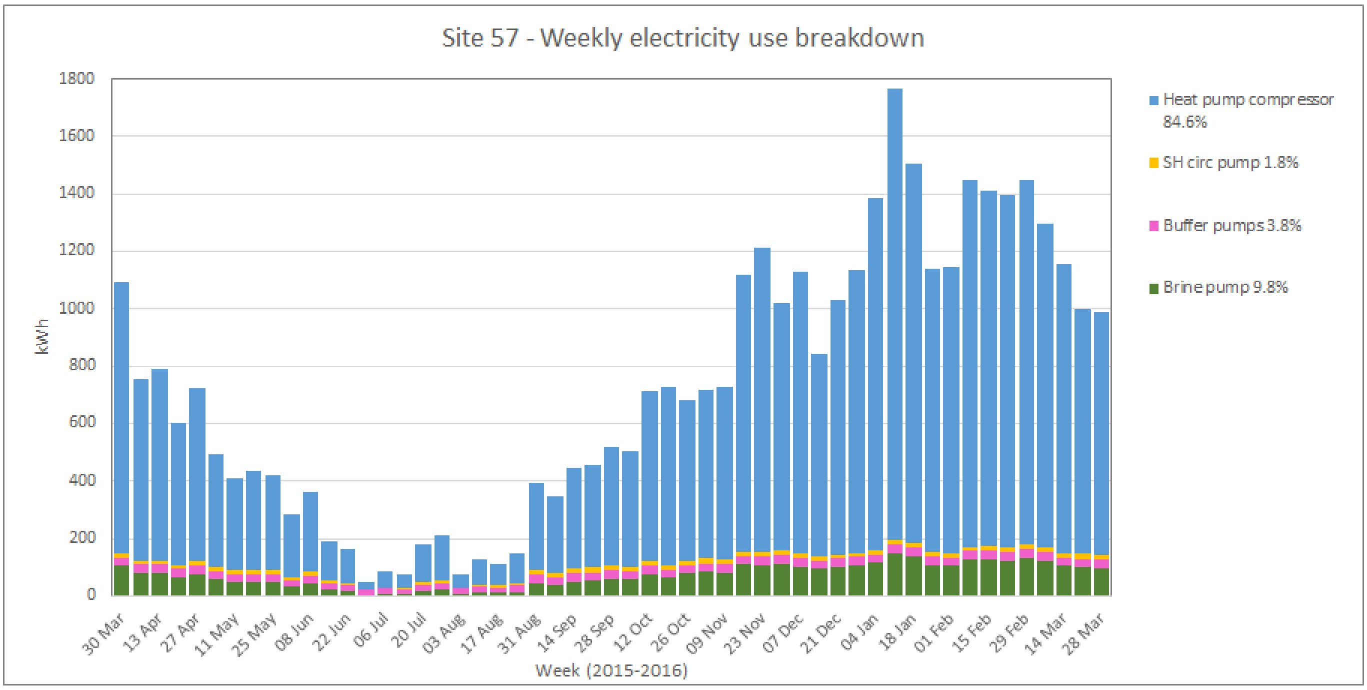

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 9th December when the outdoor temperature was between 3 and 10 °C. The indoor temperature was 23 ±0.5 °C.

The space heating circulating pump was running continuously all day, and it appears that there was no change in the indoor temperature set point during the night.

The heat pump cycled on/off all day, approximately every 75 minutes. Each run was for between 30 and 60 minutes. Both compressors were used for part of the time during each run.

The temperature of the heat pump output to the buffer tank varied between 34 and 59 °C. The output temperature was highest when the outdoor temperature was lowest – indicating operation of the weather compensation function.

There was no perceptible loss of temperature through the buffer tank.

The heat pump provided heat to domestic hot water twice during the day. The maximum temperature of the heat pump output to domestic hot water was 65 °C.

The temperature of the brine flow to the heat pump was between 2 and 4 °C.

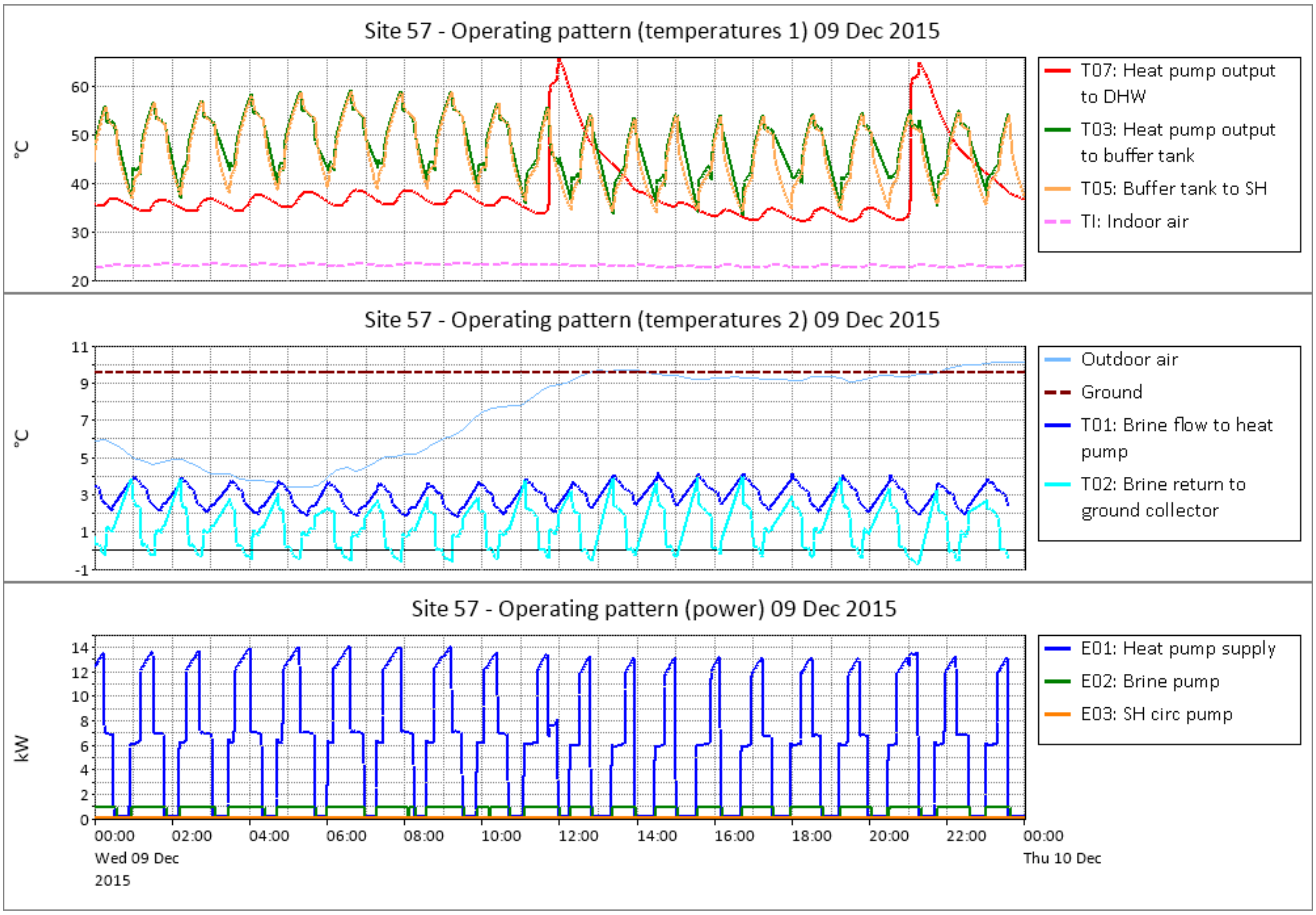

Figure 6 – Operating pattern 9th December 2015

Figure 7 shows the operating pattern on 24th June when the outdoor temperature was between 9 and 23 °C. The indoor temperature was between 21 and 22 °C.

The space heating circulating pump was running until 09:00, indicating a demand for space heating.

The heat pump ran for 6 intervals of between 16 and 38 minutes. The higher compressor power drawn during the fourth run was because heat was provided to domestic hot water, requiring a higher output temperature. The heat pump ran for 15 minutes during the afternoon to provide heat to domestic hot water.

The maximum temperature of the heat pump output to the buffer tank was 51 °C, and the maximum temperature of the output to domestic hot water was 65 °C.

There was a temperature loss of approximately 5 °C through the buffer tank. This may have been due to some of the radiator thermostatic valves being closed, resulting in reduced flow through the heating circuit.

The temperature of the brine flow to the heat pump was between 7 and 9 °C while the heat pump was running.

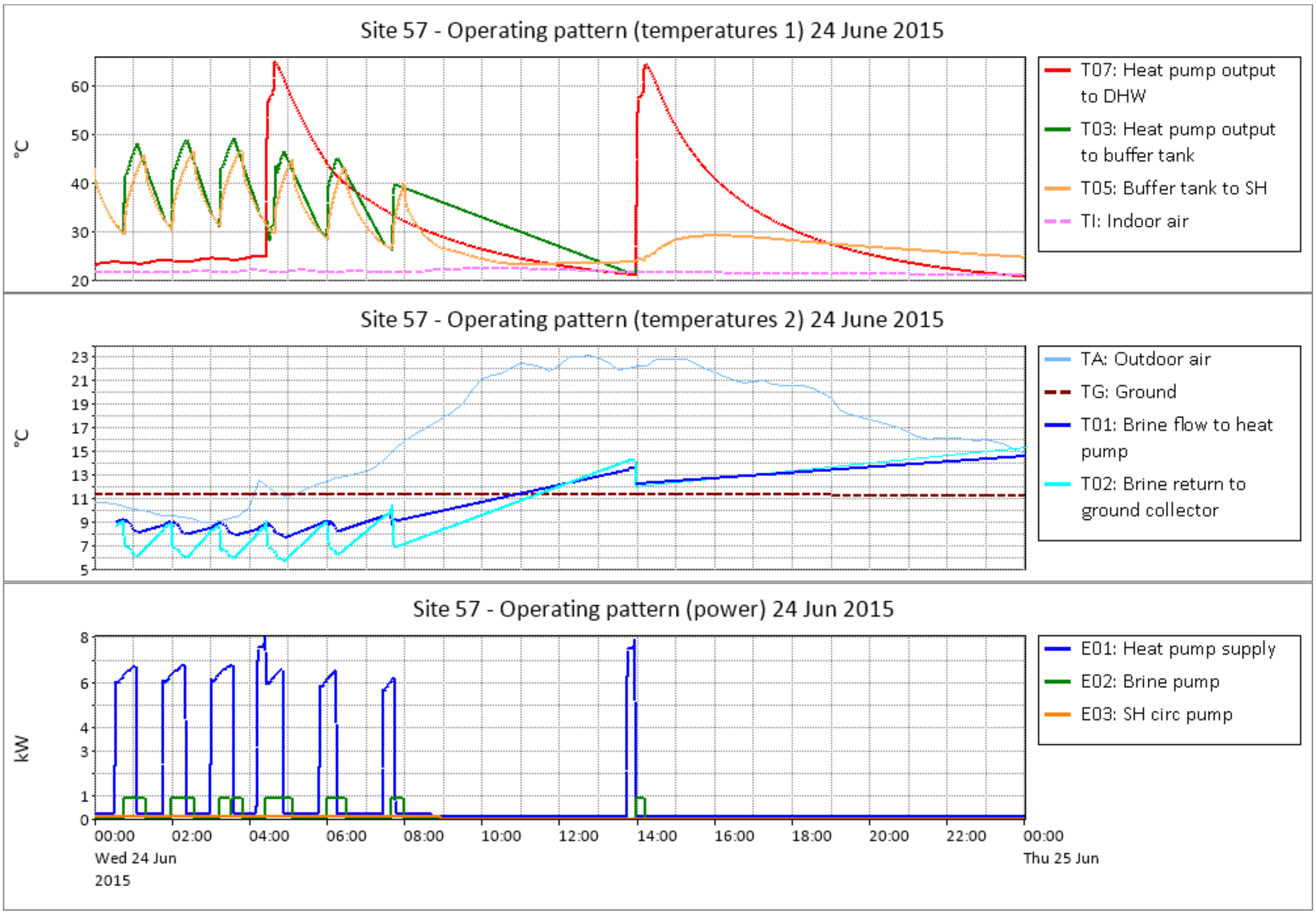

Figure 7 – Operating pattern on 24th June 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the ground, outdoor air, brine, output from the heat pump, and flow and return from the buffer tank to space heating, plotted over the year[4]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running. There was no data from the indoor temperature sensor after 23rd December.

The temperature of the brine flow to the heat pump was approximately 7 °C below the ground temperature during winter conditions. The lowest brine temperature was -1 °C on 21st January.

The temperature of the output to domestic hot water was high: the daily maximum was generally between 64 and 65 °C. It is worth noting that, while these are high output temperatures for a heat pump, no auxiliary immersion heater was used and the difference between the SPFH2 and SPFH4 performance was relatively small.

The output from the buffer tank to space heating varied with outdoor temperature (as a result of the weather compensation function): the daily maximum varied from 42 °C in early June to 65°C in January.

The temperature loss through the buffer tank (noted above) was evident during warmer weather conditions: the heat pump output temperature (green line) was several degrees higher than the buffer tank output temperature (orange line) between May and October.

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[4] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor and indoor temperatures were recorded every 15 minutes and the ground temperature every hour.

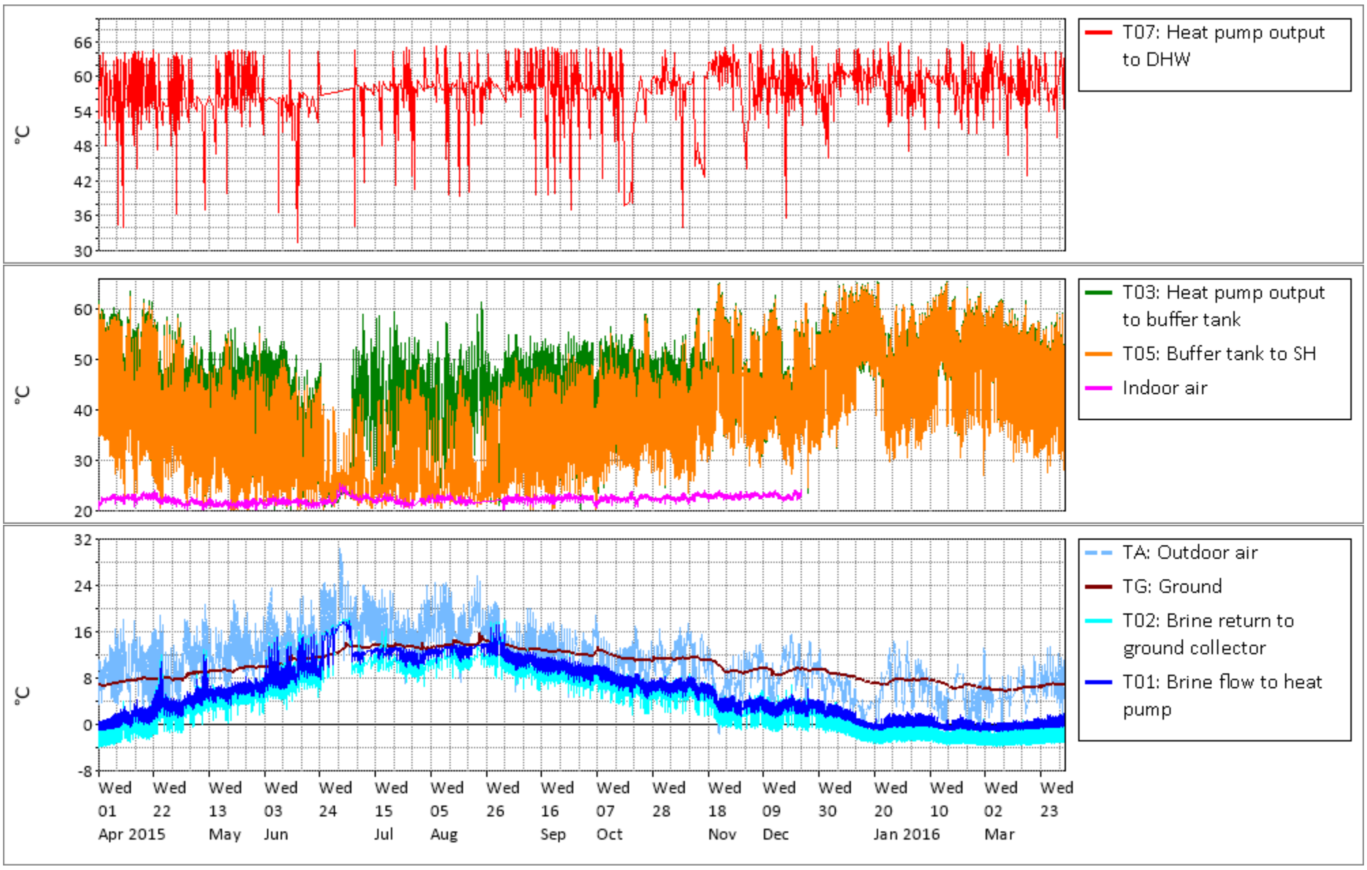

Figure 8 – Key temperatures measured during the period 1st April 2015 – 31st March 2016

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures (at the heat pump) of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were below average compared to other systems. This would have had a negative influence on system performance.

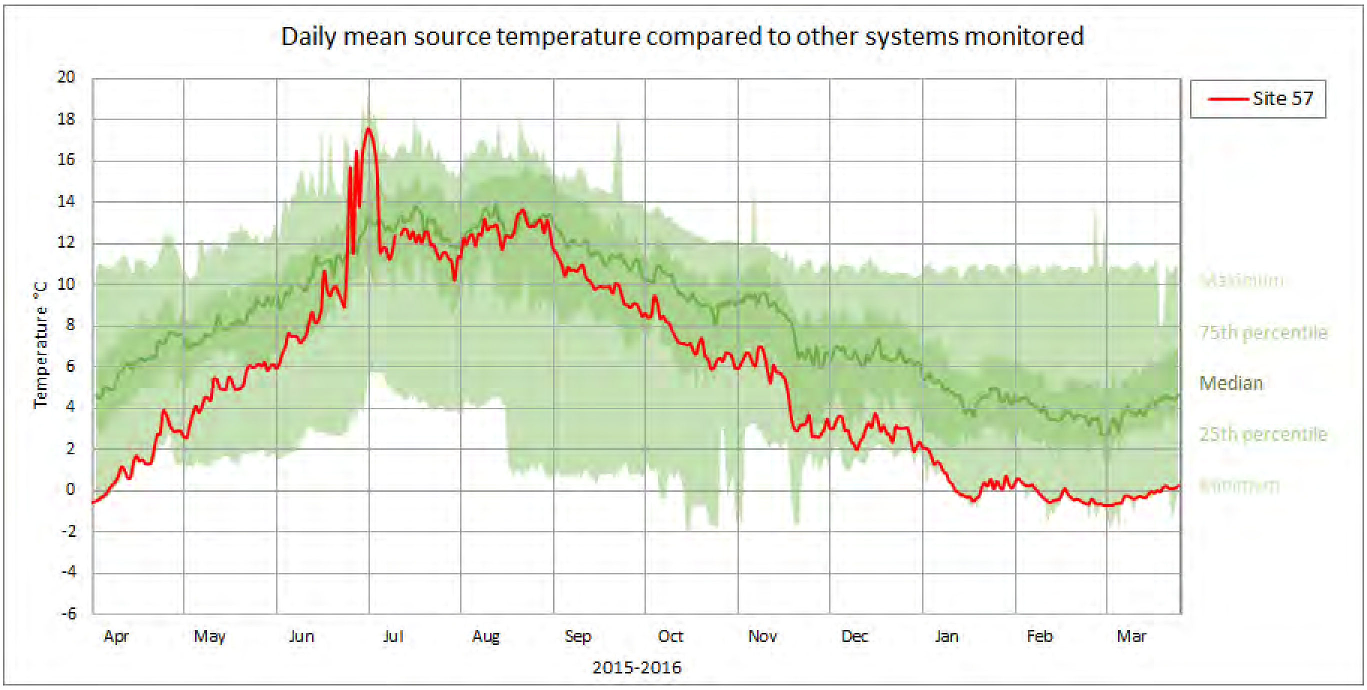

Figure 9 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 57 is shown in red)

Ground collector effectiveness

Figure 10 shows the mean temperature difference between the ground and the brine flow to the heat pump, compared to other systems with horizontal ground collectors. The high temperature difference on this system suggests poor collector performance.

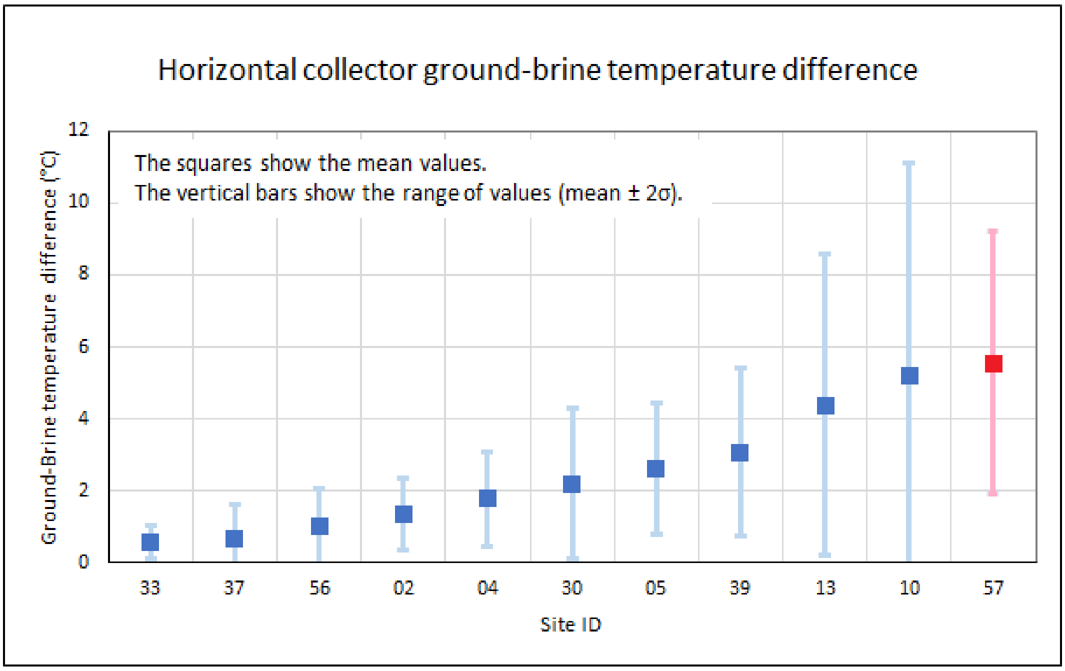

Figure 10 – Ground-brine temperature difference compared to other horizontal ground-source systems monitored in this project (site 57 is shown in red)

Figure 11 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were above average compared to other systems. This would have had a negative influence on the system performance.

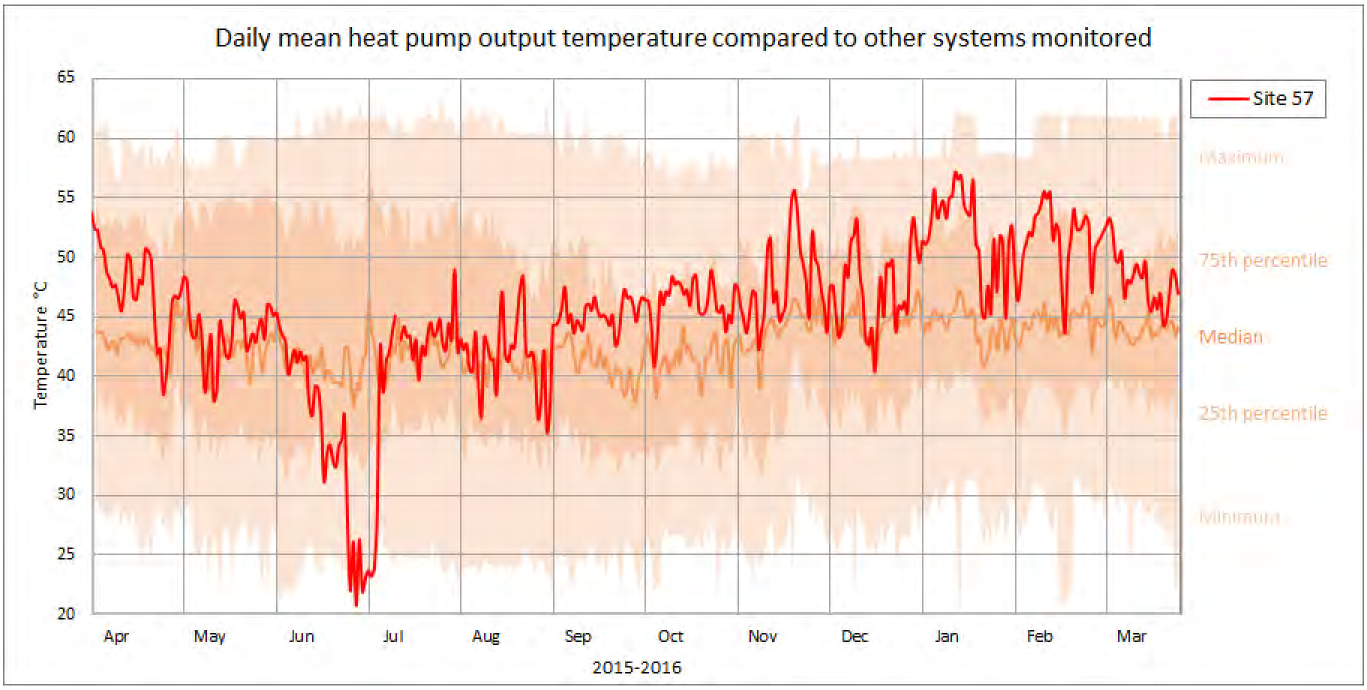

Figure 11 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 57 is shown in red)

Comments

The overall performance of this system (SPF_{H4} = 2.73) was above average compared to other systems providing both space heating and domestic hot water that were monitored in this project (SPF_{H4} range: 1.54 to 3.13, median value 2.41).

Aspects of this system that positively influence its performance are:

- No auxiliary heat was used.
- Weather compensation was used.
- The electricity used by the buffer pump and the space heating circulating pump (5.6% of the electricity) was below average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).

Aspects of the system that may have negatively influenced its performance include:

- The temperature of the brine flow to the heat pump was below average compared to other systems monitored. The range of brine temperatures was greater than for most other systems monitored. This may indicate that the ground collector is not optimally sized. Reference to the design data would be needed to establish whether this is the case.
- The electricity used by the brine pump (9.9% of the total electricity) was above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The temperature of the heat pump output was above average compared to other systems monitored.
- Only an estimated 2.6% of the heat pump output was used for domestic hot water. It would probably be better to install point-of-use water heaters and use the heat pump only for space heating. This would potentially allow it to operate with lower output temperatures and fewer annual run hours, with resultant improvement in system performance and a reduction in overall electricity use.
- This is a high-temperature heat pump system (maximum output temperature 65 °C) that does not use auxiliary immersion heaters. As would be expected, the performance was lower than that of other systems operating with lower output temperatures, but better than systems that use immersion heaters to achieve high temperatures. (If the system did not provide domestic hot water, a high-temperature heat pump would not be needed.)
- The temperature loss through the buffer tank varied between 0 and 5 °C. The 3-pipe arrangement is unusual. It is possible that a different arrangement would yield better system performance. However, the design of buffer tank systems is a complex topic that is outside the scope of this report.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[3] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.,” EN 14511.

[4] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps - Interim Report. URN 16D/013.,” DECC, 2016.

[5] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 60

Prepared by GRAHAM Energy Management
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January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 60 and performance results from 12 consecutive months of monitoring data.

Site 60 is a public hall which was refurbished in 2014 with the addition of a new extension that houses a public café. A single heat pump (thermal capacity 40 kW) with dual vapour-compression units provides space heating to the entire building, via underfloor heating pipes, and domestic hot water. A solar thermal collector also provides heat to the domestic hot water cylinder, and an immersion heater in the cylinder is used for auxiliary heat and to ensure that the water is heated above 60 °C every day for Legionella control.

The heat source is 8 x 100 m vertical boreholes located beneath the car park immediately adjacent to the hall.

The seasonal heating performance factors measured over a year of operation (1st April 2015 to 31st March 2016) were:

SPFH2	[Heat delivered by the heat pump (excluding internal buffer pumps)] -- Electricity used by: [heat pump (excluding buffer pumps)] + [brine pump]	3.23
SPFH4	[Heat delivered by the heat pump] + [heat from immersion heater] + [heat added by heating circ pumps] -- Electricity used by: [heat pump] + [brine pump] + [immersion heater] + [heating circ pumps]	2.37

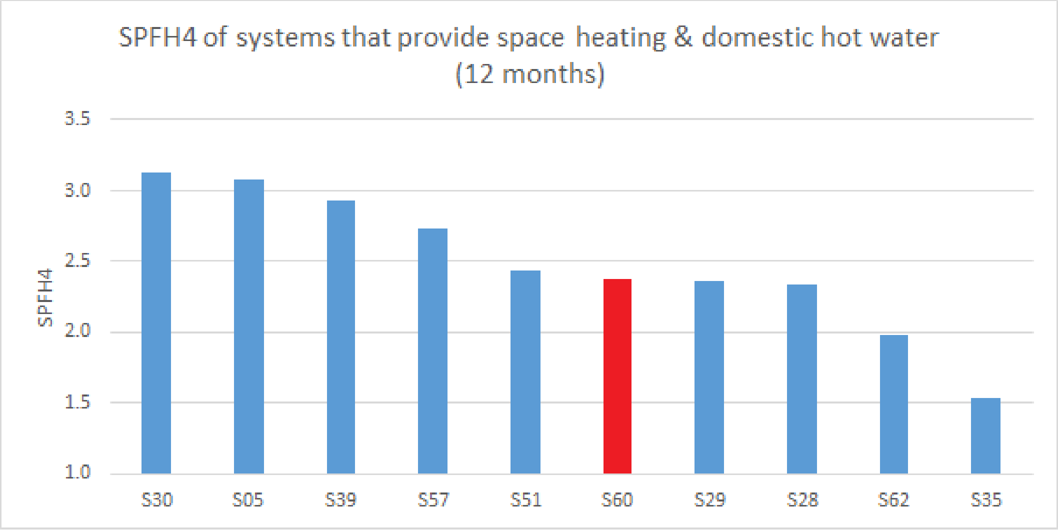

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature during warmer weather.
- The source temperature was higher than average compared to other systems monitored.
- The brine pump used 6.6% of the total electricity, which was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

Aspects of the system that may have negatively influenced its performance include:

- The domestic hot water immersion heater use was very high: 15.6% of the total electricity.
- The buffer pumps were run continuously, using an estimated 12.9% of total electricity.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	60
Survey date	28/01/2015
Monitoring installed	25/03/2015
G/WSHP	GSHP
Building type	Public hall with a café
Location	Village
Heat pump capacity kW$_{TH}$	40
Number of heat pumps	1
Number of compressors	2
Heat source	Vertical boreholes: 8 x 100 m
Heat emitters	Underfloor heating pipes
DHW	Yes
Auxiliary heat	9 kW immersion heater in DHW cylinder
Source pump	External to heat pump: 890 W
Buffer pumps	Internal to heat pump: 2 pumps of 100 W
SH circulating pumps	2 pumps of 333 W max (variable-speed)
DHW circulating pump	1 pump of 25 W
Buffer tank	500 litre 4-pipe
DHW cylinder	400 litre
Control	Heat pump controller + programmable thermostat
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	2
Heat meter interface	M-Bus
Comments	A solar thermal collector also provides heat to the DHW cylinder.

Table 1 – System details

Site 60 is a public hall, originally built in 1901 and refurbished in 2014, when an extension was added to incorporate a public café.

This application entails extracting heat from the ground to provide space heating and domestic hot water to a building that is reasonably well insulated and is in a location with an outdoor temperature that was below average compared to other sites monitored. (The mean outdoor temperature at the site during the period monitored was 9.1 °C. The range for all sites was 8.1 – 12.6 °C, median 10.5 °C.) The design performance of this system would be expected to be above average.

Heat pump and monitoring systems

A ground-source heat pump of 40 kW thermal capacity is installed in a plant room inside the building. The heat pump comprises two vapour compression circuits. One of these is capable of providing high-temperature (up to 65 °C according to the manufacturer’s specification) heat to domestic hot water or space heating; the other is used for space heating only

The heat emitters are underfloor heating pipes throughout the old and new areas of the building.

A solar thermal collector also provides heat to the domestic hot water cylinder, and an immersion heater in the cylinder is used for auxiliary heat and to ensure that the water is heated above 60 °C every day for Legionella control[1].

The heat source is 8 x 100 m vertical boreholes located beneath the car park immediately adjacent to the hall. The underfloor heating is arranged in 10 zones, with a room thermostat in each zone. A central programmer controls the times for heating each zone, while the thermostats control the relevant zone valves on the underfloor heating manifold. The heat pump controller manages the heat pump system.

A 500-litre 4-pipe buffer tank is installed between the heat pump output and the heating circuits. This tank is within the heat envelope so the heat loss from the tank has not been deducted from the system heat output.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output to space heating, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2]. The indoor and outdoor air temperatures are also monitored.

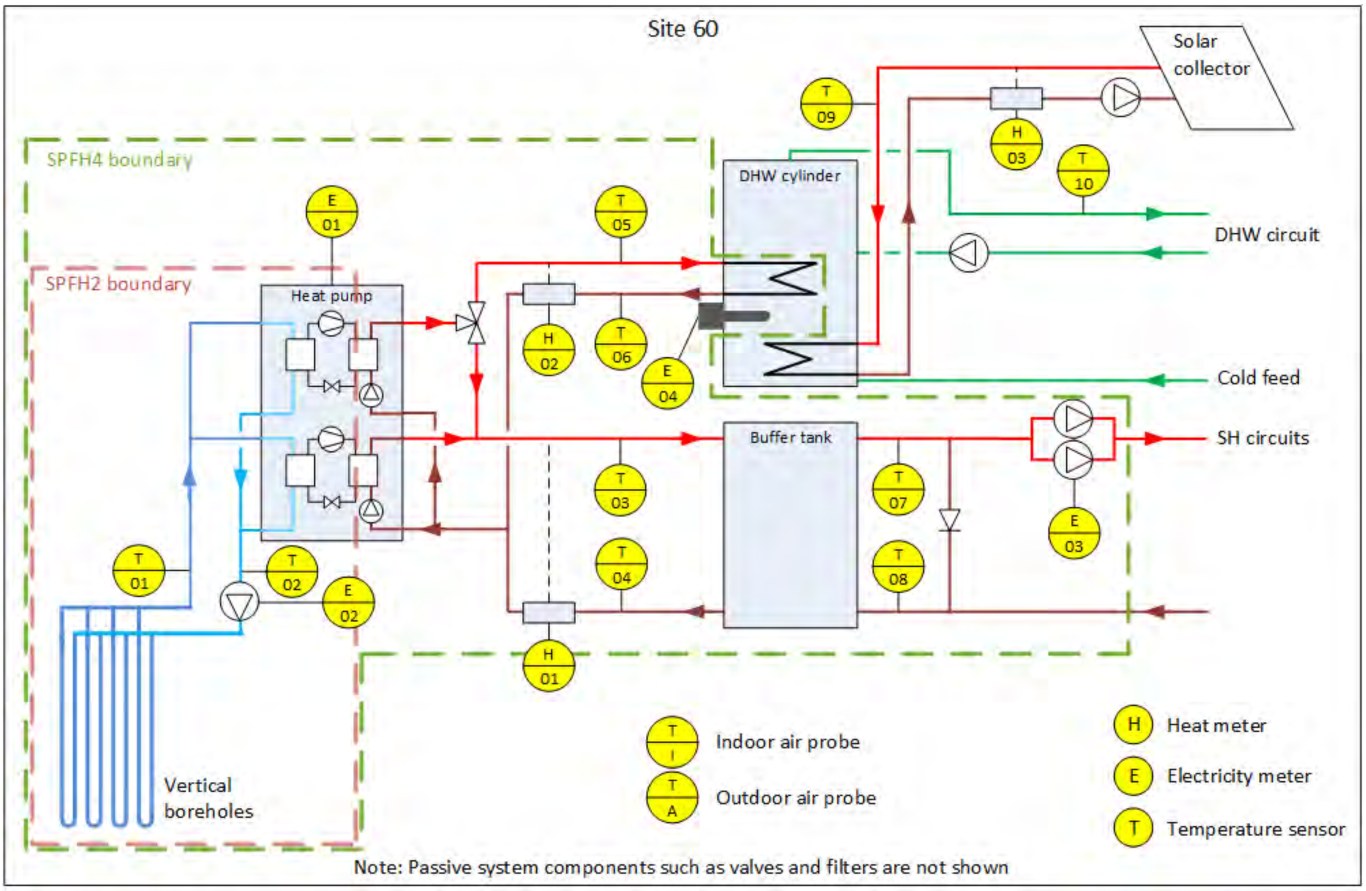

Figure 2 – System schematic showing the monitoring instrumentation installed

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[1] This is understood to be a requirement of the Legionella risk assessment for the site.

[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pump. The heat meters on this system are installed between the heat pump and the buffer tank and between the heat pump and the domestic hot water accumulator. Ultrasonic flow meters are installed in the return pipes, with matched pairs of temperature sensors installed in fittings with the probes in pockets in the flow and return pipes. The calculators are mains-powered. Monitoring was via the M-Bus interfaces.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump (excluding the internal buffer pumps) together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and the immersion heater in the domestic hot water cylinder, but excluding heat provided by the solar collector

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

Solar collector excluded from calculation

The SEPEMO project [2] recommends that for this type of bivalent system (heat pump + solar collector) the heat from the solar collector be included in the numerator of the SPF_{H4} calculation and the electricity used by the solar circulating pump in the denominator.

Inclusion of these values in the SPF_{H4} calculation is likely to yield very high SPF_{H4} values that are not very meaningful for comparison with systems without solar collectors – because the ratio of heat to electricity in a solar thermal system can be very high and does not have the same meaning as the SPF of a heat pump.

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

The SPF$_{H4}$ results for this system do not include the heat output of or electricity used by the solar thermal collectors.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat output of heat pump to SH \& DHW] – [heat added by internal buffer pumps]}}{\text{Electricity used by: [heat pump excluding buffer pumps] + [brine pump]}}$$

- This calculation required the electrical energy used by the buffer pumps inside the heat pump to be subtracted from the heat pump electricity meter readings. The buffer pump electricity was estimated from the rated power of the pumps, calculated for intervals that the associated heat pump compressor was running.

- The heat added by the circulating pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pumps.

$$SPF_{H4} = \frac{\begin{array}{c}\text{[Heat output of heat pump to SH \& DHW] + [heat added by immersion heater]} \\ \text{+ [heat added by SH circ pumps]}\end{array}}{\text{Electricity used by: [heat pump] + [immersion heater] + [brine pump] + [SH circ pumps]}}$$

- The heat added by the heating circulating pumps was estimated as 30% (the assumed pump efficiency) of the electrical energy supplied to the pumps.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 20 °C.
  The buffer tank is inside the heated envelope, so the heat loss from it was deducted from the total heat output only at times when the outdoor air temperature was above 15 °C (i.e. when there was output to space heating that was probably not needed).

The number of 1-minute intervals selected as valid for analysis was 525 721, which represents 99.7% of the 12-month period.

The SPF$_{H2}$ and SPF$_{H4}$ values for this system, measured between 1st April 2015 and 31st March 2016, are shown in Table 2.

SPF$_{H2}$	3.23
SPF$_{H4}$	2.37

Table 2 – SPF values measured for the period 1st April 2015 to 31st March 2016

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [6] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

This means that for each unit of electricity used, this system delivers on average 2.37 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPFH2 and SPFH4 values for the system. The SPFH2 value was generally between 3.0 and 3.7, except during the summer months when the heat output was mainly for domestic hot water. The short run times and higher output temperatures resulted in reduced performance. However, the total heat output during this period was also low, so the effect on the overall annual performance was minimal.

The SPFH4 value dropped significantly during warmer weather when the heat pump was used mainly for heating domestic hot water, with the raised output temperatures, shorter run times and high immersion heater use (see Figure 8) combining to cause reduced system performance. It can be seen that the SPFH4 increased significantly after 17th January when the immersion heater use stopped, as shown in Figure 4 and Figure 5

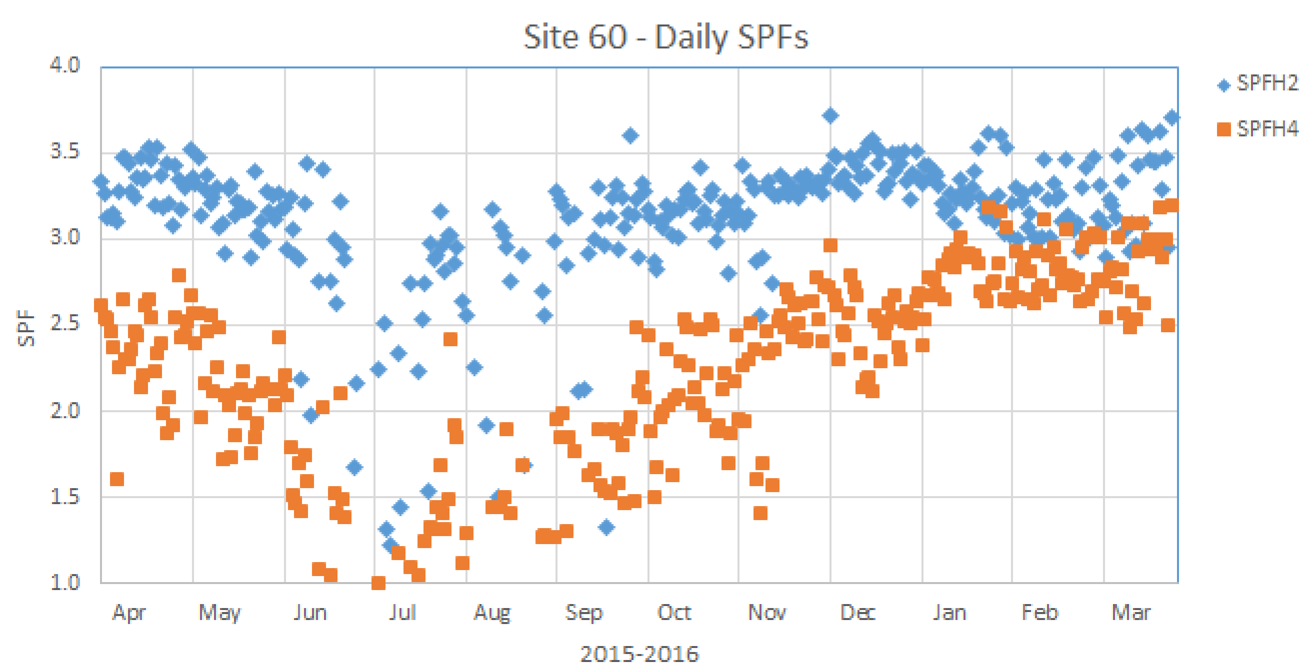

Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

An electric immersion heater is installed in the domestic hot water cylinder to provide auxiliary heat.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [3] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required to heat the building depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump, the solar collector and the immersion heater. The electricity use by the total heat pump system and the outdoor air temperature are shown for reference.

There was demand for both space heating and domestic hot water all year. The space heating demand varied with the outdoor temperature and was lowest during June/July, highest in January. The domestic hot water demand varied from day to day, and was highest during October and November.

The large spike on 30th – 31st July 2015 was due to an exceptionally high demand for domestic hot water on those days.

The very low output from the solar collector is believed to be due to the temperature in the domestic hot water cylinder being generally higher than the temperature at which the solar collector is able to deliver heat.

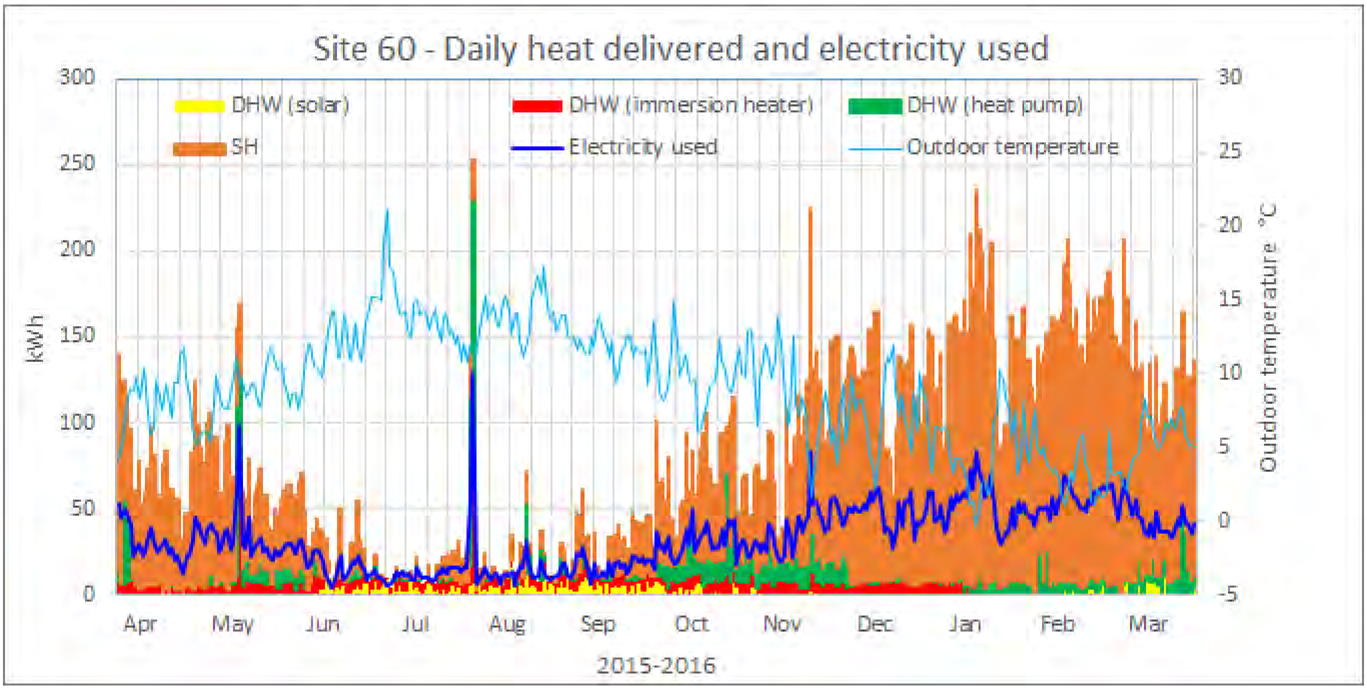

Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered to space heating and to domestic hot water

Table 3 shows the breakdown of the heat delivered from each source during the period 1st April 2015 to 31st March 2016. The figures shown are the percentages of the total heat from all sources.

Heat source	Space heating	Domestic hot water
Heat pump	81.9%	8.9%
Immersion heater		6.5%
Solar collector		2.6%
Total:	**81.9%**	**18.1%**

Table 3 – Breakdown of heat delivery between 1st April 2015 and 31st March 2016

Of the total heat to domestic hot water, the solar collector provided 14%, and the immersion heater provided 36%.

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use. The electricity used by the buffer pumps was estimated from the rating of the pumps and analysis of the detailed data from the electricity monitor.

The brine pump used 6.6% of the total electricity, which was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a positive influence on the system performance.

The buffer pumps and the space heating and domestic hot water circulating pumps together used 17.1% of total electricity, which is above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).

It is notable that both buffer pumps operated continuously (except for a few hours in July when only one pump was running) and used an estimated 12.9% of the total electricity. This is very high, and would have had a negative influence on the system performance.

The domestic hot water immersion heater accounted for 15.6% of the total electricity. This is also very high compared to other systems monitored (range 0 – 27.6%, median 0%), and would have negatively influenced performance. The immersion heater was not used after 17th January. This is understood to have been due to a fault in the immersion heater controller.

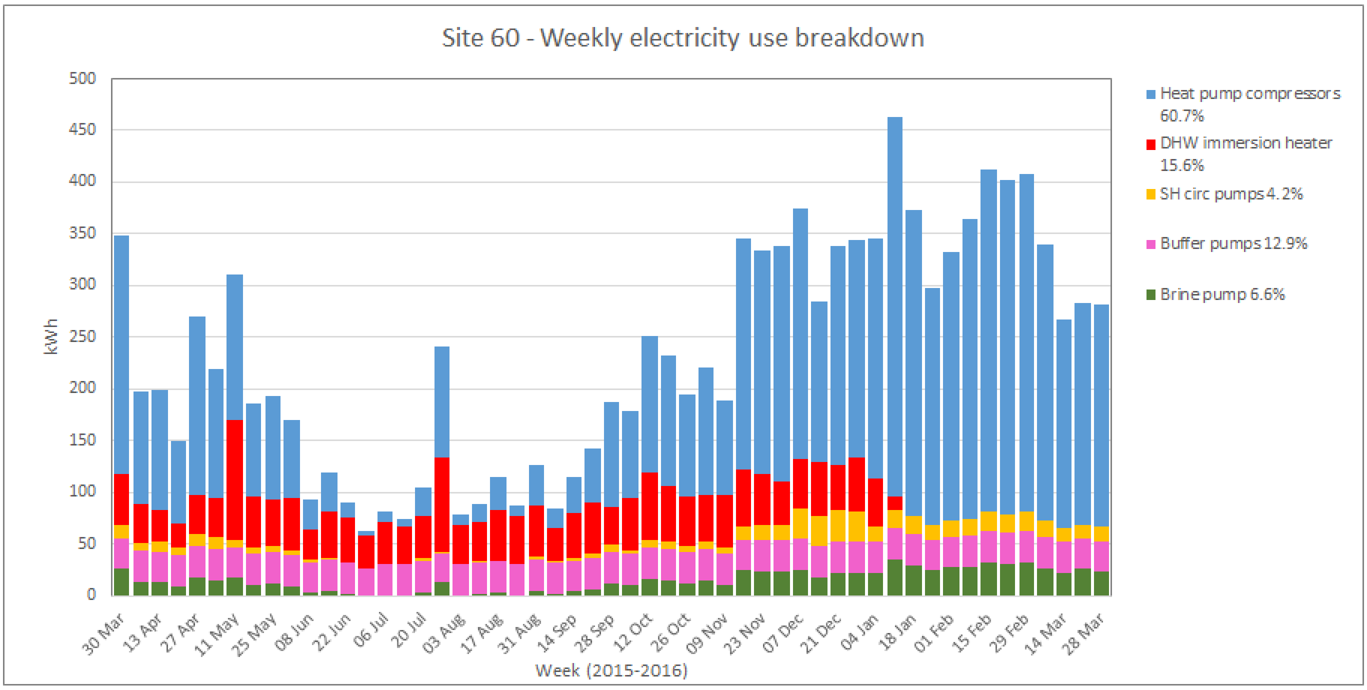

Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system, the electrical power drawn by the heat pump and the thermal output power. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 14th December when the outdoor temperature was between 4 and 5 °C. The heat pump ran several times during the day, sometimes using both compressors, to provide heat mainly to space heating. Heat to domestic hot water was provided by the heat pump and by the immersion heater in the domestic hot water cylinder. The solar collector provided a negligible amount of heat. The space heating circulating pumps were running all day until 23:30.

The temperature of the brine flow to the heat pump was between 5 and 10 °C while the heat pump was running.

The maximum temperature of the heat pump output to the buffer tank was 58 °C, whereas the maximum temperature of the output to the domestic hot water coil was 49 °C, while the heat pump was providing heat to domestic hot water. This is unusual: the temperature of the output to domestic hot water on other systems is usually higher than that to the buffer tank. This is examined in more detail below.

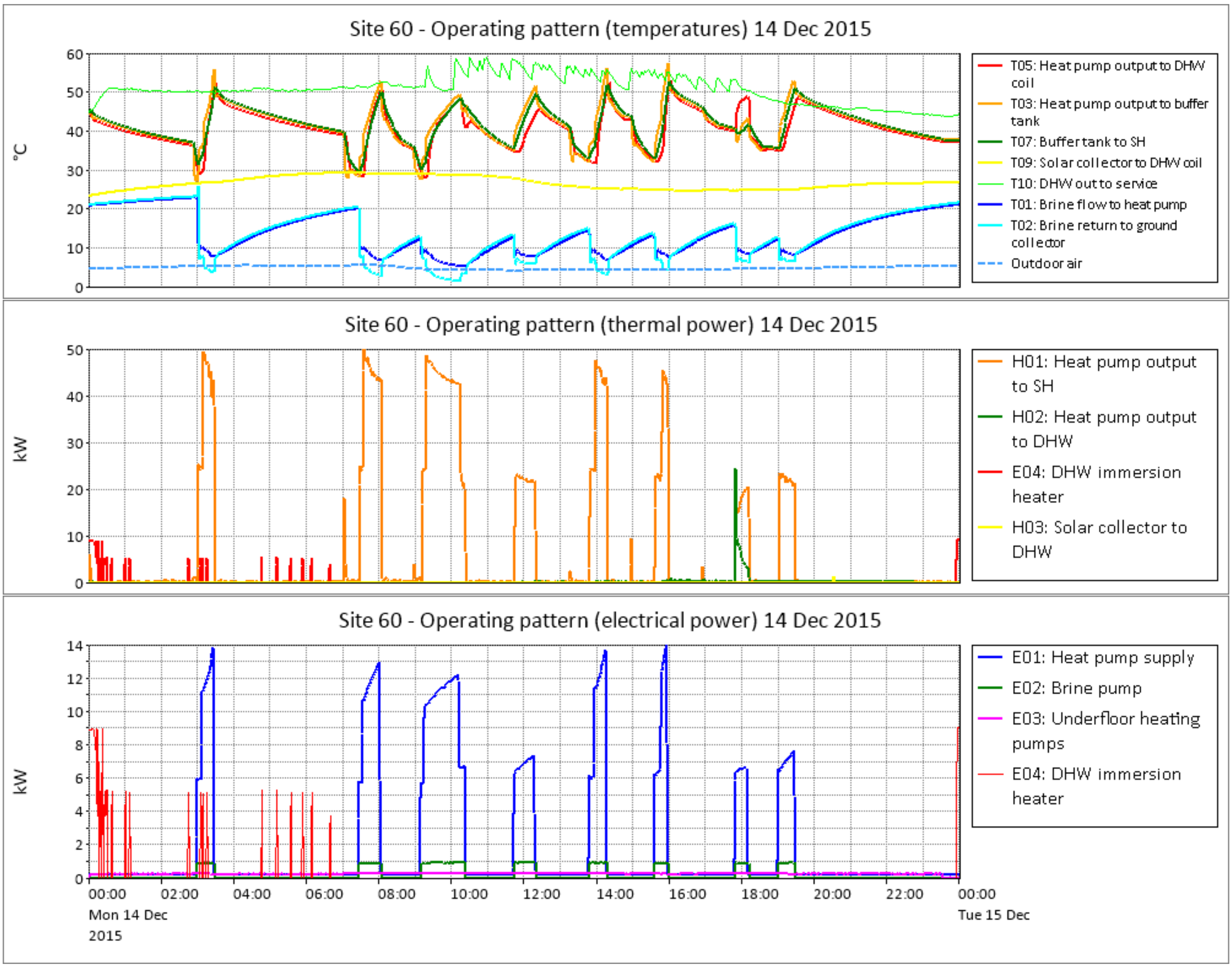

Figure 6 – Operating pattern on 14th December 2015

Figure 7 shows the behaviour during two heat pump cycles – one (from 15:35 to 15:58) that provided space heating only, the other (from 17:47 to 18:11) providing domestic hot water and space heating. There was no heat from either the solar collector or the immersion heater during the 4-hour period shown.

During the first (space heating only) cycle, both compressors were in use during the second half of the run (from 15:46). The temperature of the output to the buffer tank rose to 58 °C. The output from the buffer tank to the space heating circuits rose at the same time to 53 °C – a loss of temperature of 5 °C through the buffer tank. It is notable that the temperature of the output to the domestic hot water coil also rose to 53 °C. However, as very little heat was delivered from the heat pump to domestic hot water during this cycle, the rise in temperature was probably due to the 3-port valve not being fully closed, resulting in a small flow through the domestic hot water coil.

During the second (domestic hot water and space heating) cycle, the temperature of the output to domestic hot water rose much more rapidly. The thermal power delivered to domestic hot water (green line, middle graph) was initially up to 25 kW, but dropped quite quickly to less than 10 kW – apparently as the temperature to the domestic hot water coil approached the temperature in the cylinder. The upper light green line shows the temperature of hot water drawn off from the cylinder. This was always higher than the temperature of the heat pump output to domestic hot water – presumably as a result of the cylinder having been heated earlier in the day by the immersion heater (as seen in Figure 6).

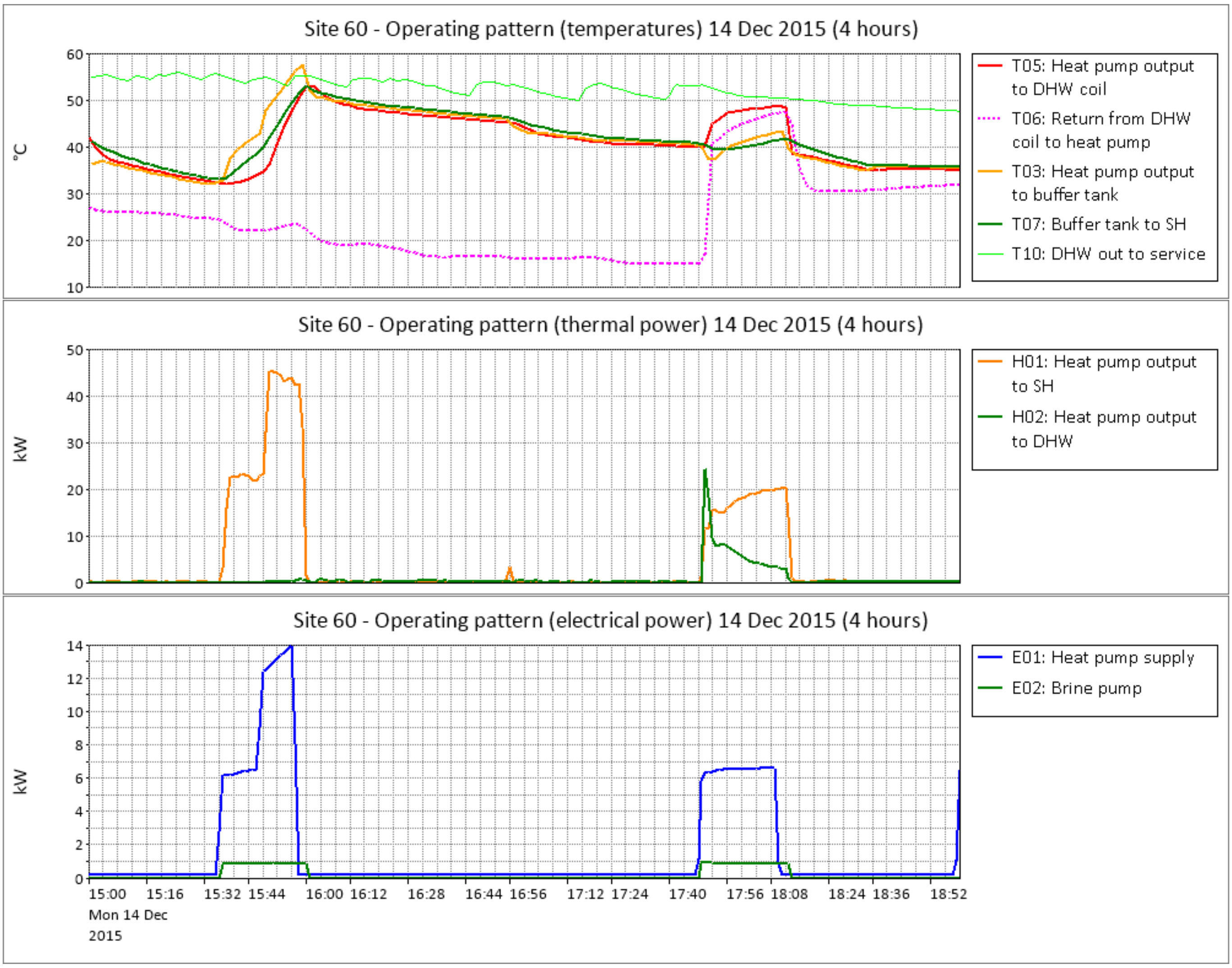

Figure 7 – Heat pump cycles for space heating and domestic hot water on 14th December

Figure 8 shows the pattern on 15th June when the outdoor temperature was between 7 and 14 °C. The heat pump ran three times to provide space heating only. The space heating circulating pumps ran for three periods: 06:00 – 07:00, 09:00 – 11:30, 14:00 – 15:30.

The domestic hot water immersion heater was on for short periods before 06:00 and again between 23:00 and midnight, providing 6 kWh of heat. The solar collector provided 3 kWh during the day.

The temperature of the output from the heat pump to the buffer tank was between 26 and 46 °C while the heat pump was running. The temperature of the output to domestic hot water followed that of the output to the buffer tank – presumably because of a small flow through the 3-port diverter valve, as there was no flow measured by the heat meter H02.

It can be seen that the temperature of the domestic hot water drawn off at 08:00 was just above 60 °C. The temperature of subsequent draw-offs during the day reduced to 56 °C at 16:40. This shows that the solar collector[5] was unable to maintain the domestic hot water temperature on this day and that the immersion heater was responsible for raising the temperature to 60 °C. It is possible that the heat pump could have been used instead of the immersion heater to heat the domestic hot water to 60 °C, as the model used is understood to be capable of providing output up to 65 °C.

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[5] Note: it appears from the graphs that the temperature from the solar collector was sometimes lower than the temperature of the DHW and that heat transfer could not have taken place. However, the solar heating coil is at the bottom of the DHW tank where the temperature is lower due to stratification.

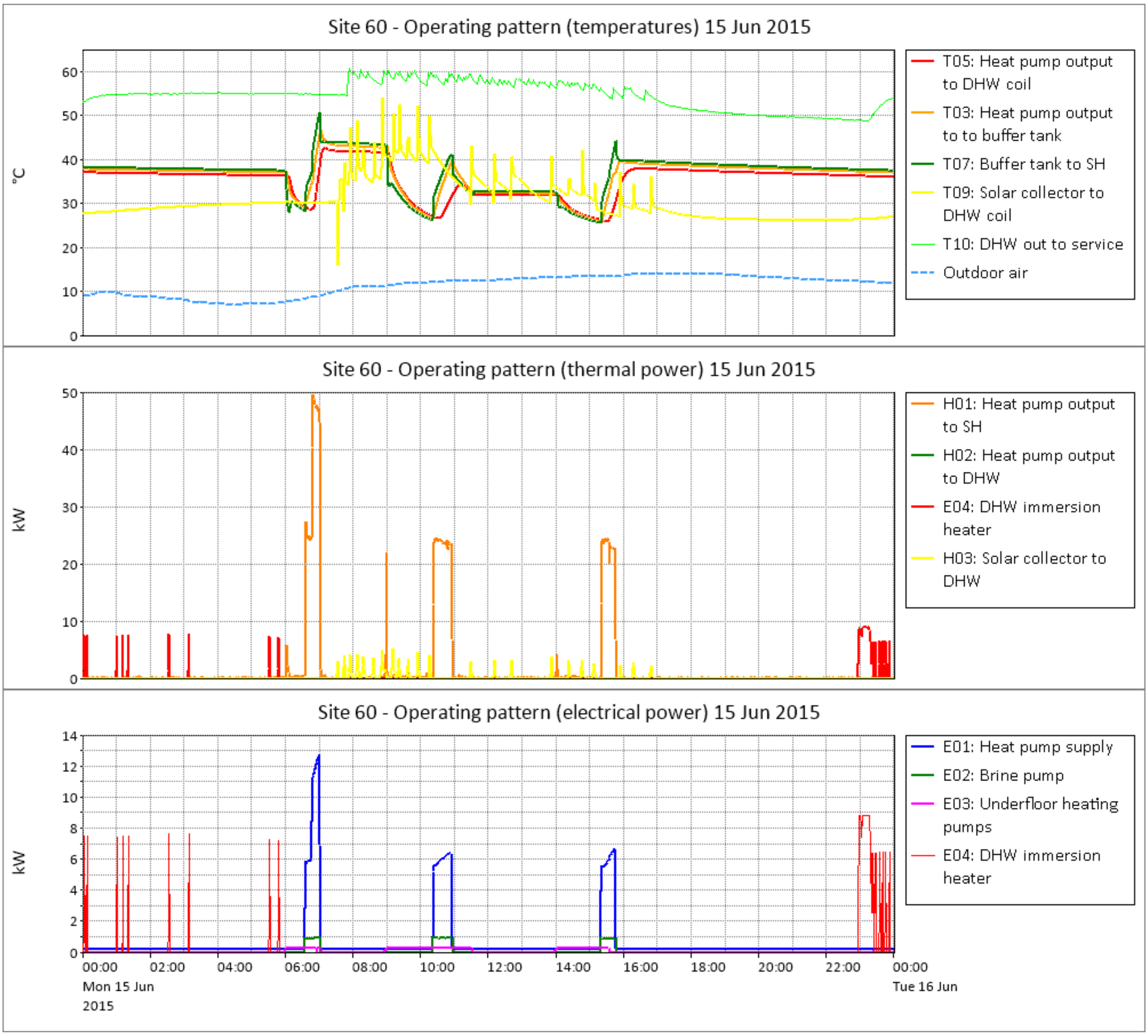

Figure 8 – Operating pattern on 15th June 2015

Source and sink temperatures

Figure 9 shows the principal temperatures of the outdoor air, brine and the outputs from the heat pump, plotted over the year[6]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The available data from the indoor temperature sensor is also shown. (No data was received from this sensor after 13th May.)

The effect of the weather compensation can be seen, with the temperature of the output to space heating being lower during warmer weather. The daily maximum temperature of the output from the buffer tank to space heating varied between 34 and 62 °C from day to day throughout the year.

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[6] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor temperature was recorded every 15 minutes and the ground temperature every hour.

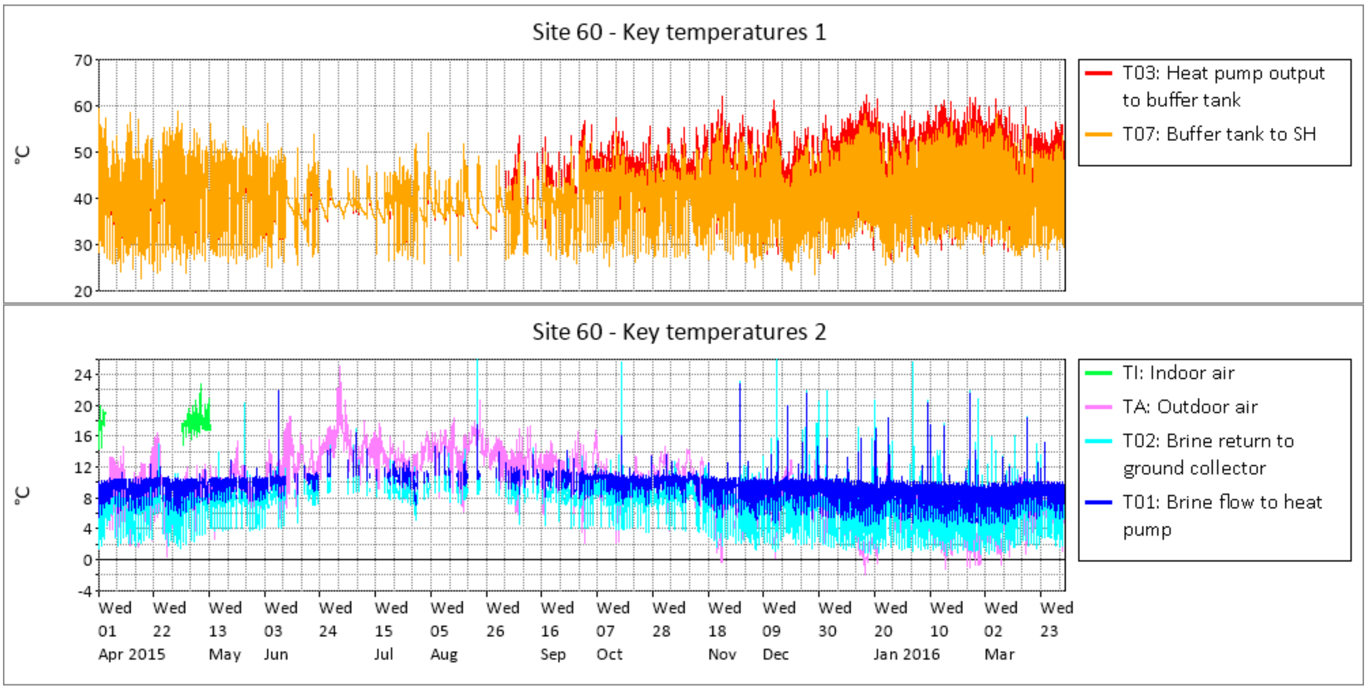

Figure 9 – Key temperatures measured during the period 1st April 2015 – 31st March 2016

Figure 10 shows the temperatures of the heat pump output to the upper domestic hot water coil, the flow from the solar collector to the lower domestic hot water coil and the hot potable water drawn off from the domestic hot water cylinder. The temperature available for the domestic hot water draw-off was over 60 °C every day until the immersion heater stopped being used on 17th January. The heat pump provided more heat to domestic hot water after that date, although the temperature of the domestic hot water was reduced to 45 - 55 °C.

Legionella control may not have been satisfactory after the immersion heater stopped working.

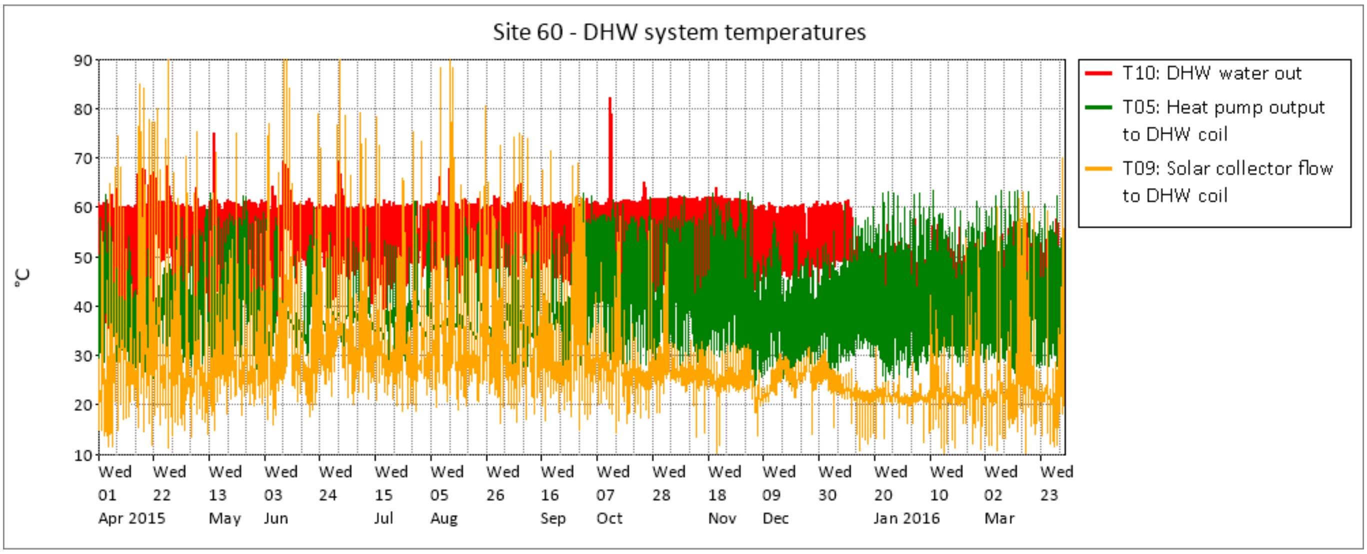

Figure 10 – Domestic hot water system temperatures during the period 1st April 2015 – 31st March 2016

Figure 11 shows the daily mean brine flow temperature compared to the source temperatures of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were above average during the winter months. This would have had a positive influence on system performance.

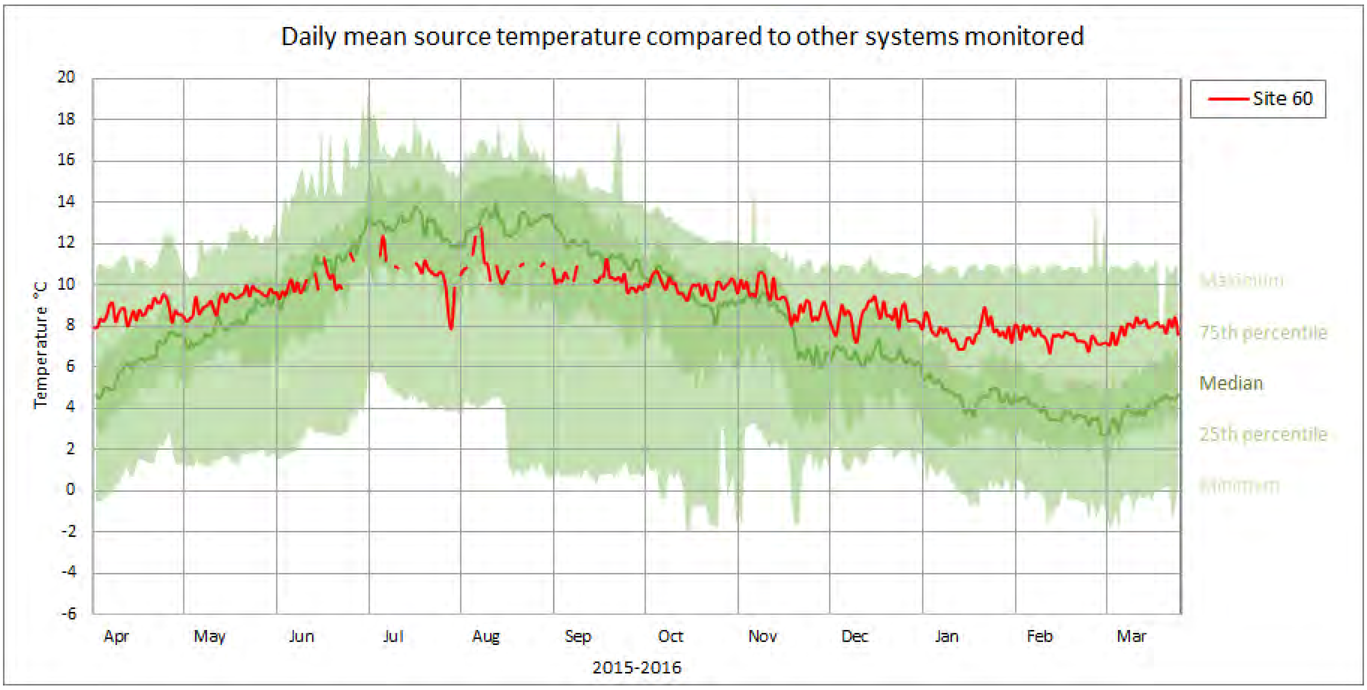

Figure 11 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 60 is shown in red)

Figure 12 shows the daily mean heat pump output temperature (to space heating) for this system compared to other systems monitored in this project. The output temperatures on this system were average compared to other systems.

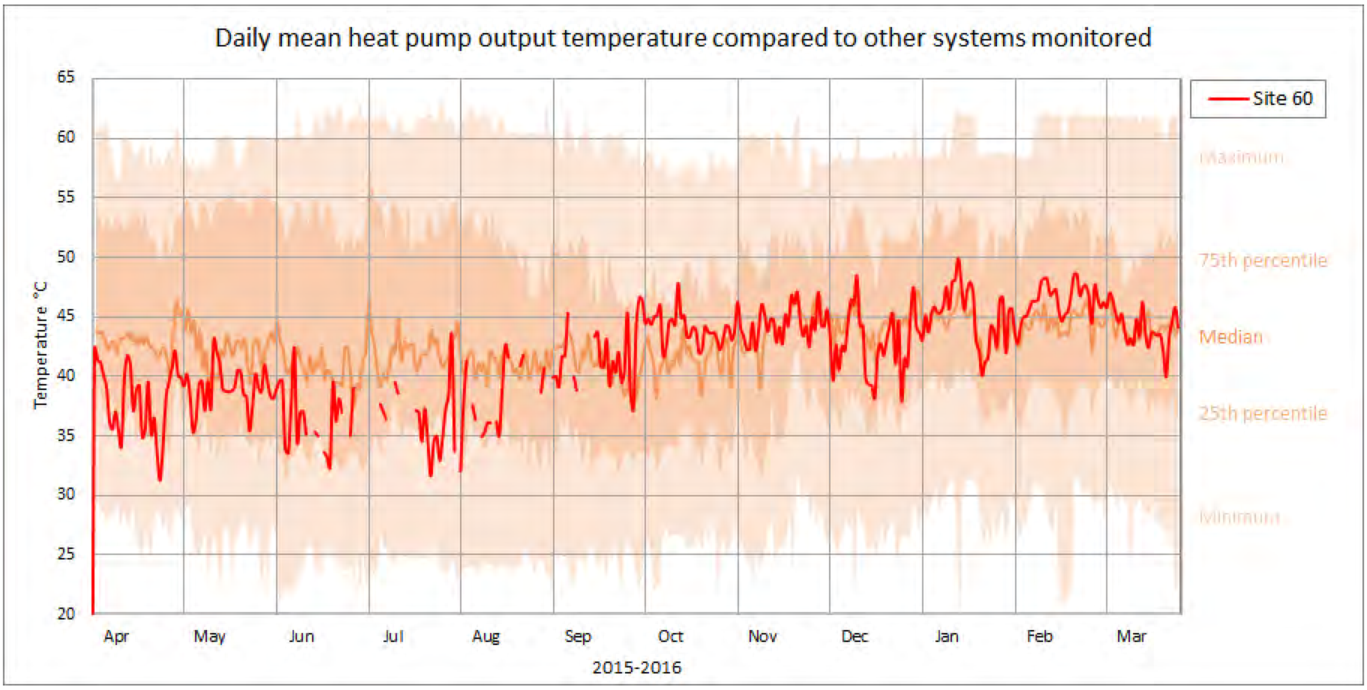

Figure 12 – Daily mean heat pump output temperature to space heating compared to those of other systems monitored in this project (site 60 is shown in red)

Figure 13 shows the daily mean temperature of the flow to the underfloor heat emitters compared to other underfloor heating systems monitored. The temperatures on this system were average.

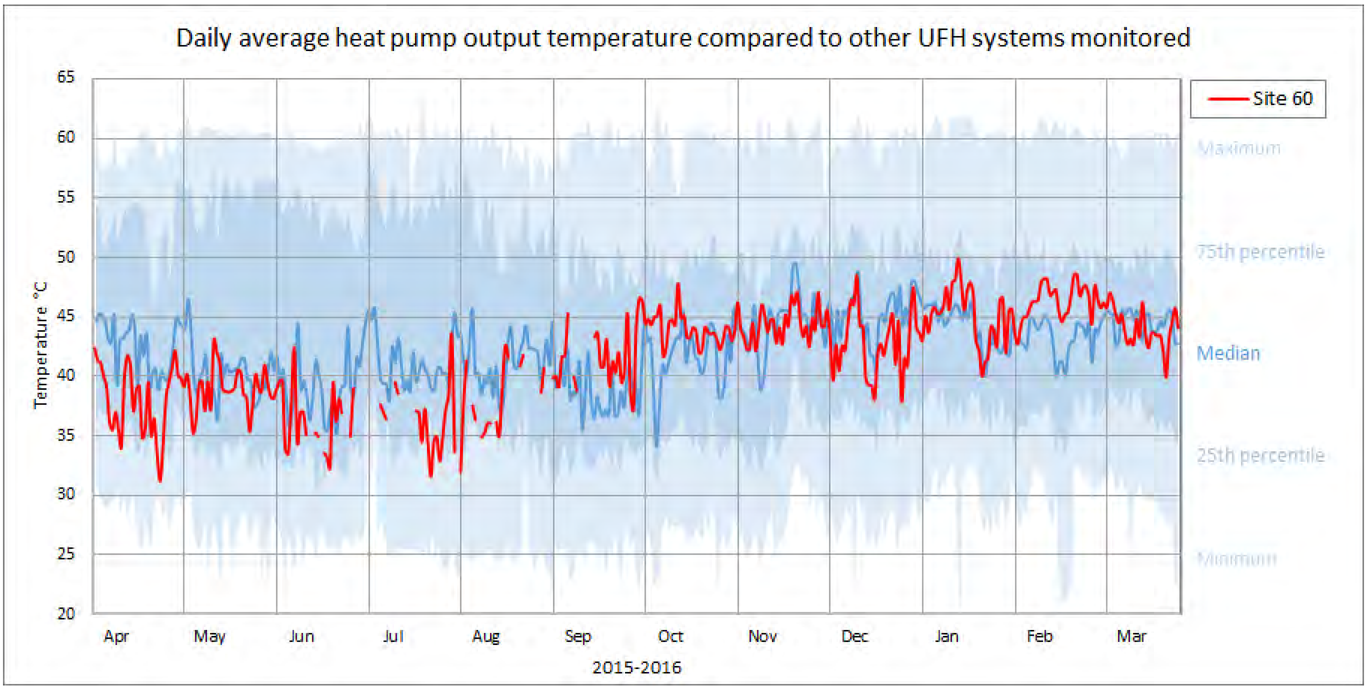

Figure 13 – Daily mean temperature of the flow to the underfloor heating compared to other systems using underfloor heating that were monitored in this project (site 60 is shown in red)

Figure 14 shows the daily maximum temperature of the heat pump output to the domestic hot water heating coil. The temperature on this system varied considerably during the 12-month period. It was notably higher after the immersion heater stopped being used on 17th January. This suggests that the heat pump could have been used more than it was for domestic hot water heating, with an improvement in overall system performance.

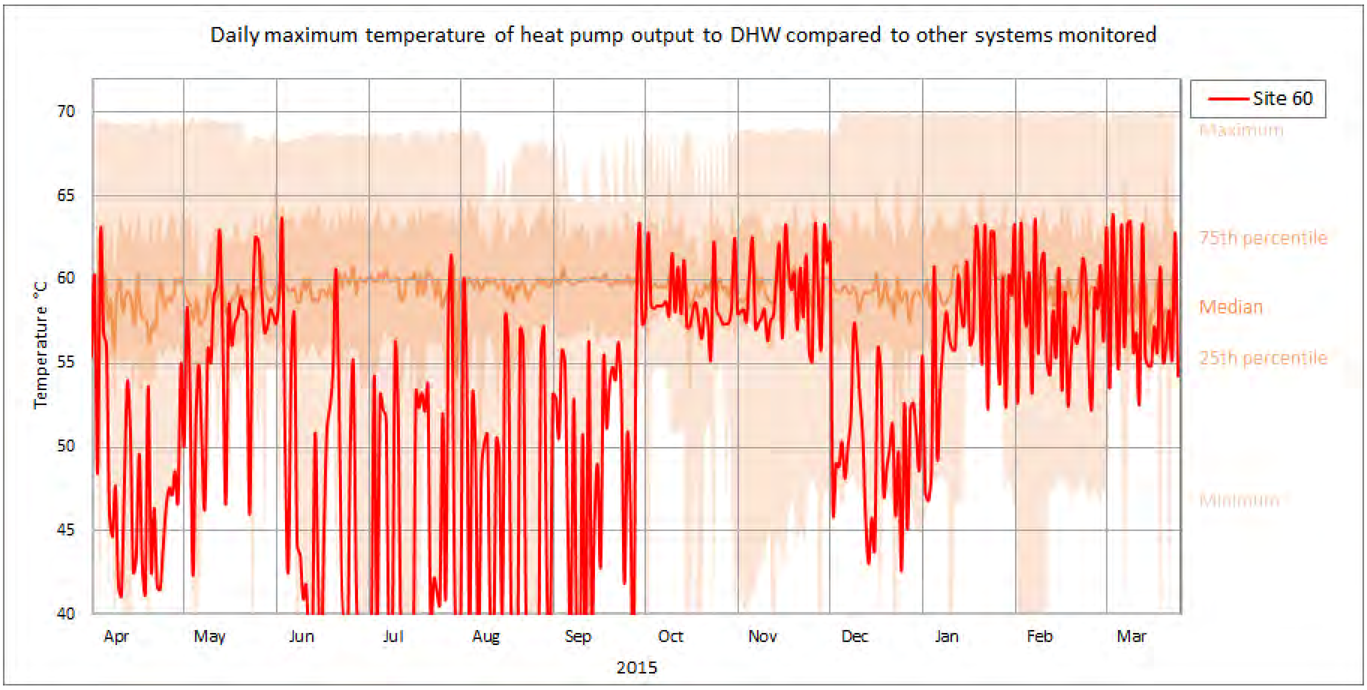

Figure 14 – Daily maximum heat pump output temperature to domestic hot water compared to those of other systems monitored in this project (site 60 is shown in red)

Comments

The performance of this system (SPF_{H4} = 2.37) was slightly below average compared to other systems providing both space heating and domestic hot water that were monitored in this project (SPF_{H4} range: 1.54 to 3.13, median value 2.41).

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature during warmer weather.
- The source temperature was higher than average compared to other systems monitored (see Figure 11).
- The brine pump used 6.6% of the total electricity, which was below average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).

Aspects of the system that may have negatively influenced its performance include:

- The domestic hot water immersion heater use was very high: 15.6% of the total electricity. It should be possible to make greater use of the heat pump for heating the domestic hot water, as it is capable of producing output up to 65 °C. The control settings should be adjusted to maximise the use of the heat pump. This should improve the overall system performance and would increase the proportion of total heat output generated as renewable heat. It would also be worth reviewing the design of the domestic hot water system to try to make better use of the solar collector and thereby reduce overall electricity use.
- The buffer pumps were run continuously, using an estimated 12.9% of total electricity. The controls should be altered so that the buffer pumps are run only when necessary.
- There appeared to be a leakage of hot water through the 3-port diverter valve to the domestic hot water heating coil at times when the system was evidently working in space heating mode. The operation of this valve should be checked to ensure that heat is not being wasted.

Bibliography

[1] “Directive 2009/28/EC of the European Parliament and of the Council,” Official Journal of the European Union, 2009.

[2] R. Nordman, “SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector,” SEPEMO-Build project, 2012.

[3] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

[4] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps: Interim Report. URN 16D/013,” DECC, 2016.

[5] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.,” EN 14511.

[6] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 61

Prepared by GRAHAM Energy Management
for BEIS (Department for Business, Energy & Industrial Strategy)
January 2018

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This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kWTH has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 61 and qualitative[1] performance results from 12 consecutive months of monitoring data.

Site 61 is a residential care facility built in 2010 in a suburban location.

A ground-source heat pump (thermal capacity 40 kW) extracts heat from horizontal ground loops, and provides space heating via underfloor heating pipes and domestic hot water.

Seasonal performance factors are not presented because characteristics of the heat meter, previously installed for the Renewable Heat Incentive and used to monitor this system, have led to unacceptably high uncertainties of measurement of the heat delivered.

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature when the outdoor temperature was higher.
- The heat pump operated using a simple strategy, and a good load factor was realised. In other words, the capacity of heat pump was well matched to the heating load of the building, allowing it to run for a high proportion of the time during the winter (up to 75% during the period monitored) with consequent efficient operation.
- No auxiliary electric heat was used (although the backup gas-fired boiler was used for a period because of a fault in the building management system.)

Aspects of the system that may have negatively influenced its performance include:

- The brine pump accounted for an estimated 16.2% of the total electricity used, which was above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The space heating circulating pumps used an estimated 14.3% of the total electricity. This was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).
- Heating and cooling were observed to have occurred on some occasions during the same day.

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[1] One of the temperature probes used for heat metering on this system was found to be incorrectly installed. The performance values could therefore not reliably be determined.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh$_{TH}$	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF$_{H2}$	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF$_{H4}$	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	**61**
Survey date	22/01/2015
Monitoring installed	19/03/2015
G/WSHP	GSHP
Building type	Residential care facility
Location	Suburban
Heat pump capacity kW$_{TH}$	80
Number of heat pumps	1
Number of compressors	2
Heat source	Vertical boreholes: 15 x 100 m
Heat emitters	Underfloor heating pipes
Auxiliary heat	Gas-fired boiler (backup only)
Source pump	External to heat pump: 1 pump of 1.7 kW max
Buffer pump	N/A
SH circulating pump	External to heat pump. Pump set: 2 pumps of 1.6 kW max (duty/standby)
DHW circulating pump	N/A
Buffer tank	2000 litre (estimate) 2-pipe in return from SH
Control	BMS + heat pump controller
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	2
Heat meter interface	M-Bus (heat pump meter); pulse (backup boiler)
Comments	The boreholes are used for cooling in warm weather: brine is pumped through a plate heat exchanger. The heat pump is not used for cooling.

Table 1 – System details

Site 61 is a two-storey residential care facility built in 2010 in a suburban location.

This application entails extracting heat from the ground to provide space heating via underfloor pipes to a reasonably well-insulated building in a location with slightly above-average outdoor air temperatures. (The mean outdoor temperature at the site during the period monitored was 10.7 °C. The range for all sites was 8.1 – 12.6 °C, median 10.5 °C.) The ground collector is used to provide space cooling during warm weather. The design performance of this system would be expected to be above average.

Heat pump and monitoring systems

A dual-compressor heat pump with a thermal capacity of 80 kW is installed in a ground-floor plant room inside the building.

The heat source is 15 x 100 m vertical boreholes located in the grounds of the facility. The brine pumped through the loops in the boreholes is also used for cooling during the summer. (The heat pump is not used for cooling.)

The heat emitters are underfloor heating pipes. Summer cooling is provided via separate fan-coil units.

A 2000-litre 2-pipe buffer tank is installed in the return from the underfloor heating. The pipework arrangement is such that if there were no demand for heat but the heat pump was running, there might be no water flow through the condenser. This could cause short-cycling of the heat pump, although there is no evidence of this happening.

A gas-fired boiler provides backup heat. Domestic hot water is provided separately via a solar thermal / gas-fired system.

The system is controlled by a building management system (BMS).

Figure 1 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output, and temperatures at key points in the system. The system boundaries for calculation of SPFH2 and SPFH4 are also shown.

Electricity meters (denoted by the circular "E" symbols) have been installed to measure the electricity used by the heat pump and by the circulating pumps. Temperatures ("T") are monitored at key points in the system using surface-mounted probes[2]. The ground, outdoor air and indoor air temperatures are also monitored.

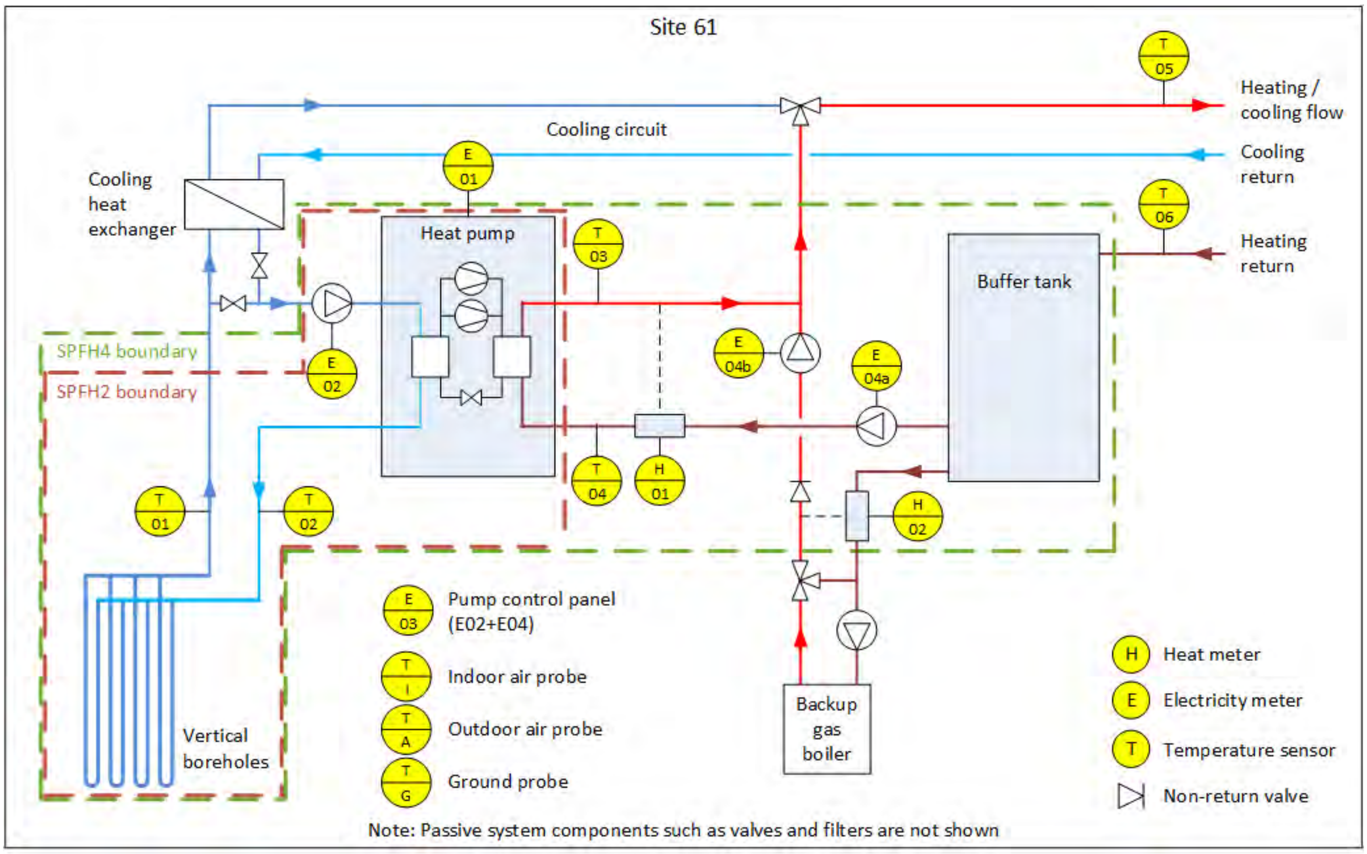

Figure 1 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meter previously installed to meet RHI metering requirements was used to measure the heat output of the heat pump. The heat meter on this system is installed between the heat pump and the buffer tank. It uses an ultrasonic flow meter installed in the return pipe, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator is mains-powered. Monitoring was via the M-Bus interface.

Note: the temperature probe in the flow pipe was found to be incorrectly installed using a made-up fitting that prevents the probe tip being properly immersed in the flow inside the pipe. This is very likely to introduce error

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[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

into the heat meter readings. It has therefore not been possible reliably to determine the performance of this system.

A second heat meter measures the output from the gas-fired backup boiler.

Electricity metering of the liquid pumps

It was discovered during data analysis that there was an error in the installation of the brine pump electricity monitor (E02): the current transformer was attached to the wrong phase of the circuit. The readings from this meter are therefore incorrect and cannot be used to determine the electricity used by the brine pump. However, the readings do indicate the times of operation of the pump.

Fortunately, the total supply to the brine pump + the heating circulating pump is measured by a separate electricity monitor (E03). The total electricity used by the heat pump system has therefore been measured correctly (E01 + E03). The electricity used by the brine pump and by the heating circulating pump has been estimated from the rating of each pump and from analysis of the 1-minute electrical power readings which indicate the operation of the pumps.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pump together with the source pump.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters (if used).

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU’s Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interface of the heat meter provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a “raw data” database. The raw data was subsequently processed by custom software to generate a “clean” database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meter was determined for each 1-minute interval and summed as for the electricity values.

$$\mathrm{SPF_{H2}} = \frac{\text{[Heat output of heat pump]}}{\text{Electricity used by: [heat pump] + [brine pump]}}$$

$$\mathrm{SPF_{H4}} = \frac{\text{[Heat output of heat pump]} - \text{[heat loss from buffer tank]} + \text{[heat added by heating circ pump]}}{\text{Electricity used by: [heat pump] + [brine pump] + [heating circulating pump]}}$$

- The heat added by the circulating pump was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pump.

- The heat loss from the buffer tank was estimated from published heat loss data for buffer tanks, using the measured flow and return temperatures at each calculation interval to determine the temperature in the tank and an assumed plant room temperature of 15 °C.

The number of 1-minute intervals selected as valid for analysis was 498 434, which represents 94.6% of the 12-month period. Intervals when the heat pump was operating in cooling mode were excluded.

SPF results presented as relative values

Because of the heat metering issues noted above, it has not been possible to determine the system performance with any useful degree of accuracy. The performance factors $\mathrm{SPF_{H2}}$ and $\mathrm{SPF_{H4}}$ are therefore presented in this case study as "relative" values, whereby each value is shown as an amount above or below a nominal performance.

Figure 2 shows the daily $\mathrm{SPF_{H2}}$ and $\mathrm{SPF_{H4}}$ behaviour of the system. The lower values during July and August were a consequence of the very low space heating load factor resulting in reduced system efficiency. The total heat delivered to space heating during the summer was very small, so the overall effect of the lower $\mathrm{SPF_{H4}}$ values is minimal.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

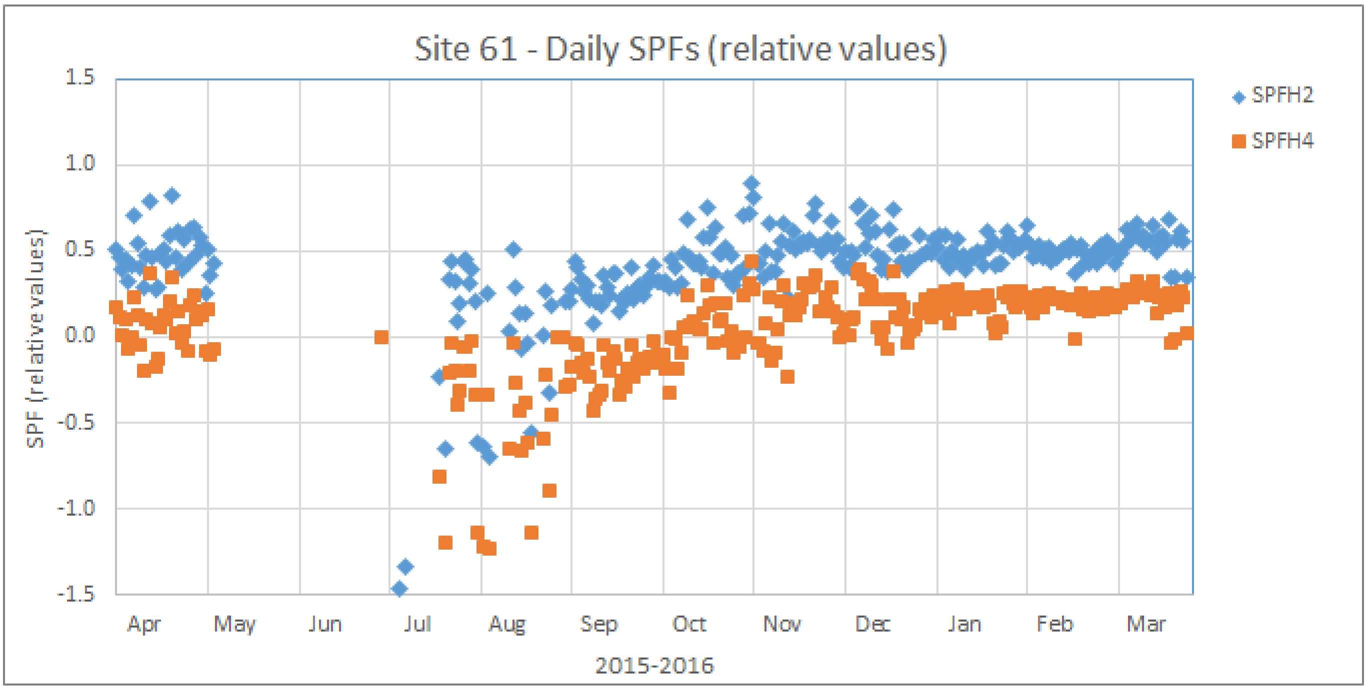

Figure 2 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the ground and the sink is the space being heated.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the ground and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump the brine through the ground collector, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required by the building depends on various factors, particularly the outdoor temperature.

Figure 3 shows the weekly heat output from the heat pump. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. The periods of cooling mode operation are indicated by the cyan-coloured vertical bars. Note that the kWh values have been removed from the graph because of the high uncertainty of measurement of the heat meters.

The heat provided to space heating varied with the outdoor air temperature. The backup gas-fired boiler was used during May and June because of a problem with the building management system.

The brine loop was used for cooling for several periods during July and August. The heat pump was not used during these periods.

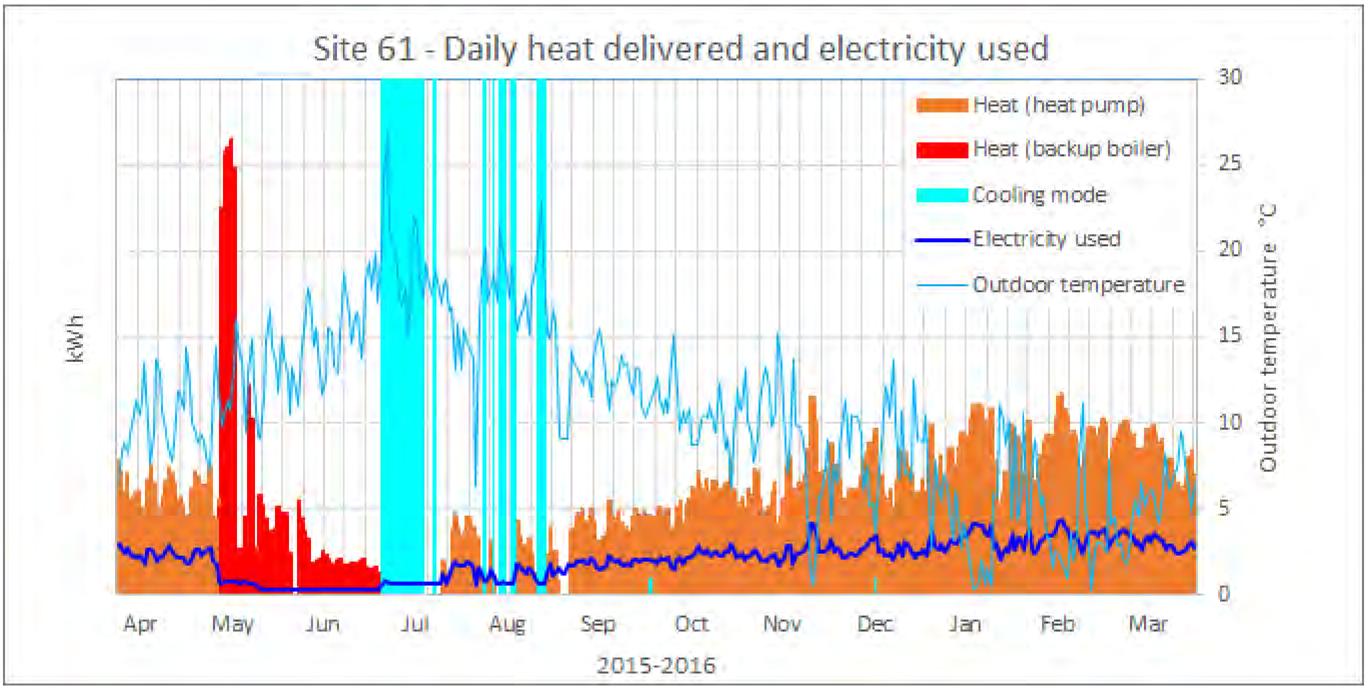

Figure 3 – Weekly heat delivered and electricity used by the total heat pump system

Breakdown of electricity use

Figure 4 shows the weekly breakdown of electricity use. The heat pump was not used during May and June (the backup gas-fired boiler was being used). Cooling mode operation has been excluded from the data presented.

The brine pump accounted for an estimated[5] 16.2% of the total electricity used, which was above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance.

---

[5] The sum of the electricity used by the brine + heating pumps was metered. The split between the pumps was estimated as described above.

The space heating circulating pumps used an estimated 14.3% of the total electricity. This was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%) and would have had a negative influence on the system performance.

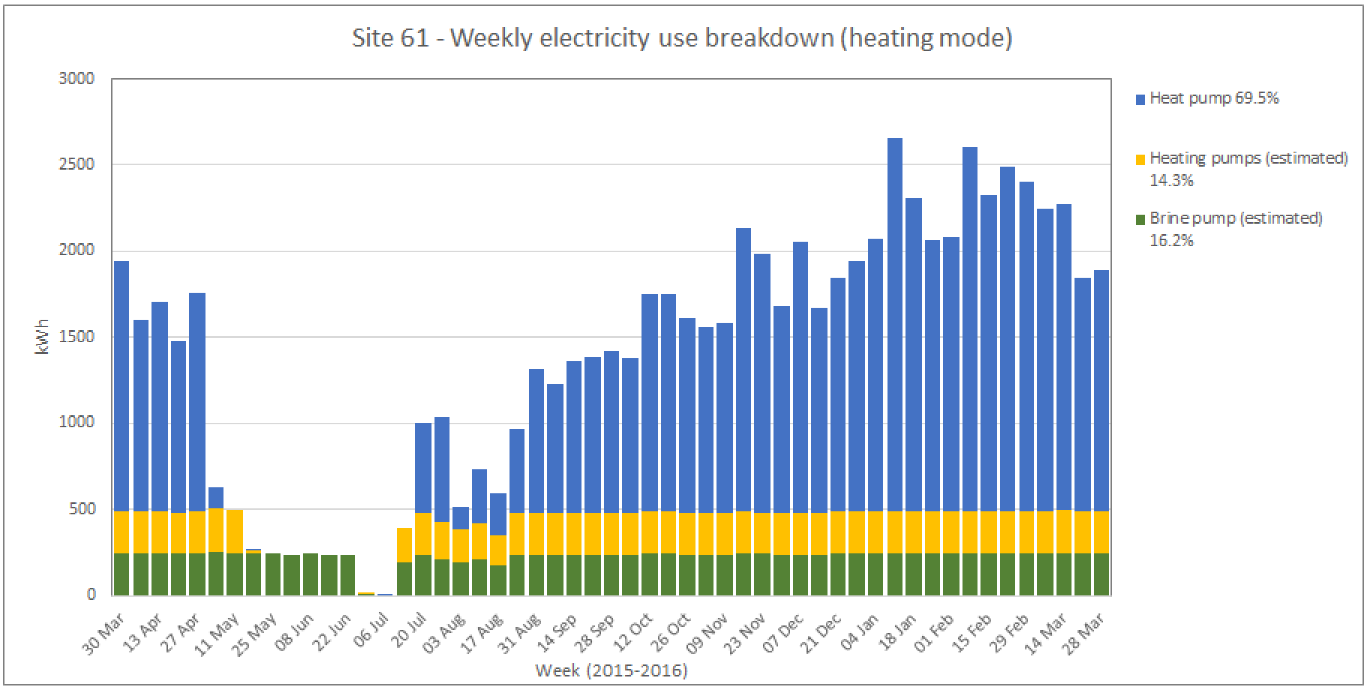

Figure 4 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 5 shows the operating pattern on 21st January 2016 when the outdoor temperature was between -4 and +4 °C

The brine pump and the space heating circulating pumps were running continuously all day.

The heat pump cycled on/off all day, approximately every hour. The longest run was for 2 hours, the shortest for 20 minutes. Both compressors were used during each run until 20:30, after which time only one compressor was needed – presumably because the outdoor temperature had risen, reducing the heating load.

The temperature of the heat pump output to space heating varied between 38 and 48 °C. The output temperature was highest when the outdoor temperature was lowest – indicating operation of the weather compensation function.

The temperature of the brine flow to the heat pump was between 2 and 4.5 °C.

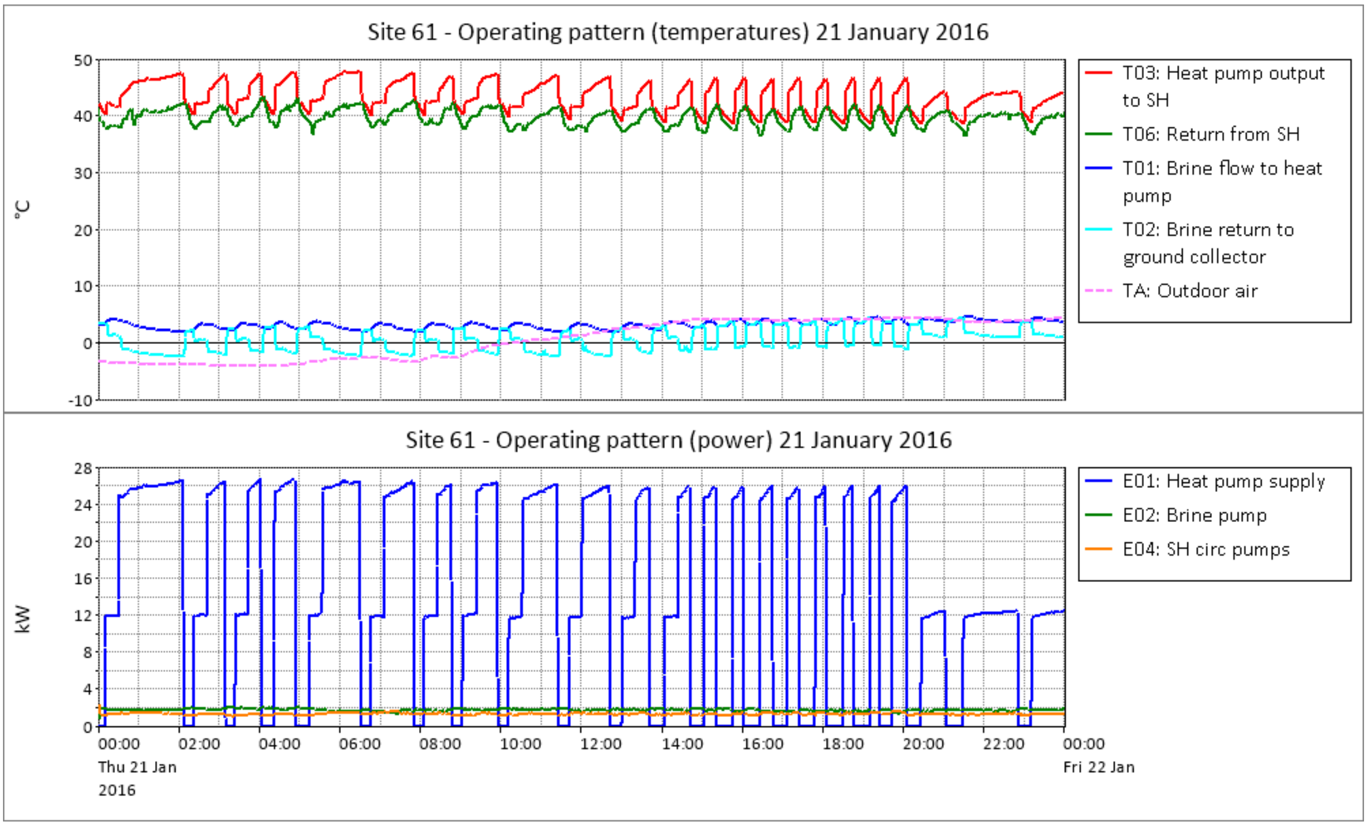

Figure 5 – Operating pattern on 21st January 2016

Figure 6 shows the operating pattern on 6th August 2015 when the outdoor temperature was between 13 and 27 °C. The indoor temperature was between 23 and 26 °C.

The brine pump and the space heating circulating pumps were running continuously all day.

The heat pump ran approximately every hour for 10 minutes during the early part of the day when the outdoor temperature was below 18 °C. Both compressors appear to have been used during each run. The cycling behaviour was well within the recommendations from previous research [4].

The heat pump was not used again during the day, and the cooling system operated from 19:00 to 20:30 with brine being pumped from the borehole loops through the plate heat exchanger.

The temperature of the brine flow to the heat pump was between 8 and 9 °C while the heat pump was running. During cooling mode operation, the temperature of the brine return to the ground collector was between 14 and 18 °C.

It is not known why cooling was required during a day when heat was also needed. The indoor air temperature, measured on the ground floor, did not increase towards the end of the day. However, it is possible that higher temperatures were reached elsewhere in the two-storey building.

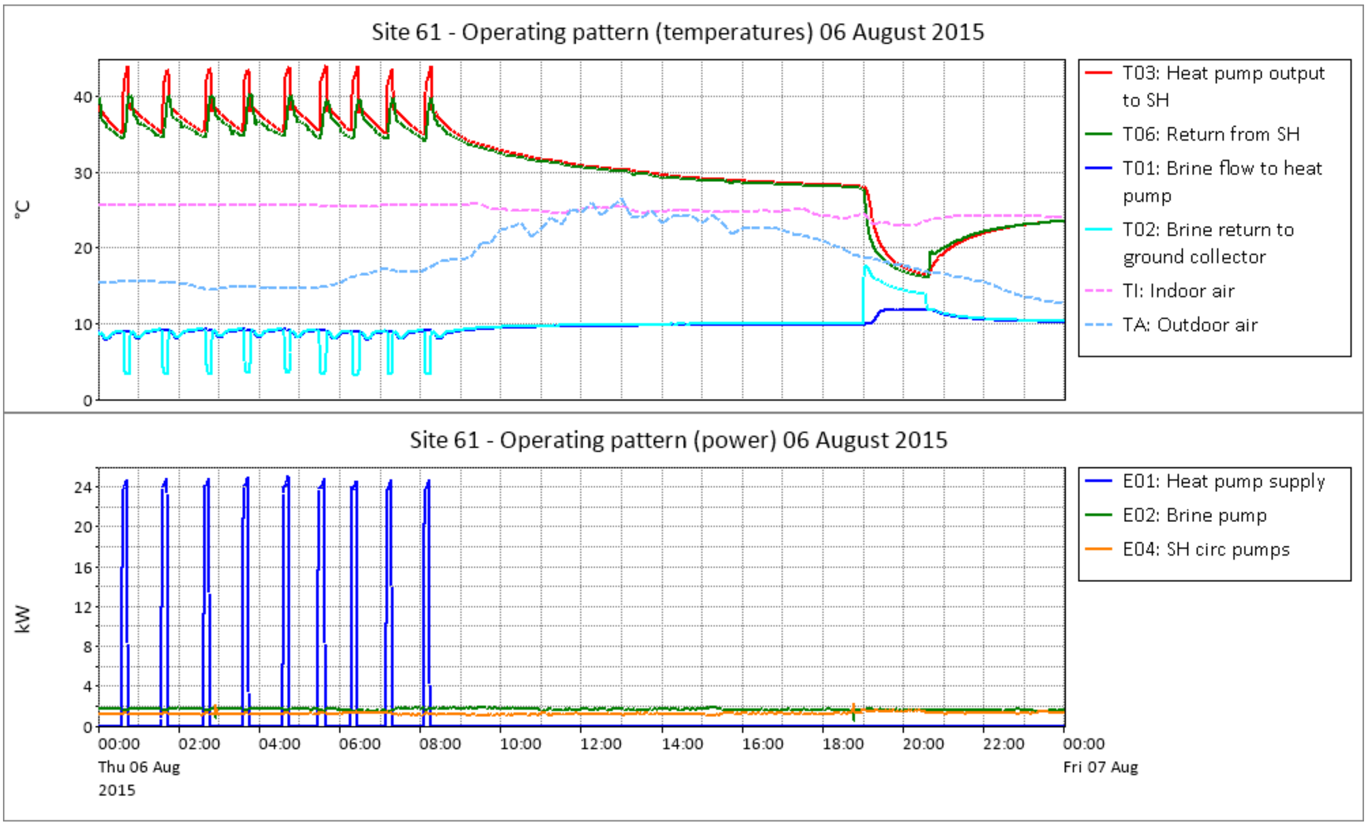

Figure 6 –Operating pattern on 6th August 2015

Source and sink temperatures

Figure 7 shows the principal temperatures of the ground, outdoor air, brine, output from the heat pump to space heating, and return via the buffer tank, plotted over the year[6]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The indoor air temperature on this site was high, usually between 23 and 26 °C. This is presumably because it is a residential care facility. No data was received from the indoor temperature sensor after 14th October.

The heat pump was not used between 7th May and 20th July. The brine circuit was used for cooling from 29th June to 15th July and for several shorter periods during July and August.

The output from the heat pump to space heating varied somewhat with outdoor temperature, presumably as a result of weather compensation: the daily maximum ranged from 43 °C in August to 48 °C in January.

The lowest temperature of the brine flow to the heat pump was 1.7 °C on 14th February. The maximum was 10.5 °C on 13th August.

The difference between the temperatures into and out of the buffer tank (which is in the return pipe) varied between -3 and +3 °C. Considering that the average temperature difference was approximately zero, it seems unlikely that this would have had a significant influence on overall performance.

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[6] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor and indoor temperatures were recorded every 15 minutes.

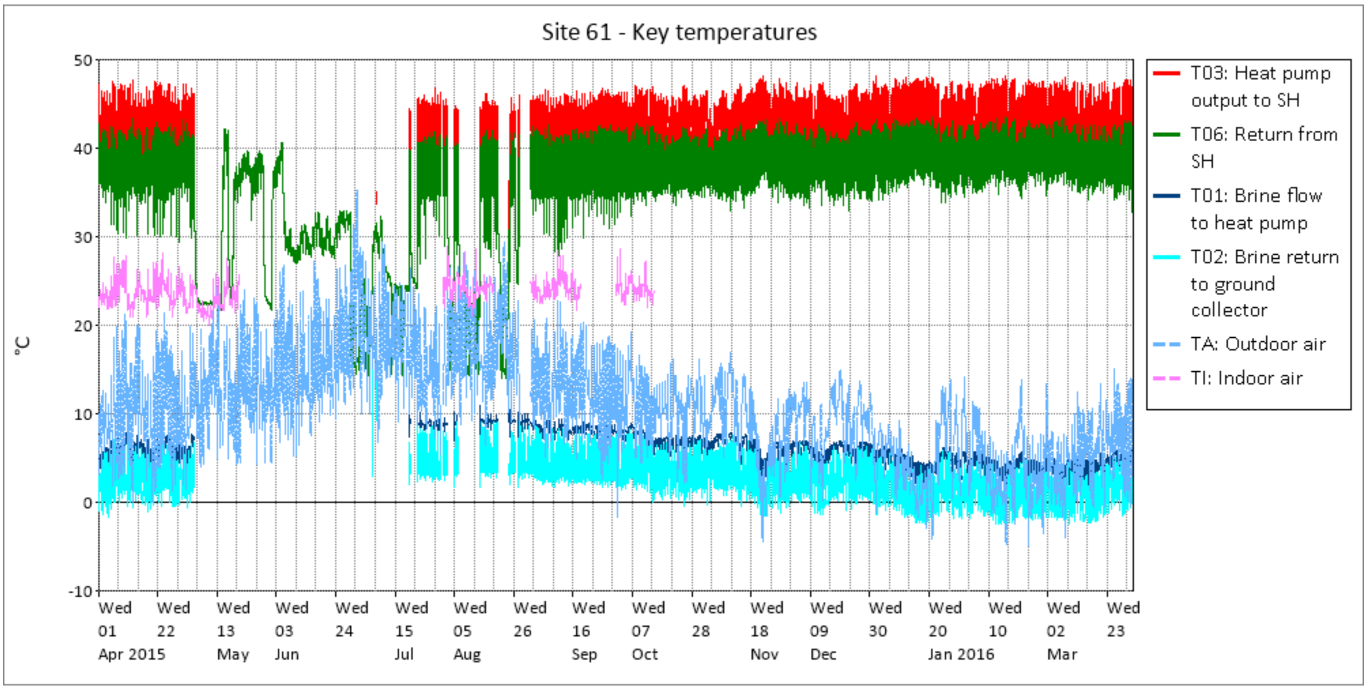

Figure 7 – Key temperatures measured during the period 1st April 2015 – 31st March 2016

Figure 8 shows the daily mean brine flow temperature compared to the source temperatures (at the heat pump) of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were average compared to other systems.

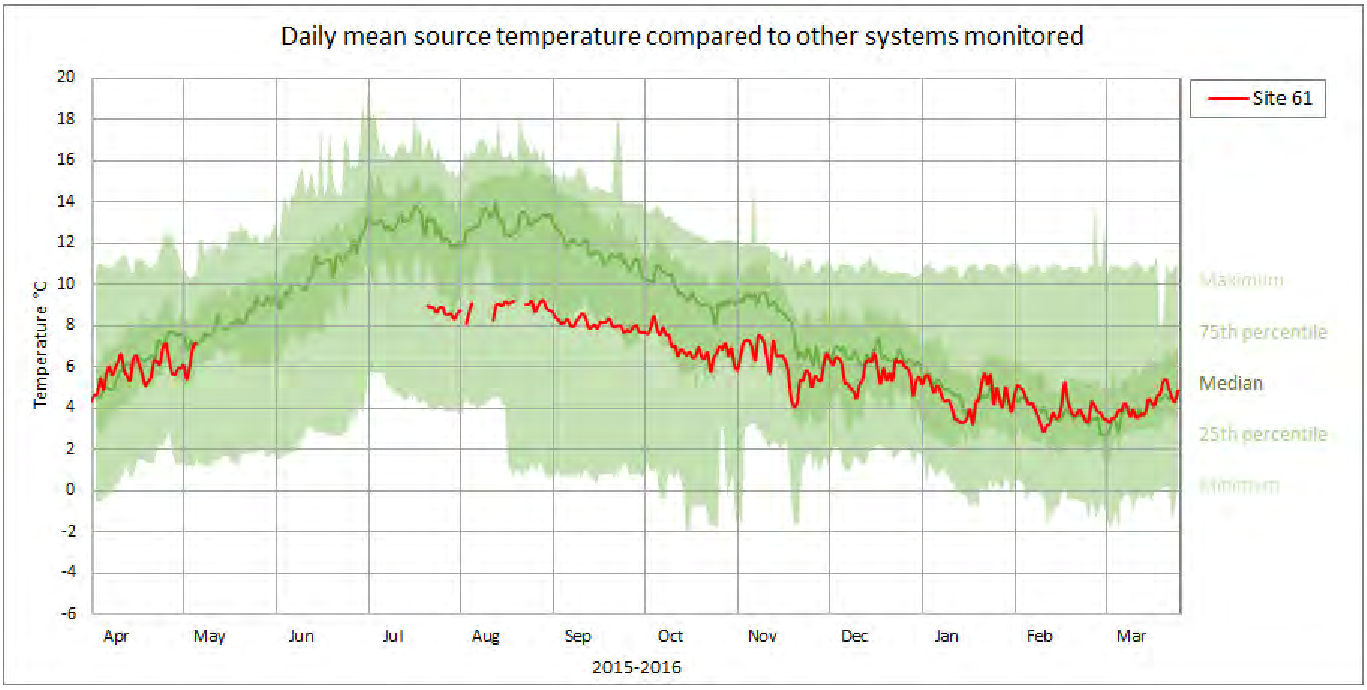

Figure 8 – Daily mean brine flow temperature compared to the source temperatures of other systems monitored in this project (site 61 is shown in red)

Figure 9 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were average compared to other systems.

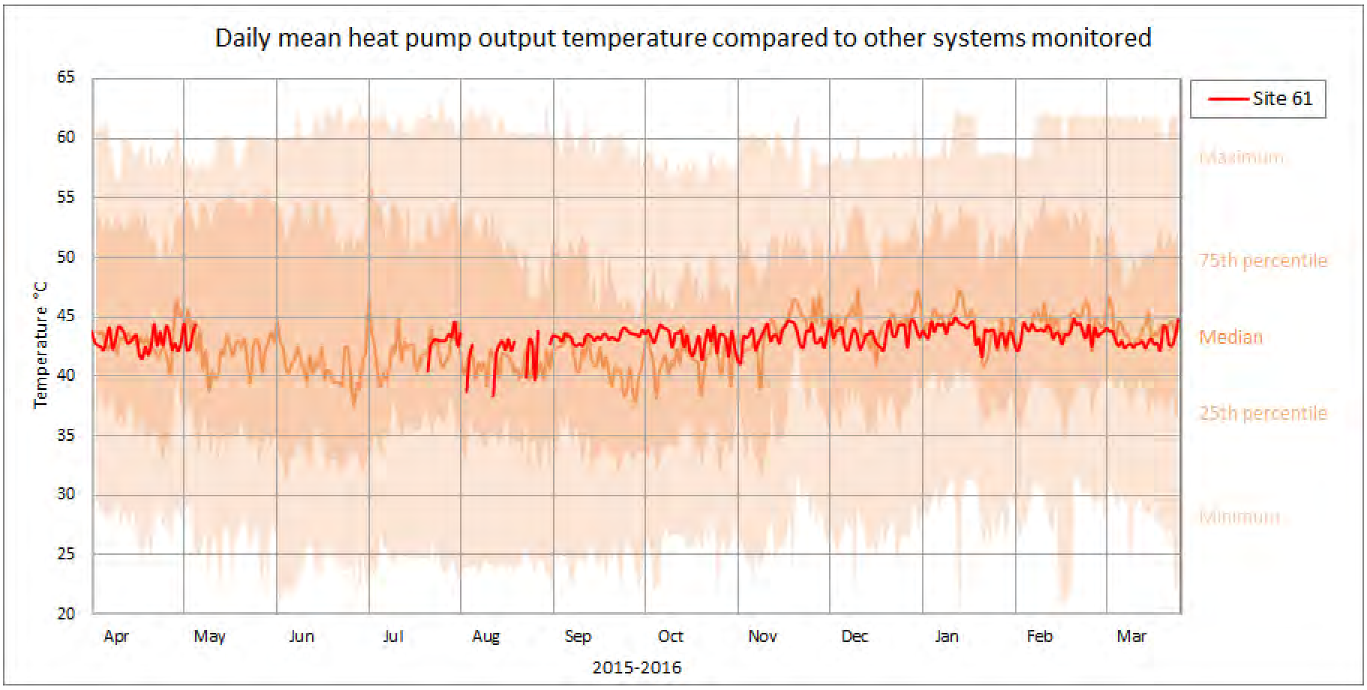

Figure 9 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 61 is shown in red)

Figure 10 shows the daily mean temperature of the system output to the underfloor heating pipes, compared to other underfloor heating systems monitored. The temperatures on this system were above average, which would have had a negative influence on system performance.

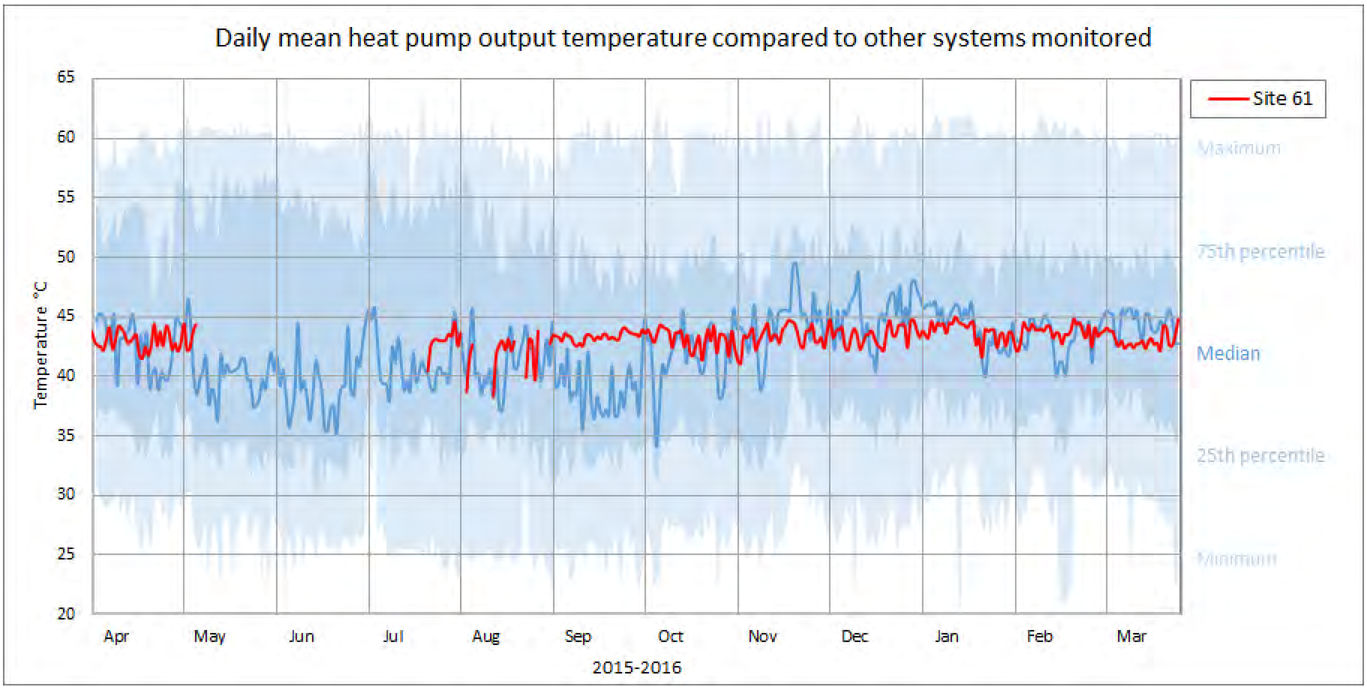

Figure 10 – Daily mean temperature of flow to underfloor heating compared to other underfloor heating systems monitored (site 61 is shown in red)

Comments

The performance of this system could not be determined with reliable accuracy because of known issues with the heat metering arrangement installed.

Aspects of this system that positively influenced its performance are:

- Weather compensation was used to reduce the heat pump output temperature when the outdoor temperature was higher.
- The source temperatures were reasonable – average compared to other systems monitored.
- The system was not used to provide domestic hot water.
- The heat pump operated using a simple strategy, and a good load factor was realised. In other words, the capacity of heat pump was well matched to the heating load of the building, allowing it to run for a high proportion of the time during the winter (up to 75% during the period monitored) with consequent efficient operation.
- No auxiliary electric heat was used. (Use of the backup gas-fired boiler for a period is understood to have been due to a fault in the building management system.)

Aspects of the system that may have negatively influenced its performance include:

- The brine pump accounted for an estimated 16.2% of the total electricity used, which was above average compared to other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance.
- The space heating circulating pumps used an estimated 14.3% of the total electricity. This was above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%) and would have had a negative influence on the system performance.
- Heating and cooling were observed to have occurred on some occasions during the same day. It would be worth investigating whether the control strategy could be altered to take better account of the high inertia of underfloor heating by stopping heating earlier in the day. This might help avoid the undesirable use of intra-day heating and cooling and would reduce overall electricity use.

Bibliography

[1] "Directive 2009/28/EC of the European Parliament and of the Council," Official Journal of the European Union, 2009.

[2] EA Technology, "The effects of cycling on heat pump performance," DECC, 2012.

[3] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.," EN 14511.

[4] D. Hughes, "Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps - Interim Report. URN 16D/013.," DECC, 2016.

[5] "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.," EN 14511-3.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps

Case Study – Site 62

Prepared by GRAHAM Energy Management
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January 2018

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Dr David Hughes asserts his moral right under the Copyright, Designs and Patents Act 1988 to be identified as the author of this work.

This case study has not considered the detailed design of the heat source or ground loop, sizing of the buffer vessel nor sizing (or nature) of the heat emitters. All of these factors are known to be critical to the overall performance of a heat pump. The data presented in this document should therefore not be taken as necessarily representing the performance of other installations using the conceptual designs described. No information has been presented on the suitability of the systems as to their intended purpose. Caution should be taken when extrapolating the data presented in this report to other applications.

Any enquiries regarding this publication should be sent to siceteateam@beis.gov.uk.

Contents

Executive summary

The in-service performance of 28 non-domestic Renewable Heat Incentive ground- and water-source heat pumps with a combined installed capacity of 1600 kW_{TH} has been monitored over at least one heating season from mid-2014 for the Department for Business, Energy and Industrial Strategy (former Department of Energy and Climate Change).

This case study provides a brief description of the heat pump installation at Site 62 and performance results from 12 consecutive months of monitoring data.

Site 62 is a large house with an outbuilding. A group of four heat pumps (total thermal capacity 268 kW) installed in the outbuilding extract heat from surface water to provide space heating and domestic hot water to the main house and to the outbuilding.

There were operational difficulties following storm damage to some of the equipment during the monitoring period that affected the system performance.

The seasonal heating performance factors measured over a year of operation
(1st April 2015 to 31st March 2016) were:

SPF_{H2}	[Heat delivered by the heat pumps] -- Electricity used by: [heat pumps] + [brine pumps] + [source water pumps]	2.62
SPF_{H4}	[Heat delivered by heat pumps] + [heat added by buffer pumps] + [heat added by heating circ pumps] – [heat loss from buffer tanks and underground pipes] + [heat from immersion heaters] -- Electricity used by: [heat pumps] + [brine pumps] + [source water pumps] + [heating circulating pumps] + [immersion heaters]	1.98

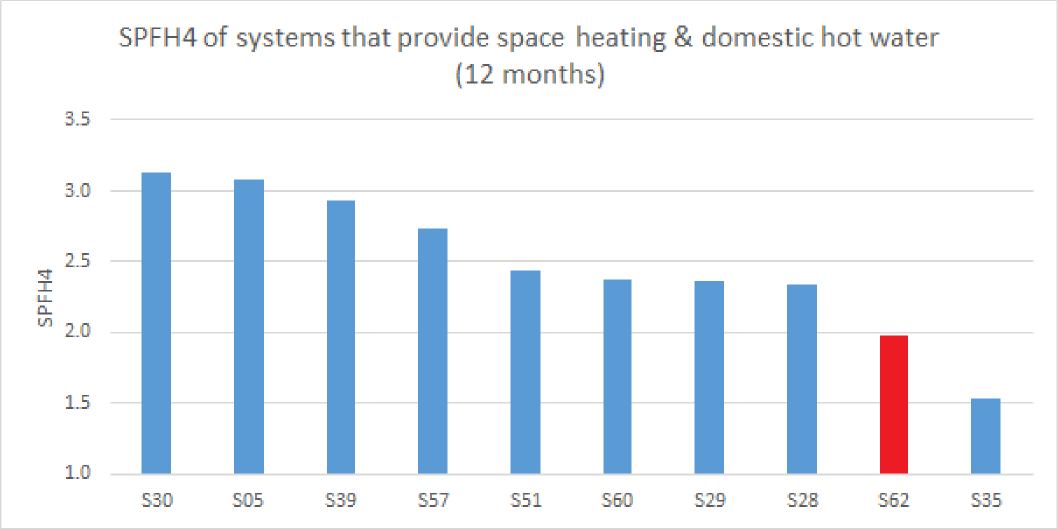

Figure 1 – Performance of this system compared to other installations in the monitored sample that provide space heating and domestic hot water

Aspects of this system that positively influenced its performance are:

- The source temperature was generally above average compared to other systems monitored.

Aspects of the system that may have negatively influenced its performance include:

- The output temperature from the heat pumps was generally very high compared to most other systems monitored. This was partly due to the use of radiators originally installed for use with an oil-fired boiler and the relatively poor insulation in the 18th century buildings, but also to the system design requiring high temperatures at all times to provide domestic hot water via the common heat pump output circuit.

- Approximately 12% of the heat output of the heat pumps was lost from the heat distribution system that includes a 125-metre underground pipe run to the main house.
- The source water pumps and brine pumps accounted for 13% of the total electricity used by the heat pump system. This is high compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The buffer pumps and space heating circulating pumps together used 10.3% of the total system electricity. This is above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).
- The domestic hot water immersion heaters used 5% of total system electricity. This is above average compared to other systems monitored.
- There is an apparent problem with the control strategy in that all four heat pumps are often operated together under low load conditions, when one or two heat pumps would suffice. Starting all four heat pumps for short runs will have a negative influence on system performance and will result in excessive wear and tear on the equipment.
- The LPG-fired boiler was used extensively during the monitoring because of problems resulting from storm damage to parts of the installation.
- Weather compensation was not used because of the common output to space heating and domestic hot water.

Glossary

Auxiliary heat	Additional heat sources which are part of the heat pump system and which supplement the output of the heat pump vapour compression cycle
Brine	A water-glycol (antifreeze) mixture used for transferring heat at low temperature
DHW	Domestic hot water
EPC	Energy Performance Certificate
GSHP	Ground-source heat pump
kW	Kilowatt – measurement of power (electrical or thermal)
kWh	Kilowatt-hour – measurement of energy (electrical or thermal)
kWh_{TH}	Kilowatt-hour (thermal)
MCS	Microgeneration Certification Scheme
Pulse	An electrical pulse, typically the momentary closing of a circuit, used by an energy or flow meter as an output signal to indicate that a certain quantity of energy or fluid has been measured
RHI	Renewable Heat Incentive
SEPEMO	SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector – see http://sepemo.ehpa.org/
SH	Space heating
SPF	Seasonal performance factor: the ratio of [thermal energy delivered] to [electrical energy used], usually calculated over a year
SPF_{H2}	SPF (in heating mode) of the heat pump, taking into account the energy used by the heat source pump(s) (but excluding auxiliary heaters and the pumps needed to deliver the heat to the sink)
SPF_{H4}	SPF (in heating mode) of the total heat pump system, taking into account all auxiliary pumps and heaters
SQL	Structured Query Language: a programming language designed for managing data held in a relational database management system
Temperature lift	The difference between the source (input) temperature and the sink (output) temperature, measured at the heat pump
Weather compensation	A control mechanism that reduces the temperature of the water circulated to heat emitters as the outdoor temperature increases
WSHP	Water-source heat pump

System details

Site ID	62
Survey date	25/02/2015
Monitoring installed	28/03/2015
G/WSHP	WSHP
Building type	Large house and outbuilding
Location	Rural
Heat pump capacity kWTH	268 (total)
Number of heat pumps	4
Number of compressors	4
Heat source	Open water
Heat emitters	Radiators
DHW	Yes
Auxiliary heat	Immersion heaters in DHW cylinders LPG-fired boiler (backup duty)
Source pumps	2 water pumps of 5.5 kW max (variable-speed) 2 brine pumps of 11 kW max (variable-speed)
Buffer pumps	4 pumps of 600 W max (variable-speed)
SH circulating pumps	1 dual pumpset (duty/standby) of 1.3 kW max (variable-speed) 1 dual pumpset (duty/standby) of 1 kW max (variable-speed)
Buffer tanks	2 x 1000 litre 4-pipe (heat pumps) 1 x 1000 litre 4-pipe (boiler)
DHW cylinders	1 x 500 litre 1 x 300 litre
Control	BMS
Weather compensation	Yes
Heat meter type	Ultrasonic
No. of heat meters	4
Heat meter interface	M-Bus (3 meters); pulse (meter on boiler)
Comments	

Table 1 – System details

Site 62 is a large 18th century house and a substantial outbuilding, situated in a rural location.

This application entails extracting heat from surface water to provide space heating and domestic hot water to buildings that are not well insulated, in a location with above-average outdoor temperatures (the mean outdoor temperature at the site during the period monitored was 11.5 °C. The range for all sites was 8.1 – 12.6 °C, median 10.5 °C). Heat to the main house is provided via a lengthy underground pipe. The design performance of the system would be expected to be below average.

Heat pump and monitoring systems

A group of four heat pumps (total thermal capacity 268 kW) installed in the outbuilding provide space heating and domestic hot water to the main house and to the outbuilding.

The heat source is surface water, pumped through a plate heat exchanger to transfer heat to brine circulated through the heat pump evaporators. The heat exchanger and the source water pumps are located in a small plant room beside the water source, approximately 120 metres from the heat pump plant room.

Three 1000-litre 4-pipe buffer tanks are installed in the heat pump plant room. Two of these are connected to the heat pumps; the third one is used with the backup LPG-fired boiler.

Hot water from the buffer tanks is circulated to the heating circuits in the outbuilding, and to the main house via an underground heating main comprised of polymer pre-insulated pipe approximately 125 metres in length.

The heat emitters are radiators that were originally sized for an oil-fired heating system.

Domestic hot water is provided via two domestic hot water cylinders: one in the heat pump plant room (300 litres) to service the outbuilding, the other in the main house plant room (500 litres). Each of these domestic hot water cylinders is heated indirectly using the hot water from the heat pump. Two immersion heaters in each domestic hot water cylinder provide auxiliary heat if needed. (The immersion heaters in the main house domestic hot water cylinder were switched off[1] during the monitoring period.)

Legionella control is provided by ultraviolet lamp disinfection units: one at the outlet of each domestic hot water cylinder. This avoids the need to raise the temperature in the domestic hot water cylinders above 60 °C.

The system is controlled by a building management system (BMS).

Backup boiler

The LPG-fired boiler is intended for backup duty only and not normally to be run at the same time as the heat pumps. During the monitoring period, there were exceptional operational difficulties that required the boiler to be used for extended periods. However, the system has not been analysed as a bivalent system as that is not how it is intended to operate.

Figure 2 shows the schematic arrangement of the heat pump installation and the placement of the sensors installed for monitoring electricity use, heat output, and temperatures at key points in the system. The system boundaries for calculation of SPF_{H2} and SPF_{H4} are also shown.

Electricity meters (denoted by the circular “E” symbols) have been installed to measure the electricity used by the heat pump, the circulating pumps and the immersion heaters. Temperatures (“T”) are monitored at key points in the system using surface-mounted probes[2]. The ground, outdoor air and indoor air temperatures are also monitored.

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[1] This was confirmed by the proprietor.

[2] The temperature probes used for monitoring were surface-mounted using a laboratory-validated technique. See Appendix I of the interim report for this project [4] for further details. Note that these temperature measurements were not used for heat metering.

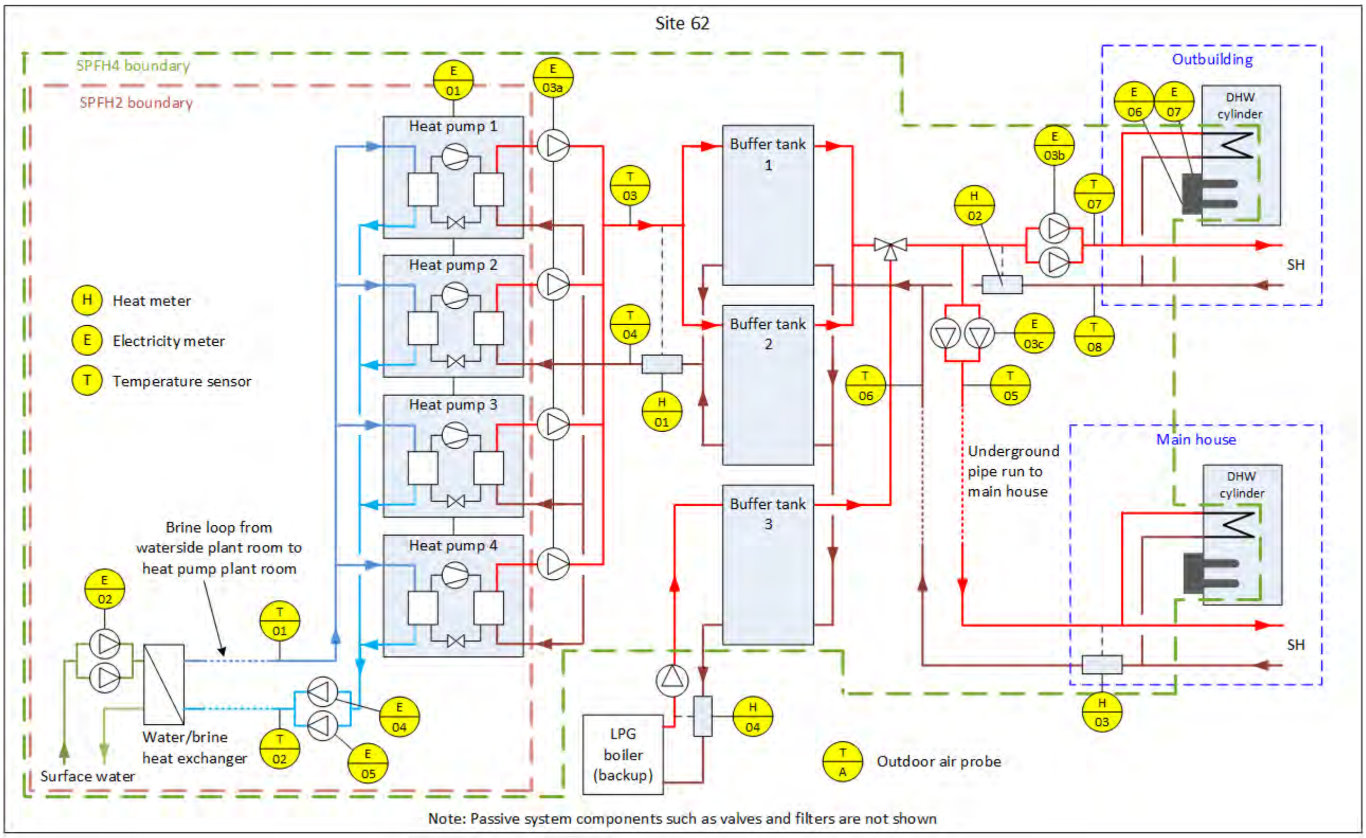

Figure 2 – System schematic showing the monitoring instrumentation installed

Heat metering

The heat meters previously installed to meet RHI metering requirements were used to measure the heat output of the heat pumps. Four heat meters are installed: H01 between the heat pumps and the buffer tanks measures the output from the heat pumps; H02 measures the heat delivered to the outbuilding; H03 measures the heat delivered to the main house; H04 measures the output from the backup boiler.

The heat meters use ultrasonic flow meters installed in the return pipes, with matched temperature sensors installed in fittings with the probes inside the flow and return pipes. The calculator of H01 is mains-powered with 1-minute monitoring via the M-Bus interface. H02 and H03 are battery-powered with monitoring every hour via the M-Bus interfaces. H04 uses a battery-powered calculator with monitoring every 5 minutes via the pulse interface.

Operational problems

There were some operational problems with this system during the monitoring period which have led to the system performance being lower than would otherwise be expected.

In October 2015, there was a heavy rain storm that caused flooding damage to the electricity supply system and to the inverters and source water pumps. Consequently, the heat pumps could not be operated and the backup LPG-fired boiler had to be used for much of the period until March 2016.

It is also understood that there were some difficulties caused by preventive maintenance of filters not being carried out correctly. This also resulted in pumps not working correctly.

Performance results

The performance of the systems monitored in this project is presented in terms of the Seasonal Performance Factor (SPF).

The SPF is a measure of average heat pump performance over time as external temperature and heat demand changes. It represents the ratio of total heat output to total electrical input at different system boundaries (denoted by SPF_{H1}, SPF_{H2}, etc., with a higher number indicating a wider system boundary with more ancillary electrical equipment taken into account).

Two system boundaries have been considered for calculation of SPF:

- SPF_{H2} represents the performance of the heat pumps together with the source pumps.
- SPF_{H4} represents the performance of the complete system, including all auxiliary pumps and heaters and allowing for heat losses from the buffer tanks and heat distribution pipework.

Heat pumps achieving an SPF_{H2} of 2.5 or more are considered as producing renewable energy under the EU's Renewable Energy Directive [1].

Data analysis

Readings of cumulative electrical energy and instantaneous power were recorded from the electricity meters at 1-minute intervals. The M-Bus interfaces of the heat meters provided readings of total energy, flow and return temperatures, temperature difference, flow rate and thermal power at 1-minute intervals. Readings from the battery-powered temperature sensors and the pulse counter connected to the boiler heat meter were recorded every 2 minutes.

Data was transmitted securely from the monitoring system via the cellular network and the Internet to a data server, where it was recorded in a "raw data" database. The raw data was subsequently processed by custom software to generate a "clean" database of readings from all sensors at 1-minute intervals. Linear interpolation was used to generate the 1-minute temperature and pulse count values from the raw 2-minute data.

The clean data generation process incorporated screening to ensure that each value was within the expected range: out-of-range readings were discarded. Temperature sensor calibration adjustments were also applied at this stage. The clean data was transferred to a Microsoft SQL Server® database for analysis using SQL[3] procedures tailored to suit this heat pump system.

The SPF values were calculated as follows:

- The electrical energy used by the heat pump and the circulating pumps was determined for each 1-minute interval. These values were summed to generate daily, weekly and annual totals.

- The heat output recorded by the heat meters was determined for each 1-minute interval and summed as for the electricity values.

$$SPF_{H2} = \frac{\text{[Heat measured by heat meter } H_{01}\text{]} - \text{[heat added by buffer pumps]}}{\text{Electricity used by: [heat pumps] + [brine pumps] + [source water pumps]}}$$

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[3] Structured Query Language: a programming language used for managing data held in a relational database management system.

$$SPF_{H4} = \frac{\begin{array}{c}\text{[Heat measured by heat meter } H_{01}\text{] + [heat added by buffer \& SH circ pumps]} \\ \text{– [heat loss from buffer tanks and pipework] + [heat added by immersion heaters]}\end{array}}{\begin{array}{c}\text{Electricity used by: [heat pumps] + [source water pumps] + [brine pumps]} \\ \text{+ [buffer \& SH circ pumps] + [immersion heaters]}\end{array}}$$

- The heat added by the buffer pumps and space heating circulating pumps was estimated as 30% (the assumed pump efficiency[4]) of the electrical energy supplied to the pumps.

- The heat loss from the heat distribution system (buffer tanks and pipework between the heat pumps and the heat meters in the main house and the outbuilding) was calculated using a simple heat loss model based on the measured heating circuit temperatures and the outdoor air temperature. The empirical coefficient used in this model was validated using readings from the heat meters and is such that the total calculated heat loss during the monitoring period is the same as that measured by the heat meters.

$$\text{Heat loss from buffer tanks \& pipes} = (((T_{05} + T_{06}) / 2) – T_{A}) * 0.260 \text{ kW}$$

The number of 1-minute intervals selected as valid for analysis was 523 065, which represents 99.2% of the 12-month period.

The SPF_{H2} and SPF_{H4} values for this system, measured between 1st April 2015 and 31st March 2016, are shown in Table 2.

SPF_{H2}	2.62
SPF_{H4}	1.98

Table 2 – SPF values measured for the period 1st April 2015 to 31st March 2016

This means that for each unit of electricity used, this system delivers on average 1.98 units of heat – whereas a direct electric heater would deliver only one unit of heat for each unit of electricity.

Figure 3 shows the daily SPF_{H2} and SPF_{H4} values for the heat pump system. Note that the heat provided by the LPG boiler is not included in the calculation of these values.

The SPF_{H4} values are considerably lower than SPF_{H2}. This is a consequence of the heat loss from the heat distribution system, the relatively high pumping power used by the space heating circulating pumps and the fairly high use of the domestic hot water immersion heaters.

The very low SPF_{H4} values during August, September and October were due to higher than usual use of the immersion heaters and to the circulating pumps running when there was a low space heating load – presumably to supply hot water to the domestic hot water cylinder in the main house. On some days, the SPF_{H4} was below 1.0. This is unusual, but was due to the heat losses from the distribution system and to the electricity used by the heat pumps and circulating pumps then being greater than the heat delivered to the heat emitters.

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[4] A pump works by transferring energy from electricity (supplied to the pump motor) to the water being pumped. The energy is transferred mainly as kinetic energy to move the water through the pipe. However, all the energy transferred ultimately ends up as heat – mainly into the water. The proportion of the electrical energy that is transferred to the water is related to the pump efficiency. For the calculations used in this analysis, the pump efficiency has been taken as 30% – the figure used in EN 14511-3 [5] – and it has been assumed that the proportion of energy transferred to the water is also 30%. While this figure is unlikely to be correct for every pump, a sensitivity analysis has shown that the effect of assuming a higher energy transfer to the water of, say, 50% of the electrical energy (rather than 30%) has only a minor effect on the calculated system performance of typically less than 1% (depending on the number, size and placement of pumps in the system being considered).

The high SPFH2 values in September/October were due to the heat pumps operating with lower than usual temperature lift.

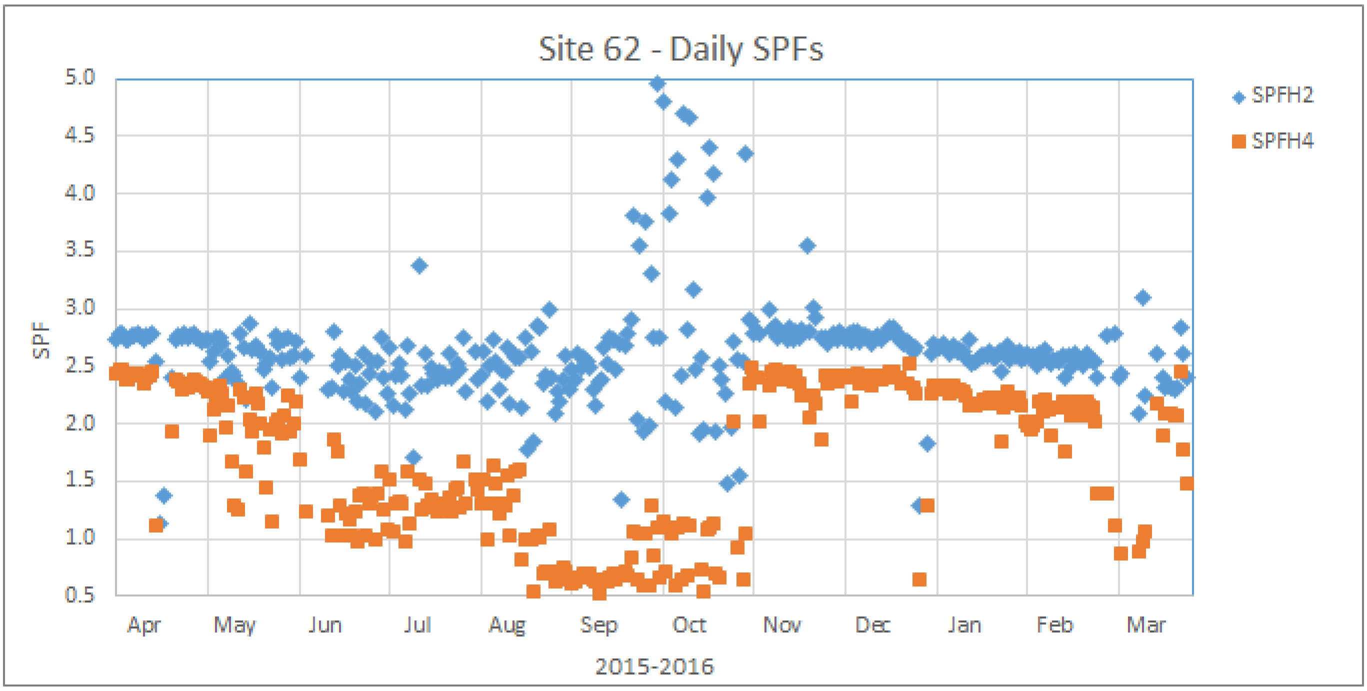


Figure 3 – Seasonal performance factors SPFH2 and SPFH4 calculated daily

Factors that influence performance

Temperature lift

The main factor that influences the performance of a heat pump is the difference between the temperature of the cold source at the input to the heat pump and the temperature of the hot output from the heat pump – referred to as the "temperature lift". In theory, and generally in practice, performance is best when the temperature lift is lowest. Therefore, it is desirable for the source temperature to be as high as possible and for the output temperature to be as low as possible.

For this system, the source from which heat is being extracted is the open water and the sink is the space being heated and the domestic hot water.

Heat extraction from the source to the heat pump is via a brine circuit. The brine will always be colder than the source, because a temperature difference between the source water and the brine is needed to transfer the heat.

Heat delivery from the heat pump to the heated space is via a hot water circuit. Again, this water will always be warmer than the space because of the need for a temperature difference to transfer the heat.

An objective of good system design and operation should be to maximise the temperature of the brine at the input to the heat pump, and to minimise the temperature at the heat pump output.

Ancillary equipment

Pumps are needed to pump water and brine through the water/brine heat exchanger, and to circulate the hot water from the heat pump via the buffer tank to the heat emitters in the building. These pumps use electricity, which can be a significant part of the total electricity used by the system.

Immersion heaters are installed in the domestic hot water cylinders to provide auxiliary heat if needed.

It is desirable to minimise the electricity used by ancillary equipment.

Cycling

A heat pump will usually cycle on and off a number of times each day, depending on the heat demand. The number and length of the run times will tend to reduce during warmer weather because of the reduced heat demand.

Previous research [2] recommended that systems be designed to achieve a minimum run time of circa 6 minutes under all conditions, to avoid the worst excesses of performance impairment due to short cycling.

Variation of heat demand with outdoor temperature

The amount of heat required for the buildings depends on various factors, particularly the outdoor temperature.

Figure 4 shows the daily heat output from the heat pump, the LPG-fired boiler and the domestic hot water immersion heaters. The electricity used by the total heat pump system and the outdoor air temperature are shown for reference. Note that the heat from the heat pumps, boiler and immersion heaters is presented as a stacked bar graph.

There was demand for heat every week. The total heat delivered apparently did not depend only on the outdoor temperature, as the lowest heat demand was not coincident with the maximum outdoor temperature. It is probable that the occupancy of the premises varied throughout the year, causing variation in the demand for both space heating and domestic hot water.

It is notable that the use of the domestic hot water immersion heaters varied throughout the year. This suggests that a variation in demand for domestic hot water required additional heat from the immersion heaters, especially during the summer when the output temperature of the heat pumps was lower than at other times, because of reduced demand for space heating.

The extensive use of the backup boiler following the storm damage can be seen from October.

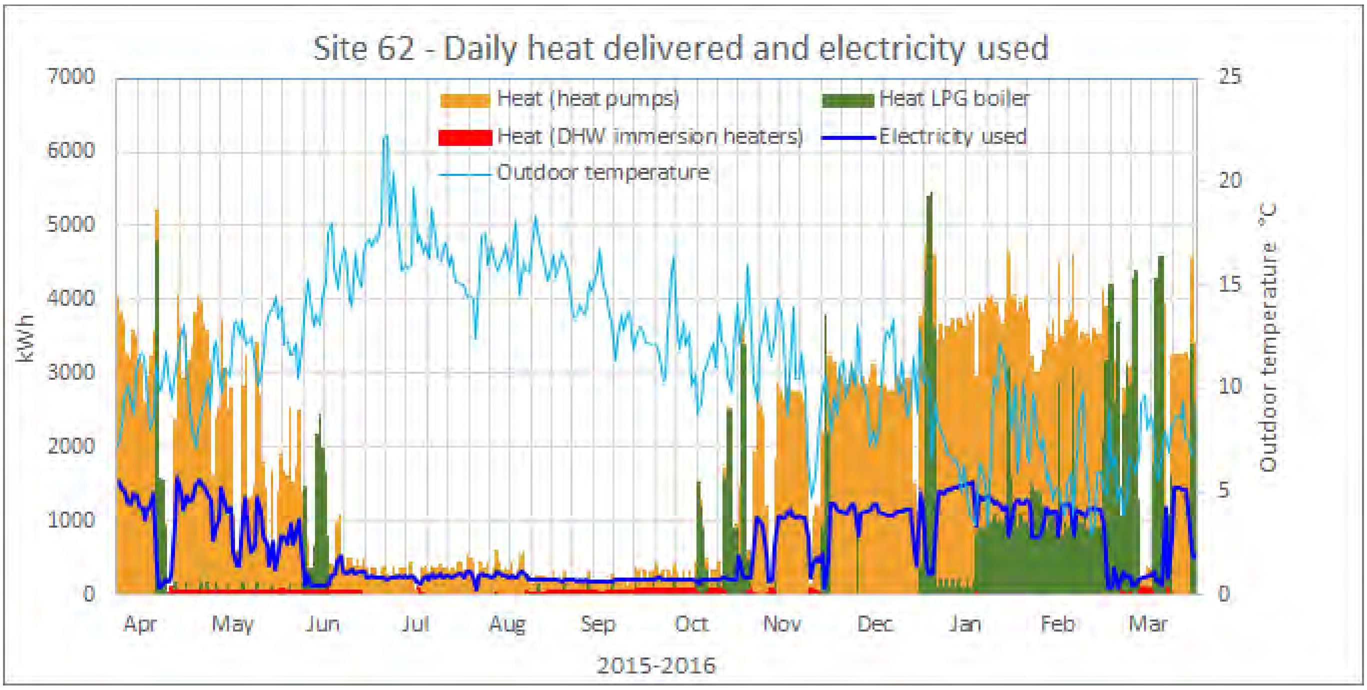


Figure 4 – Daily heat delivered and electricity used by the total heat pump system

Breakdown of heat delivered

It was not possible to determine a breakdown of the heat delivery to space heating and domestic hot water on this system.

Breakdown of electricity use

Figure 5 shows the weekly breakdown of electricity use.

The source water pumps and the brine pumps together accounted for 13% of the electricity used by the total heat pump system, which is above average compared to the source pumps of other systems monitored (range 2.3% - 29.8%, median 7.6%). This would have had a negative influence on the system performance.

The buffer pumps and the heating circulating pumps together used 10.3% of the total electricity used by the system, which is above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%). This would have had a small negative influence on the system performance.

The domestic hot water immersion heaters used 5% of the total electricity. This is above average compared to other systems monitored (range 0% - 27.6%, median 0.0%) and would have had a negative influence on the system performance.

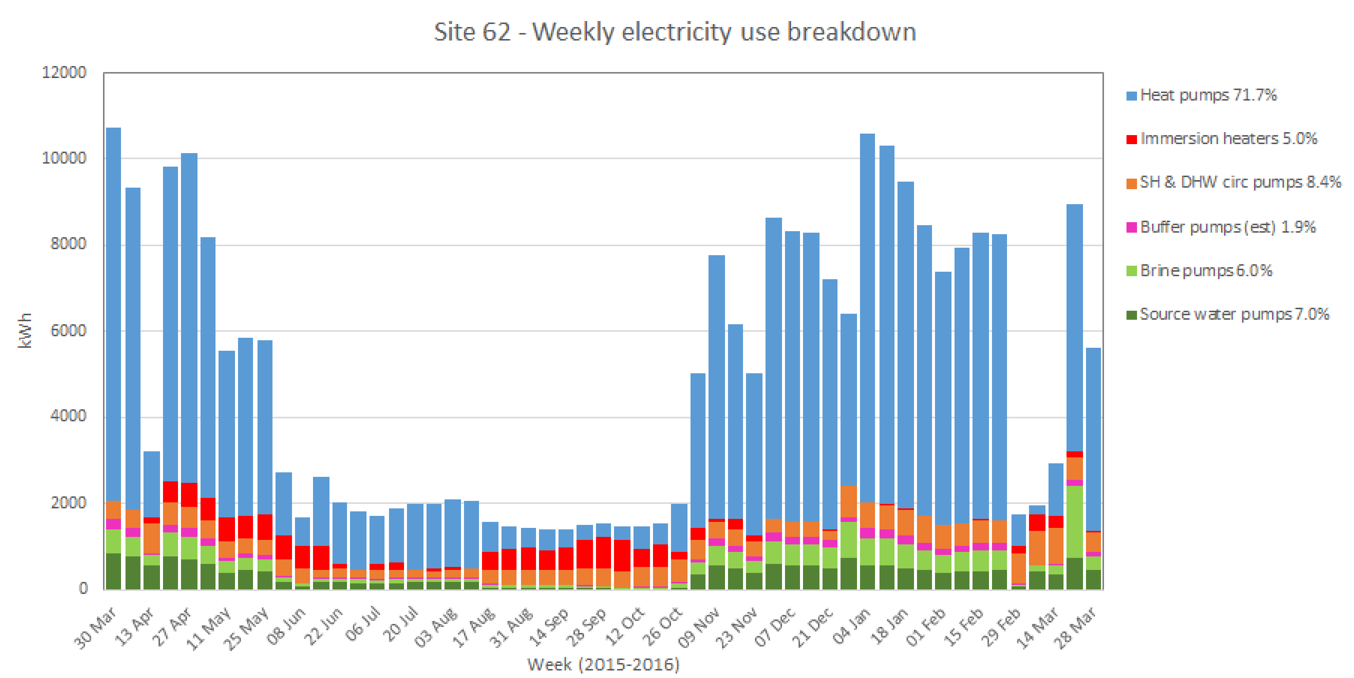


Figure 5 – Weekly electricity use breakdown

Operating pattern

To help understand the day-to-day operation of the system, it is useful to examine the detailed temperature and power data recorded during typical high-load winter operation and during light-load operation in warmer weather.

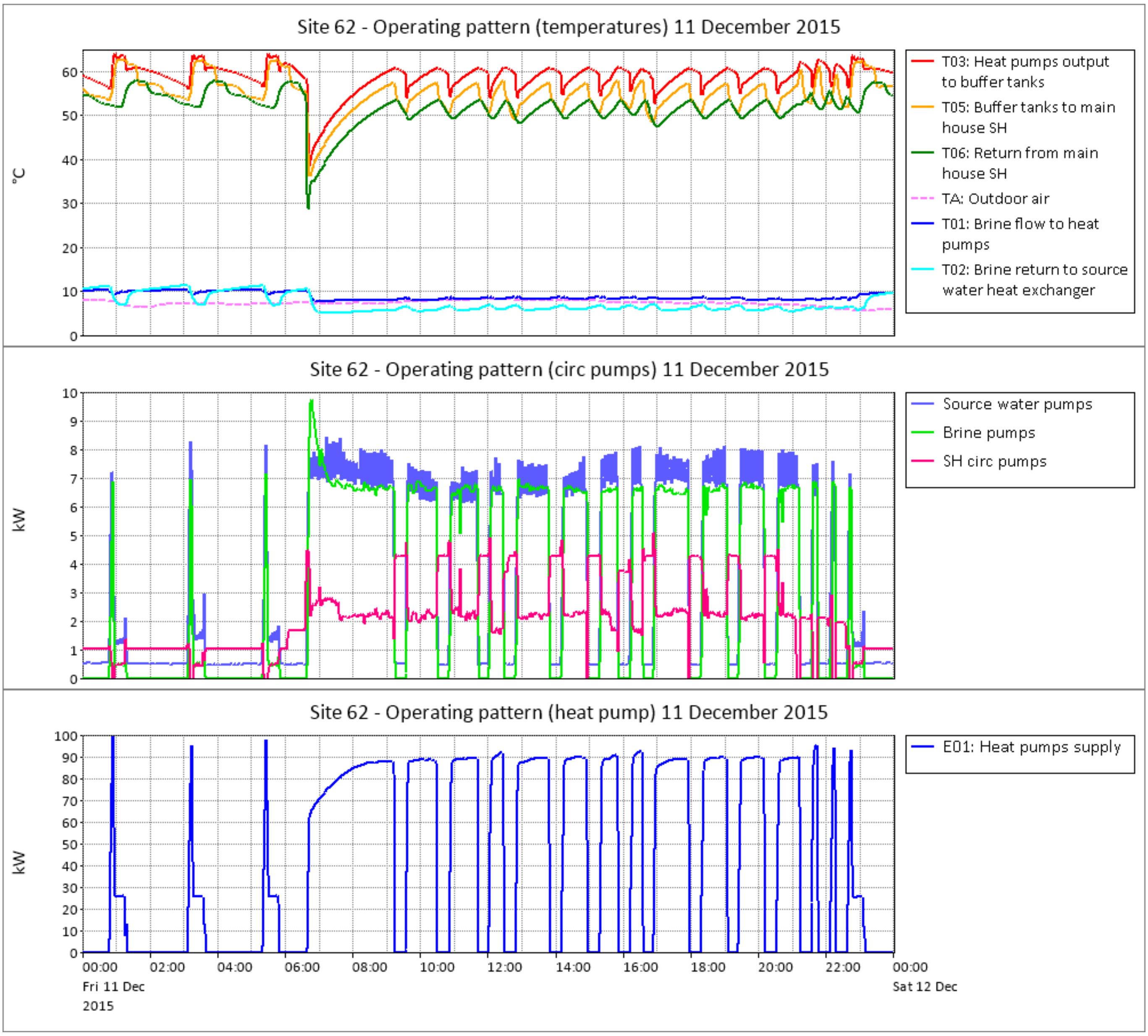
The graphs presented below show the key temperatures of the system and the electrical power drawn by the heat pump, circulating pumps and immersion heaters. The heat pump operating cycles are indicated by the heat pump supply power graph.

Figure 6 shows the operating pattern on 11th December when the outdoor temperature was between 6 and 8 °C. The heat pumps operated for three short runs of approximately 40 minutes during the early part of the day. On each run, it appears that all four heat pumps started and ran for a few minutes, with all but one then stopping again. These very short runs are probably unnecessary and are undesirable as they will cause additional wear and tear on the compressors and other components. The main space heating circulating pump started at 06:40, and all four heat pumps then cycled on and off together for the remainder of the day, until 22:30 when the heating demand reduced – probably under control of the building management system.

The temperature of the brine flow to the heat pumps was steady all day, between 8 and 10 °C.

The temperature of the output from the heat pumps to the buffer tanks was generally between 52 and 64 °C, with a brief dip to 38 °C at 06:40 when the main space heating circulating pump was started.

The temperature loss through the 4-pipe buffer tanks was generally between 3 and 4 °C.


Site 62 - Operating pattern (temperatures) 11 December 2015

Site 62 - Operating pattern (circ pumps) 11 December 2015

Site 62 - Operating pattern (heat pump) 11 December 2015

Figure 6 – Operating pattern 11th December 2015

Figure 7 shows the operating pattern on 19th August when the outdoor temperature was between 14 and 19 °C. The heat pumps ran approximately every 2 hours for around 10 minutes each time. All four heat pumps appear to have been started on all but one run. However, this cycling behaviour is within the recommended limits determined from previous research [2].

The temperature of the brine flow to the heat pumps while they were running was between -1 and +3 °C. These temperatures are lower than measured during winter conditions. A possible explanation is that the source water pumps were operating at very low power and the heat transfer from the source water to the brine was not very effective. This would have had a negative influence on the system performance.

The temperature of the output from the heat pumps was not more than 54 °C – lower than during winter operation. This would have had a positive influence on system performance.

The temperature loss through the buffer tanks was slightly higher than during winter operation, between 4 and 8 °C.

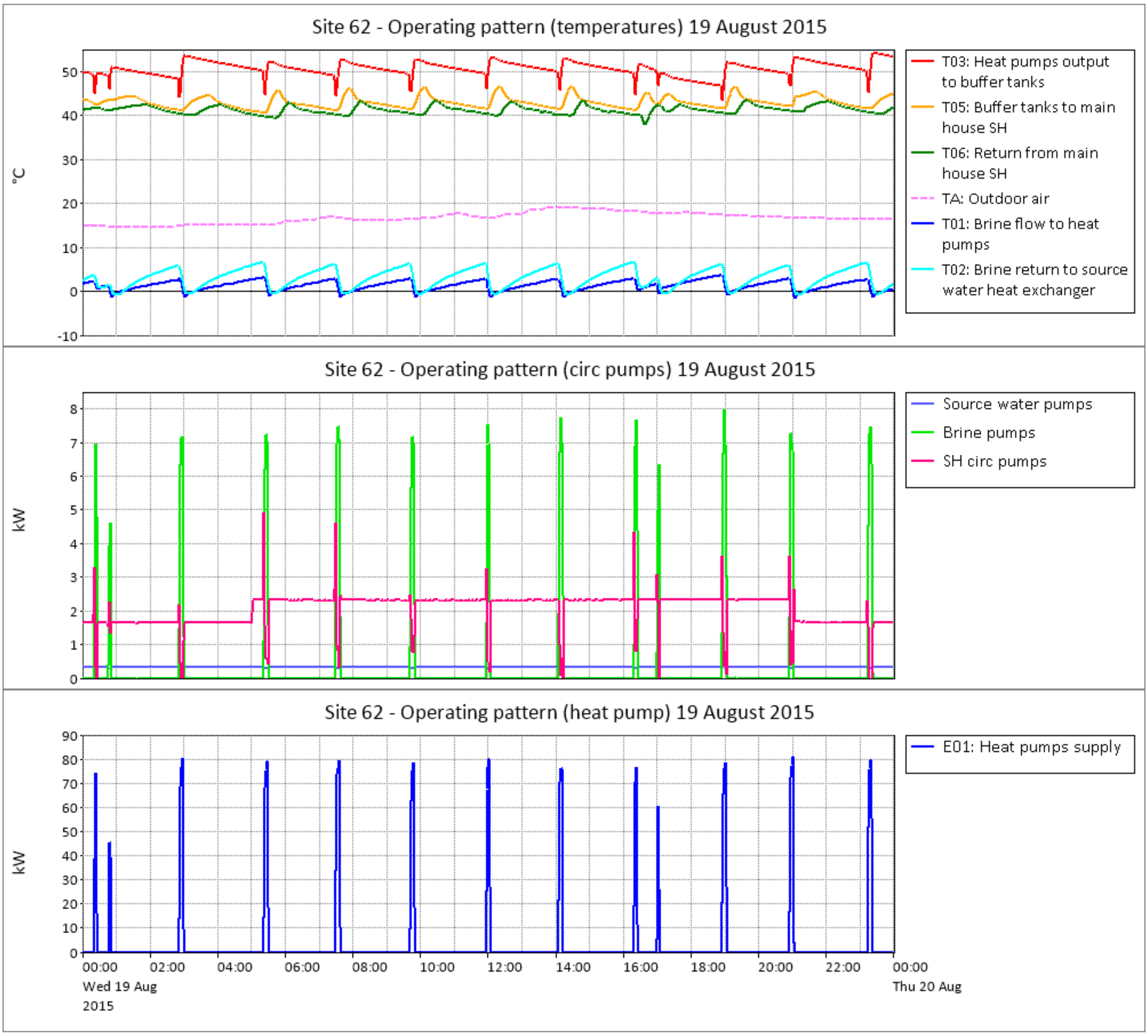


Figure 7 – Operating pattern on 19th August 2015

Source and sink temperatures

Figure 8 shows the principal temperatures of the outdoor air, source water[5], brine, output from the heat pump, flow and return from the buffer tank to space heating, plotted over the year[6]. The brine and heat pump output temperatures have been plotted only for times when the heat pump was running.

The temperature of the brine flow to the heat pumps tended to follow the temperature of the source water, except during the period from 17th August to 2nd November when it was much lower. The source water pumps used much less power than normal during this period. This was reportedly because of a problem with the blocked filters. The SPFH4 values were low during this period (see Figure 3).

The temperature of the output from the heat pumps was above 60 °C on most days, and sometimes up to 65 °C. This is high compared to most other systems monitored, and would have had a negative influence on system performance. The temperature of the output to the space heating circuits was sometimes higher (up to 77 °C on 30th March) than the output from the heat pumps. This was when the backup boiler was being used.

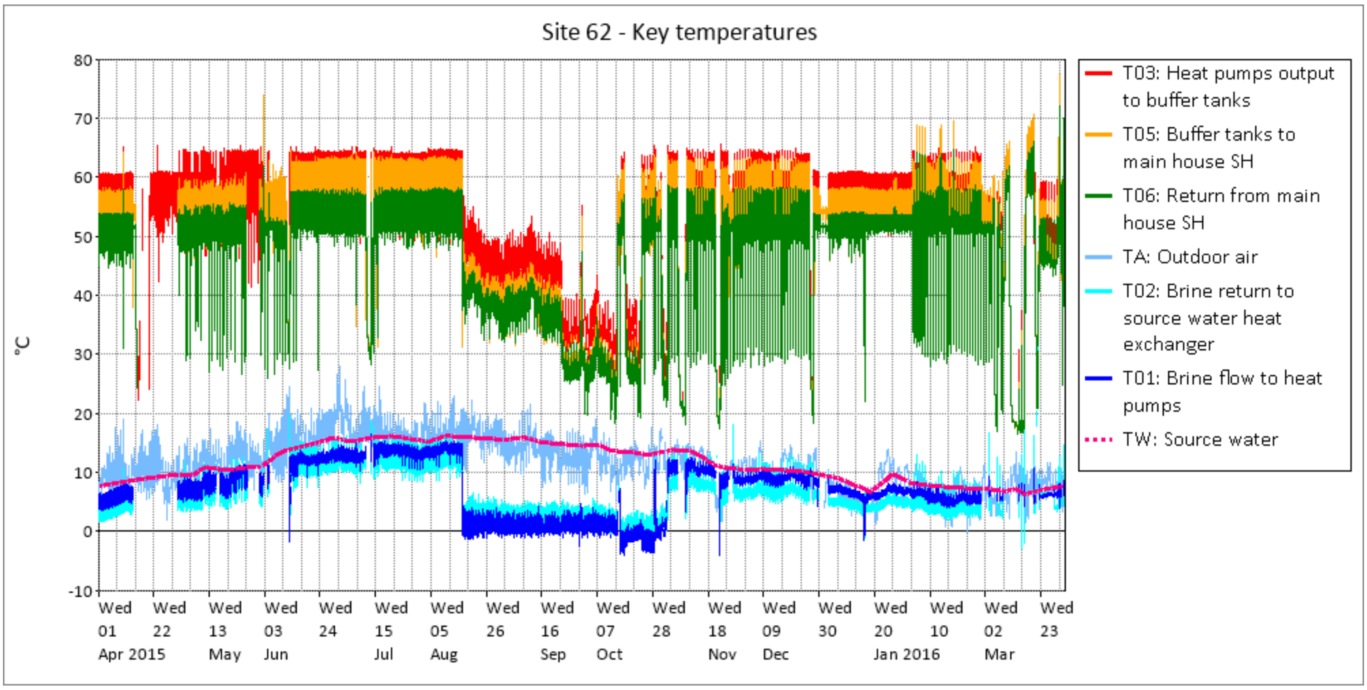


Figure 8 – Key temperatures measured during the period 1st April 2015 – 31st March 2016

Figure 9 shows the daily mean brine flow temperature compared to the source temperatures (at the heat pump) of all other ground-source and water-source systems monitored in this project. The temperatures realised on this system (plotted in red) were average or above average for most of the year (apart from the period when there may have been a problem with the source water pumps) compared to other systems. This would have had a small positive influence on system performance.

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[5] Source water temperatures were kindly provided by the Technical Support Team based at Bangor University's School of Ocean Sciences.

[6] Temperatures of the heat pump system were recorded at 2-minute intervals. The outdoor and indoor temperatures were recorded every 15 minutes and the ground temperature every hour.

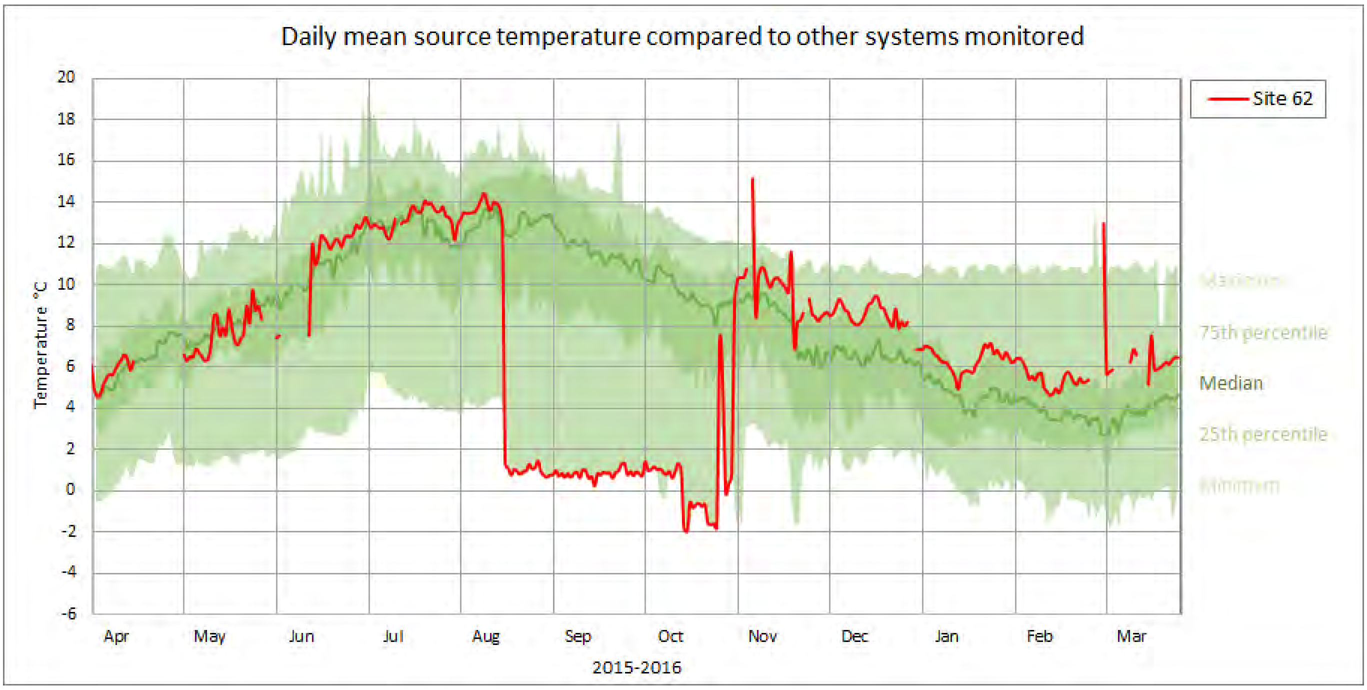

Figure 9 – Daily mean brine flow temperature at the heat pump compared to the source temperatures of other systems monitored in this project (site 62 is shown in red)

Figure 10 shows the daily mean heat pump output temperature for this system compared to other systems monitored in this project. The output temperatures on this system were generally high compared to other systems. This would have had a negative influence on the system performance. The lower temperatures between August and October were due to the reduced heat pump output because of problems with the source water pumps. The dips in the temperature during November, December and March were due to the heat pumps being off for periods.

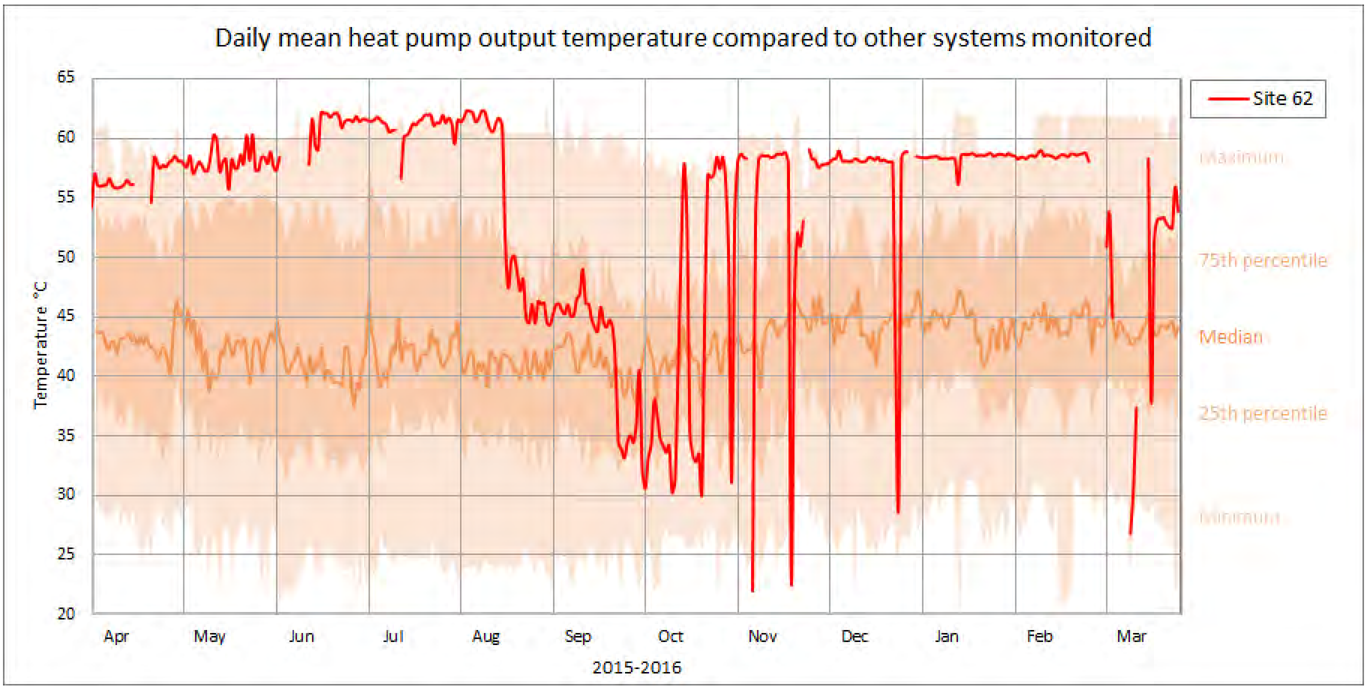

Figure 10 – Daily mean heat pump output temperature (to space heating) compared to those of other systems monitored in this project (site 62 is shown in red)

Comments

The overall performance of this system (SPF_{H4} = 1.98) was below average compared to other systems providing both space heating and domestic hot water that were monitored in this project (SPF_{H4} range: 1.54 to 3.13, median value 2.41).

The damage caused by the storm in October had a significant effect on the overall performance of this system. The system performance would have been rather higher if the heat pumps had been able to operate as intended.

Aspects of this system that positively influenced its performance are:

- The source temperature was generally above average compared to other systems monitored (see Figure 9).

Aspects of the system that may have negatively influenced its performance include:

- The output temperature from the heat pumps was generally very high compared to most other systems monitored. This was partly due to the use of radiators originally installed for use with an oil-fired boiler and the relatively poor insulation in the 18th century buildings, but also to the system design requiring high temperatures at all times to provide domestic hot water via the common heat pump output circuit.
- Approximately 12% of the heat output of the heat pumps was lost from the heat distribution system that includes a 125-metre underground pipe run to the main house.
- The source water pumps and brine pumps accounted for 13% of the total electricity used by the heat pump system. This is high compared to other systems monitored (range 2.3% - 29.8%, median 7.6%).
- The buffer pumps and space heating circulating pumps together used 10.3% of the total system electricity. This is above average compared to other systems monitored (range 2.9% - 20.5%, median 8.8%).
- The domestic hot water immersion heaters used 5% of total system electricity. This is above average compared to other systems monitored (range 0% - 27.5%, median 0.0%).
- There is an apparent problem with the control strategy in that all four heat pumps are often operated together under low load conditions, when one or two heat pumps would suffice. Starting all four heat pumps for short runs will have a negative influence on system performance and will result in excessive wear and tear on the equipment. The controls should be adjusted to avoid this behaviour.
- The LPG-fired boiler was used extensively during the monitoring because of the problems resulting from storm damage.
- Weather compensation was not used because of the common output to space heating and domestic hot water. It may be possible to configure the BMS to detect when the system is operating in space-heating only mode and to reduce the heat pump output temperature during such operation.
- There was a temperature loss of up to 8 °C through the 4-pipe buffer tanks. It is possible that a different buffer tank arrangement would yield higher system performance.
- It might be worth considering bypassing the buffer tanks during warm weather when there is no space heating load, with the output from the heat pumps going directly to the domestic hot water cylinders. This would avoid the loss of temperature through the buffer tanks and yield an improvement in performance. However, the design of buffer tank systems is a complex topic that is beyond the scope of this report.

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[2] EA Technology, “The effects of cycling on heat pump performance,” DECC, 2012.

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[4] D. Hughes, “Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source and Water-Source Heat Pumps - Interim Report. URN 16D/013.,” DECC, 2016.

[5] “Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling – Part 3: Test methods.,” EN 14511-3.