Using System Data to Understand the Performance of Multi-Occupancy and Commercial Ground Source Heat Pumps in the UK

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Chapter 3, the case study on The Crystal, is a further developed version of (Turner, Loveridge and Rees, 2021), a case study report produced for the IEA Heat Pumping Technologies Annex 52. In this publication, the entirety of the analysis and report was conducted and written up by Joshua Turner, with the other named authors reviewing and providing oversight. Further details on publications which emerged as a result of this PhD research can be found in Appendix A.

Acknowledgements

I would like to thank my supervisors, Fleur Loveridge and Simon Rees, for their guidance and assistance on this project. I'd also like to thank the other members of the geo-technical research group at the University of Leeds for their assistance, particularly at the Heights.

I would also like to thank my family and friends for keeping me sane and putting up with me whilst I worked on this, particularly my girlfriend Verity Tether, who somehow found the time to review this thesis whilst 8 months pregnant.

I would also like to thank the following people/groups for providing data, information, and guidance for the systems analysed in this thesis:

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Abstract

With heating accounting for 23% of the UK's emissions in 2019, decarbonising this sector is vital to achieve net zero by 2050, as legislated in the UK. Ground source heat pumps will be a key technology in realising this, though little data is available on their long-term performance in the UK, particularly commercial and multi-family systems. Extracting the learning from heat pumps currently in operation will be crucial to inform the systems being installed at present, helping them reach higher overall efficiencies.

This thesis provides insight on three different case studies, each with more than one year of operational data. This includes a system using geothermal foundations, two buildings utilising shared ground heat exchangers, and an open loop well doublet system.

The systems generally perform at comparable efficiencies to those in the literature, both in the UK and overseas, but improvements are possible.

The control of the ground loop in the first case study appears sub-optimal, with heat primarily extracted from the boreholes and rejected to the energy piles. This negates the potential of the ground as an inter-seasonal energy store. Case study two investigates the long-term data on the diversity within shared ground heat exchangers for the first time, showing low utilisation in all arrays except one. In particular, the contrast between two theoretically similar arrays demonstrates the difficulty in accounting for user behaviour. Case study three has the highest efficiencies but shows large periods of unnecessary operation.

These studies highlight end users as the greatest factor on system performance, stressing the need for simple yet thorough guidance. They also demonstrate the need for at least a basic level of continual monitoring to ensure optimal usage patterns, controls, and maintenance regimes. Such understanding and monitoring must be carried across changes of ownership to ensure efficiencies are maintained.

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List of Abbreviations

ASHP – Air Source Heat Pump

BEIS – Department of Business, Energy and Industrial Strategy

BEMS (BMS) – Building Energy Management System

BHE – Borehole Heat Exchanger

BT – Buffer Tank

CFA – Continual Flight Auger

CHW – Chilled Water

COP – Coefficient of Performance

CP – Circulation Pump

DECC – Department of Energy and Climate Change

DHW - Domestic Hot Water

DPF – Daily Performance Factor

EASHP – Exhaust Air Source Heat Pump

EST – Energy Savings Trust

EWT – Entering Water Temperature

GSHP – Ground Source Heat Pump

HDD – Heating Degree Day/s

HDPE – High Density Polyethylene

HPF – Hourly Performance Factor

IPF – Instantaneous Performance Factor

KPI – Key Performance Indicator

MCS – Microgeneration Certification Scheme

MPF – Monthly Performance Factor

NDRHI - Non-Domestic Renewable Heat Incentive

PF - Performance Factor

RHI – Renewable Heat Incentive

RHPP – Renewable Heat Premium Payment

SEI – Seasonal Efficiency Index

SH – Space Heating

SPF – Seasonal Performance Factor

TRT – Thermal Response Test

TRV – Thermostatic Radiator Valve

WSHP – Water Source Heat Pump

1 Introduction

1.1. Research Context

With the announcement of a climate emergency, the emphasis for ‘renewable’ and low carbon solutions across all industries continues to grow. The need for large scale, rapid development and adoption of these technologies is vital if the UK government is to meet the targets made under the Paris agreement, and limit the warming of the planet to below 2°C.

Within the UK, 23% of the emissions across the country were attributable to heat in 2019, as shown in Figure 1, (UK Department for Business Energy & Industrial Strategy, 2021). Decarbonising this industry is, therefore, vital for the government to be successful in their pledges. Indeed, the recent Heat and Buildings strategy ‘aims to …reduce emissions from buildings to…between 0 and 2 MtCO2e by 2050’ (*ibid*.).

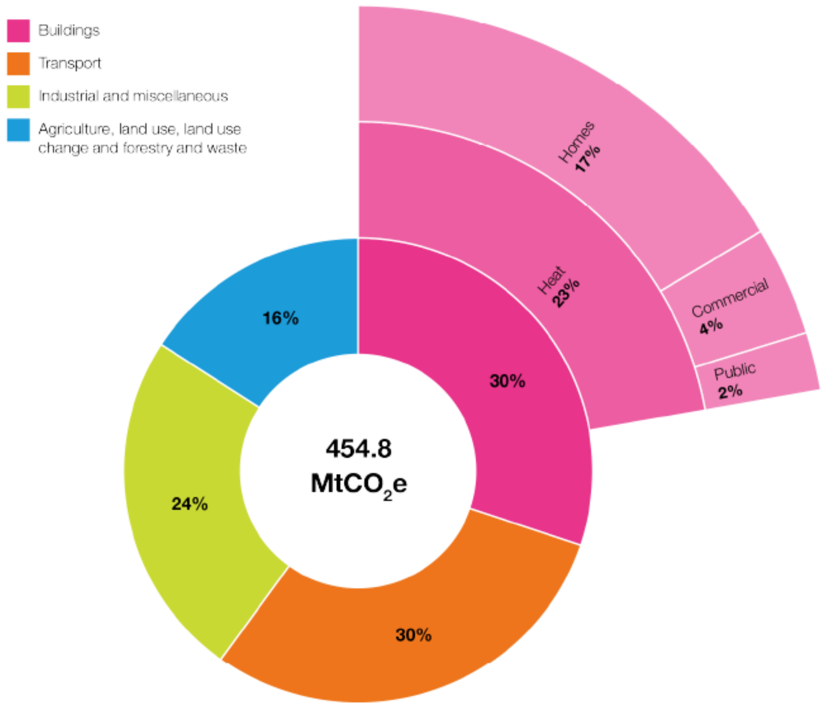


Figure 1 - UK Emissions 2019 (UK Department for Business Energy & Industrial Strategy, 2021)

Heat pumps offer a potential solution in this respect, exchanging heat from the environment to heat space and/or water for use in commercial and/or domestic buildings. A recent review of pathways to decarbonise heat in the UK highlighted the role of heat pumps in achieving Net Zero, with nearly all reports recognising heat pumps as a key technology either alongside or instead of a hydrogen-based gas grid (Mott MacDonald, 2019). Many of the pathways suggested that installing heat pumps in homes not connected to the gas grid could be considered a low regret measure and should be considered whether the UK future strategy for decarbonising heat focuses on electrification or not.

As set out in a previous review of evidence, it was noted that to decarbonise heat ‘it is unlikely that there will be a one-size-fits-all solution, so multiple technologies will play a role’ (UK Department for Business Energy & Industrial Strategy, 2018).

Despite this, the Heat and Buildings Strategy (UK Department for Business Energy & Industrial Strategy, 2021) included the often highlighted “low-regret measures” of the installation of millions of heat pumps, typically in off gas grid homes, and has introduced a number of proposals to increase the rate of installations.

The first of these is the Boiler Upgrade Scheme. This scheme is currently in operation and offers an upfront grant of £5,000 for Air Source Heat Pumps (ASHPs), and £6,000 for Ground Source Heat Pumps (GSHPs) to encourage their uptake, with £450m made available in total. This scheme has recently been extended to 2028(Department for Energy Security and Net Zero, 2023).

The Heat and Buildings Strategy also declared an “ambition” of phasing out new gas boilers from 2035 and promised to “look at options to shift or rebalance energy levies and obligations away from electricity to gas over this decade”.

Additionally, the government’s 10-point Green Plan (HM Government, 2020) announced a target of 600,000 heat pump installs per year by 2028. This is to be achieved by installing roughly 200,000 per year in new homes, and the remainder is to be met by a market-based mechanism obligating boiler suppliers to sell a certain number of heat pumps per year. This 10-point plan also suggested that new homes would be expected to be built with low carbon heat sources from 2025.

Even more recently, a £30 million “Heat Pump Investment Accelerator” scheme has been announced by the UK government which aims to increase the manufacturing and supply of heat pumps within the UK(Department for Energy Security and Net Zero, 2023).

From these recent policy developments it is clear that heat pumps are expected to play an increasingly large and important role in the decarbonisation of heat, and in meeting the country’s legally binding net zero target. As such, it is imperative to fully understand the common pitfalls found in these systems, and where the different types are most applicable.

Monitoring of such systems, through various trials and case studies, has been useful in verifying technical issues, costs, and policy effectiveness as well as user experience.

This research aims to add to the existing knowledge base on ground source heat pumps by undertaking a cross-investigation of three systems in operation in the UK, providing greater insight into the performance of each of the systems. This cross-examination will aim to understand the factors affecting the long-term performance of such systems and any key similarities or differences between them. Data collected from these systems is interrogated to understand how to increase their seasonal efficiencies and how to prevent any potential faults from affecting the systems.

1.2. Aims & Objectives

Aims:

To assess the long-term performance of multi-occupancy and non-residential GSHPs in the UK and show how effective monitoring of these systems can be used to improve their energy efficiency.

Objectives:

1) Conduct a review of literature to:
    a. Identify appropriate case studies in the UK
    b. Identify suitable key performance indicators (KPIs)
    c. Establish the contributing factors to underperformance in heat pumps over long periods of time
    d. Assess the current methods for analysing the data;
2) Develop analysis methods to clean and interrogate multiple large data sets from case study buildings, manipulating available data sets to provide useful KPIs;
3) Analyse multiple ground source heat pump systems covering small, medium, and large installations and different ground heat exchangers to determine the performance of the heat pumps systems, and if applicable, potential causes for underperformance/over-performance;
4) Contrast the various systems to one another and to similar systems in the literature to assess how the performances compare;
5) Create a summary of transferrable recommendations for optimisation of the performance of the ground source heat pump systems and their monitoring.

1.3. Thesis Structure

The thesis has been structured into 7 chapters.

The current chapter sets out the research problem, aims and objectives, and thesis structure.

Chapter 2 introduces Ground Source Heat Pumps, providing a technological background before presenting a literature review on current monitoring methods, KPIs, and existing case studies for systems with long-term data.

Chapters 3, 4 and 5, are each dedicated to an individual case study and all follow the same structure; the building and system is introduced before the monitoring regime and instrumentation is explained. Following this, data limitations are discussed, and analysis methods are laid out. Finally, the results of the analysis are presented before a discussion on the findings.

Chapter 3 focusses on The Crystal, a large building with heating and cooling loads that utilises boreholes and energy piles as the ground heat exchangers. This system has over 8 years of data to contribute to the limited data on energy piles as heat exchangers.

Chapter 4 is centred on a distributed heat pump system at The Heights in Leeds. These buildings utilise a shared ground heat exchange system, in which multiple heat pumps in multiple residences extract heat from the same shared boreholes. At the time of writing, there is no long-term data available for such a system in the UK.

Chapter 5 investigates an open loop well doublet system installed in Cardiff, utilising an existing data set originally set up to monitor aquifer properties rather than detailed heat pump performance.

Chapter 6 then provides a comparison across the three systems, highlighting performance implications of the different systems, controls, and heat exchangers, as well as the challenges faced in monitoring such systems.

Finally, Chapter 7 provides overarching conclusions from the analyses, recommendations for monitoring systems in the future, and highlighting potential future work.

2 Literature Review

2.1 Background to Ground Source Heat Pump Systems

2.1.1 Heat Pumps

The two most commonly found types of heat pumps are Ground Source Heat Pumps (GSHPs) and Air Source Heat Pumps (ASHPS).

Whilst it is assumed that ASHPs will be the predominant technology rolled out in the UK, it has been frequently shown that GSHPs are the more efficient technology. This is due to the more stable temperature of the ground compared to the air, offering a more reliable performance year-round. However, GSHPs are often overlooked due to their upfront costs, making them more suitable to projects with larger budgets, such as commercial or multi-family residential buildings.

2.1.1.1 Ground Source Heat Pumps

A typical Ground Source Heat Pump (GSHP) operates using the vapour compression cycle as shown in Figure 2. There are however alternatives forms of GSHPs to this including Absorption or Adsorption heat pumps.

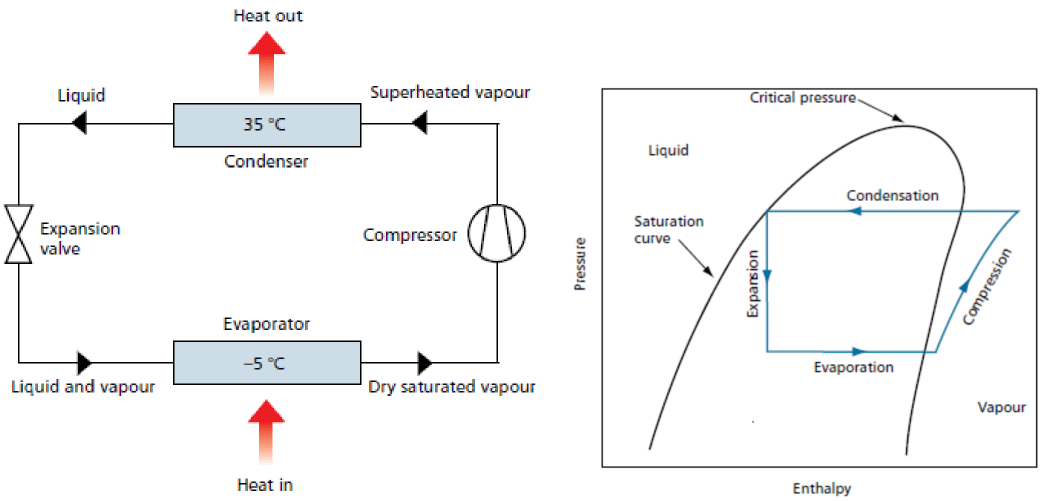


Figure 2 - Typical Vapour Compression Cycle and corresponding Enthalpy Pressure diagram - (The Chartered Institution of Building Services Engineers, 2013)

These heat pumps allow the relatively low temperature heat stored in the ground to be converted into a more useful, higher temperature to heat the building's space or the Domestic Hot Water (DHW). GSHP's can also be used for cooling by reversing the flow through the system; the building-side heat exchanger draws heat from the building which is deposited, via the refrigerant, into the ground. This can be particularly effective for a joint heating/cooling heat pump systems as the heat extracted from the ground in winter is then re-injected during the cooling period (summer), recharging the ground, and restoring it to a state such that it can then be used for heating again when required (The Chartered Institution of Building Services Engineers, 2013).

2.1.2 Ground Heat Exchangers

There are many variants of ground source heat pump systems, differentiated by their heat source, sink, and heat exchanger configuration.

The most prevalent of these are explained below, but this is not an exhaustive list. A summary is also provided in Table 1.

2.1.3 Closed Loop

Closed loop systems are defined by the presence of a closed loop of circulating fluid to absorb and reject heat from the ground. This loop transfers heat to and from the refrigerant in the heat pump through a heat exchanger. If the system is designed such that a direct heat exchange between the ground loop and the heat distribution systems is possible, and the conditions are right, 'Free Cooling' may also be possible. This is when the ground loop heat carrier fluid is cool enough to absorb the required heat from the building without the need for the heat pump, and as such can achieve higher efficiencies.

Typically, the fluid used in the ground loop will be an ethylene or propylene glycol mixture, used for its antifreeze properties, whilst the heat pump itself will contain a refrigerant to allow for appropriate evaporation and compression as required. The heat transfer fluid on the building side is typically water. In some instances, air is used to circulate the heat around the building side rather than water, called water-air systems, as opposed to water-water systems. Most GSHPs in the UK are water-water, and this is the technology of focus for the remainder of the thesis unless explicitly stated.

Closed loop systems can be categorised based on the ground heat exchanger configurations as shown below.

2.1.3.1 Vertical Borehole

Whilst the temperature of the ground varies with depth, it can be considered to be relatively constant and independent of seasonal variability past a depth of 3-5m, typically between 9°C and 14°C in the UK depending on local ground conditions, as shown in Figure 3.

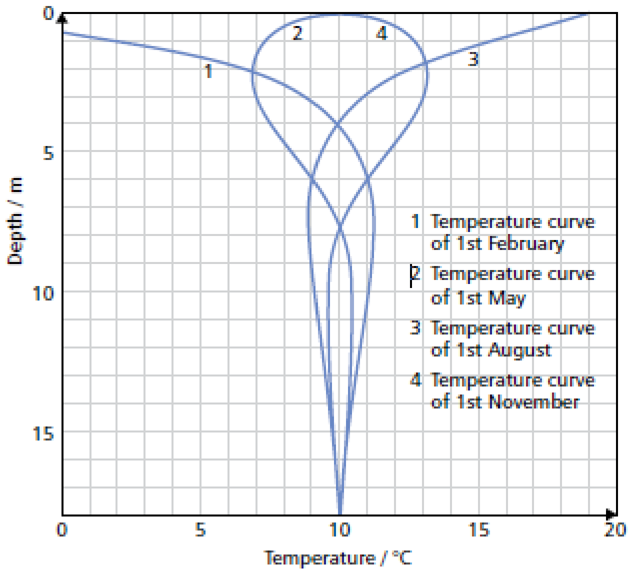


Figure 3 - Ground Temperature with Depth (The Chartered Institution of Building Services Engineers, 2013)

Vertical ground heat exchangers (borehole heat exchangers) typically contain 100-200mm diameter boreholes with a single or double U-Tube pipe inserted vertically into a borehole at a depth of between 50 and 300m. These are particularly useful if surface area is at a premium and are typically more efficient that horizontal heat exchangers due to the temperature stability compared to those at shallower depths. However, the need to drill these deep boreholes can significantly increase the capital cost of the system.

2.1.3.2 Horizontal

Horizontal heat exchangers contain pipes buried near the ground's surface, typically between 0.8m and 2.0m deep. The limited depth of the heat exchangers necessitates a large surface area to allow sufficient heat transfer, however this area can be reduced through the use of prefabricated arrays and coiled ground heat exchangers. For this reason, slinky heat exchangers are often preferred over linear horizontal heat exchangers, and spiral coil (helical) heat exchangers have begun to be investigated in industry.

2.1.3.3 Energy Piles

The incorporation of heat exchangers into a building's foundations or piles can be effective in reducing the capital costs of the systems as it eliminates the need for a dedicated drilling operation. These piles are called energy piles or thermopiles, and these systems can achieve high heat transfer rates due to the increased surface area of the heat exchangers compared to those used in boreholes. However, due to the limited number of piles per building, and their limited depth, the energy piles may not be sufficient in meeting the full building load and supplementary systems may be required.

2.1.3.4 Pond Loops

In pond systems, heat exchanger loops are typically submerged at least 3m below the water's surface but raised 0.2-0.5m above the pond floor. The output of these systems naturally varies with the water temperature however they can achieve high efficiencies.

2.1.3.5 Atypical Heat Exchangers

Less common heat exchangers include direct expansion systems and heat pipe systems.

In a direct expansion system, the heat pump refrigerant itself is pumped through the ground loop to absorb the heat required, rather than having an intermediary heat carrier fluid. This can allow high efficiencies but could cause environmental concerns depending on the refrigerant used and is limited to small systems.

A heat pipe system can be considered as a self-circulating heat exchanger; the fluid absorbs the heat from the ground, evaporates, the gas rises to the top of the pipe to a heat exchanger where it then condenses and falls to the bottom of the pipe again.

2.1.4 Open Loop

Open loop systems use groundwater as the medium to transfer heat between the ground and the refrigerant in the heat pump. This differs from a closed loop which will not directly pump the groundwater but will typically absorb the heat from the ground by pumping a brine solution through pipes in the ground. There are many configurations of open loop systems that can utilise the groundwater through multiple heat exchangers and heat pumps to provide heating and cooling loads simultaneously before then discharging it in one of two ways. The water can either be rejected to waste or surface water systems, called a consumptive system, or it can be reinjected back into the source, be that surface water or aquifer. This is known as a non-consumptive system. With most open loop systems, permission for the abstraction and reinjection of the groundwater is required from the environmental agency, sometimes in the form of permits or licenses, to ensure the sustainability of the operation. This is done to limit the impact on groundwater levels and temperature changes caused by the proposed systems. Some typical open loop systems are briefly described below.

2.1.4.1 Surface Water

In these systems surface water is used to transfer the heat, however filtration can be an issue. The variable temperature in surface water can also cause issues when designing these systems and as the water is exposed to ambient conditions, it provides a much less predictable heat source than with water from an aquifer. (The Chartered Institution of Building Services Engineers, 2019)

2.1.4.2 Water Well

In a water well system a pair of wells (doublet) is used as the source of the ground water, one abstraction well and one reinjection well, making these non-consumptive systems. These wells are typically at large enough depths such that the temperature of the groundwater is relatively stable and predictable and therefore the heat pump systems can be simply designed to achieve higher efficiencies. However, the location of the injection well relative to the abstraction well is of critical importance; if they are too close to one another the temperature of the water in one can be affected by the temperature of the water in the other. This ‘thermal breakthrough’ can affect the efficiency of the system and should be avoided. (The Chartered Institution of Building Services Engineers, 2019)

2.1.4.3 Standing Column Well

Similarly to a water well system, standing column systems are generally non-consumptive, however in this case the used water is reinjected back into the same well from which it was abstracted. This can be used if reinjection is required for environmental reasons, but the space is not available for a pair of abstraction and reinjection wells. The use of a single well would also potentially come with cost savings from not needing to drill and install the second well. In these systems there is a risk of short cycling between the injection and abstraction pipes which may detriment the performance. (The Chartered Institution of Building Services Engineers, 2013)

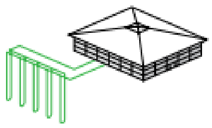
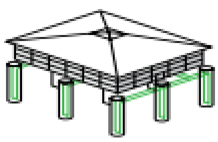
If the well gets too hot or cold, some fluid may need to be bled off to manage the temperature. In this case the well becomes consumptive, with a small proportion of the water being used rather than returned to the well.

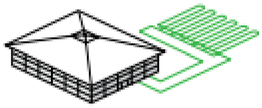
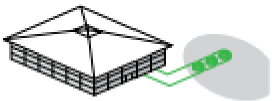
2.1.5 Hybrid

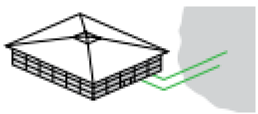
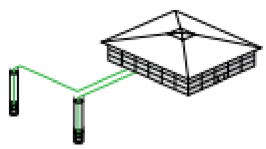
Hybrid systems are employed where the primary system is not capable of meeting the heating and/or cooling load of the buildings. These can take a few forms including the addition of back up heating/cooling capabilities (gas boiler/dry cooler etc.) or the combination of a closed and open loop system e.g. thermal piles with open loop wells for peak loads (The Chartered Institution of Building Services Engineers, 2019)

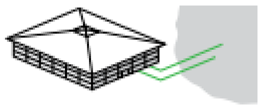
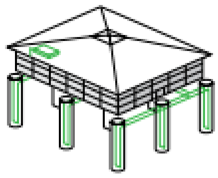
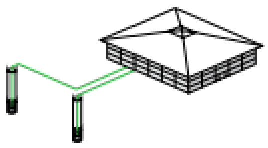
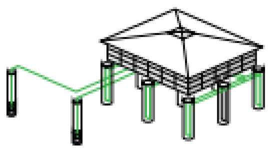
The key features of the different systems are highlighted in Table 1, developed from the CIBSE TM51 guide to ground source heat pumps. (The Chartered Institution of Building Services Engineers, 2013)

Table 1 - Summary of GSHP variants

<table>
<tr><th><u>Type</u></th><th><u>Subtype</u></th><th><u>Notes</u></th></tr>
<tr><td rowspan="2">Closed Loop</td><td>Vertical
</td><td>• Single /Double U-tube/Co-Axial HDPE Pipes
• Typically 20-55 W/m (per metre borehole depth)
• Commonly used for medium sized systems (100-1000kW)
• Suitable for wide range of building types and sizes
• Relatively high efficiency
• High Cost
• Land used can be built over
• Preferable to horizontal loops if space is at a premium
• Typically 100-200mm boreholes drilled in a suitable pattern (4-15m between holes)
• Typical depth 50-200m
• Important to balance heating and cooling loads for large borehole arrays to maximise thermal efficiency
• Can provide energy storage</td></tr>
<tr><td>Energy Piles
</td><td>• Single /Double U-tube/Co-Axial HDPE Pipes
• Preformed pipes or inserted during piling process
• Typically 20-75W/m (per metre of pile)
• Vertical loops incorporated into the building pile</td></tr>
</table>

		• Can be use in any piled building – any common piling method (only suitable for new builds) • Typically cover ~50% of building load – additional borehole or open loop systems may be required • Important to minimise the impact of the heat exchanger pipes on the pile design and installation program • Low additional cost over conventional equipment • Pile diameter: 300-1200mm • Pile Length: 10-40m
	Horizontal 	• Single/multiple/coiled HDPE or PEXa pipes • Typically 1-40 W/m^2 of ground area • Systems up to 150kW most common (due to land constraints) • Trenches 0.8-2m deep • Varying methods and geometries • Generally cheaper than vertical but less efficient • Require large area of boulder free soil (min 1.5m depth) • Cannot be built over • Risk of frost heave if undersized
	Pond 	• Coils of HDPE pipe or SS/Ti plate heat exchangers anchored close to the pond floor • Preformed ground heat exchanger plates or arrays

		• Needs sufficiently large lake or pond • Highly efficient method, can cover any sized load • Systems of many MW are common • Relatively quick and easy to install at low costs but require still/moving surface water • Constant water depth of 2-3m required • Need to avoid adverse changes in water temp • Possible risk of pollution from leakage • ~9m^2 of surface area required per kW of system capacity
Open Loop	Surface Water 	• Surface water used as a source – water taken through similar system of heat exchangers as above • Filtration is main issue – significant maintenance requirement
	Water Well 	• Abstraction and rejection pair of water wells installed at source • Water piped through heat exchanger – heat is taken or added to water • Water then returned to ground, chemically unaltered • Better suited for larger projects • Risk of water well drilling – water yields cannot be guaranteed – required hydro-geological study to mitigate risk

		• Requires an extraction license
	Standing Column Wells 	• Abstraction and rejection are taken from the same well • Advantage of reduced cost over two separate wells • Potential for short cycling between abstraction and rejection points
Hybrid System	Closed loop and Dry Cooler 	• Addition of dry coolers – cost effective alternative to increasing ground loop size • Used when cooling load dominates over heating (most commercial buildings)
	Open Loop and Dry Cooler 	• As above, using open loop rather than closed
	Closed and Open Loop 	• Closed and open loops can be combined, particularly where piles are used and piling configuration is capable <100% of building heating & cooling loads • Addition of open loop wells to cover peak periods • Together, the two systems provide much larger heating and cooling loads compared to the two in isolation

2.2 Review of Performance Measures and Existing Performance Data

2.2.1 Guidance for Long Term Performance Monitoring

There is not a wealth of formal guidance in instrumenting and monitoring the long-term performance of GSHPs.

(Lowe *et al.*, 2017) provides a list of parameters monitored in the Renewable Heat Premium Payment (RHPP) scheme, a scheme in which homeowners were provided a one-off payment to buy renewable heating technologies. though this is descriptive not prescriptive. This report, along with (Gleeson *et al.*, 2016) highlights the need for reliable metadata when monitoring these systems as well as touching on some commonly found instrumentation faults. Lazzarin and Noro (2018) suggest that the “analysis of recorded data is essential for management” of the heat pump system, whilst also noting that management services hired to maintain the equipment will focus on its continued operation rather than how efficiently it is running. Personal blogs such as Cantor (no date) and Harizanov (no date) suggest parameters to monitor in order to assess the performance of domestic heat pump systems and websites such as Open Energy Monitor (no date) sell bundles of equipment that can be used to monitor individual systems to varying degrees.

One of the more comprehensive guidelines for monitoring the long-term performance of GSHP systems is the outputs of the International Energy Agency Heat Pumping Technologies Technology Collaboration Programme - Annex 52 (IEA HPT Annex 52 or Annex 52). The first output is a guideline attempting to provide guidance on the data and instrumentation required (Davis *et al.*, 2021). This provides a range of guidance taking the user from the development of a monitoring program through considerations such as which data points should be monitored, what the sampling frequency should be for each data point, what technologies are available to measure each parameter and what the relevant considerations are when selecting equipment. This provides a useful starting point for any such monitoring project.

Beyond the determination of which parameters to monitor and meter selection, another of the outputs of Annex 52 was the a guideline on Key Performance Indicators (KPIs) and system boundaries when monitoring the long-term performance of GSHP systems (Gehlin *et al.*, 2022). Some of these KPIs and boundaries are discussed further in Sections 2.3 and 2.4 respectively.

2.3 KPIs for System Performance

There are a number of metrics that can be used to assess the performance of heat pumps and allow comparisons between systems.

2.3.1 Coefficient of Performance

The typical measure of performance of a heat pump is the coefficient of performance (COP). This is usually measured in the laboratory under specific, controlled conditions and can be useful for directly comparing heat pumps to one another at the design stage (Rees and Curtis, 2014). The COP is calculated via Equation 1 below for a heat pump in heating mode.

$$COP = \frac{Useful\ Energy}{Energy\ Input} = \frac{Heat\ Output}{Electricity\ Input} \quad (1)$$

This is used to provide instantaneous performance figures, however the COP can also be used to describe the short term performance of a system on a timescale ranging from diurnal to seasonal (Lowe *et al.*, 2017). It is to be noted that the COP does not account for the seasonal variation in external temperature which will affect the heat pump’s performance, and nor does it take into account the current climatic conditions that the heat pump is operating in. To address these pitfalls, additional performance measures are required.

2.3.2 Seasonal Performance Factor

The Season Performance Factor (SPF) is calculated in the same way as the short-term COP, but using the total values of heat, cool, and electricity over a year. This then shows the overall efficiency of the heat pump through all four seasons, accounting for the variation of heat demand and external air temperature. Performance factors can also be used for other time periods, such as monthly (MPF), daily (DPF), hourly (HPF) etc. These can be used to compare systems in actual operating conditions.

2.3.3 Seasonal Efficiency Index

Both the COP and the SPF are useful in determining the efficiency of the heat pump system and are particularly useful in comparing the performance against other systems. However, neither of the indicators can show how the heat pump is performing compared to the theoretical maximum at the current conditions. In this case, the system could be reporting a high COP, say 3.4, but could be capable of a COP of 4 and as such is actually underperforming.

System Efficiency Index (SEI) is the ratio of the measured COP to the ideal COP based on the delivered temperatures and is calculated for heating and cooling as per Equations 2 and 3 below (Lane et al., 2014). In this case the numerator is the measured COP, and the denominator is the ideal COP, also defined as the reversible Carnot COP. The ideal COP is calculated based on the measured reference temperatures, with $T_{ref,h}$ representing the reference temperature at the hot side and $T_{ref,c}$ the cold side. The reference temperatures depend on the system boundaries applied, but in general can be defined as the mean of the incoming and outgoing temperatures of the heat transfer media.

$$SEI\ heating = \frac{COP_h}{\left(\frac{T_{ref,h}}{T_{ref,h,}-T_{ref,c}}\right)} \tag{2}$$

$$SEI\ cooling = \frac{COP_c}{\left(\frac{T_{ref,c}}{T_{ref,h,}-T_{ref,c}}\right)} \tag{3}$$

The ideal COP can also be reached as the product of sub efficiencies. The following sub efficiencies are defined alongside the SEI, and can assist in determining the location of any efficiency problems in the system:

- Refrigeration cycle efficiency
- Compressor efficiency
- Pressure drop in refrigerant lines
- Heat exchanger efficiency

- Fluid transfer efficiency
- Non useful heat loss/gain

Two differing methods of calculating the SEI are proposed by Lane et al. (2014): an external method as in Figure 4 and an internal method, Figure 5.

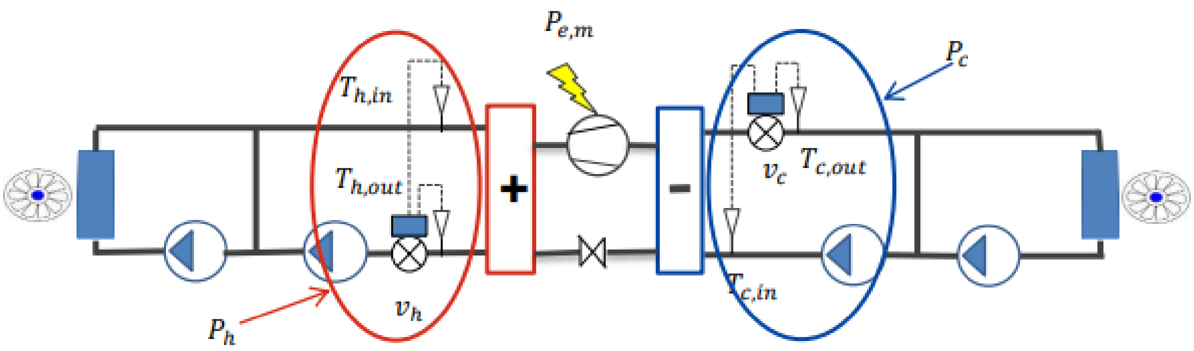


Figure 4 - Measurement points required to calculate the SEI for heating and cooling using the external method (Lane et al., 2014)

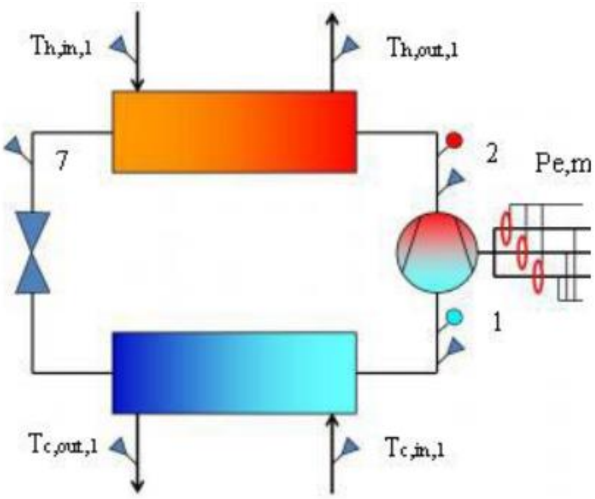


Figure 5 - Measurement points required to calculate the SEI using the internal method (Lane et al., 2014)

The external method is most commonly used and measures the heat in the system through the flow rate and temperature difference between the inlet and the outlet. The internal method, on the other hand, is based on assessing the thermodynamic process at various stages through the specific enthalpy changes. As such it requires more monitoring points including the surface temperatures in the refrigerant system, the condensing and evaporating pressures, and the power input. From these pressures and temperatures, the specific enthalpies at various points in the system can be calculated and the COP determined from them as per Equations 4 and 5, where h is the specific enthalpy and f is the thermal losses of a simple hermetic compressor expressed as a fraction of power input.

$$COP_h = \frac{(1-f)(h_2-h_7)}{(h_2-h_1)} \quad (4)$$

$$COP_c = \frac{(1-f)(h_1-h_7)}{(h_2-h_1)} \quad (5)$$

In the above equations the difference in enthalpies,$h_2 - h_7$ represents the heat delivered by the refrigerant to the condenser, and $h_2 - h_1$, represents the work supplied to the refrigerant by the compressor. One of the key advantages of the external method is the simplicity, however use of the internal method allows the sub efficiencies previously mentioned to be calculated, which aids in troubleshooting performance issues (Lane *et al.*, 2014)

Similarly, the differences in monitoring schemes used to determine the SPF was investigated in another study by Stafford (2011). The contrasting measurement schemes are shown in Figure 6. This external monitoring scheme is similar to that of the SEI external method, simply measuring the total electricity input and heat output. The internal method of measurement in this case focuses on measuring heat losses for the DHW tank rather than the sub efficiencies of the refrigerant process. In this study the estimated storage tank losses ranged from 6% to 78%, meaning that if the external method was used, up to 78% of the heat being generated would not be accounted for in the SPF value. This trial showed that the SPF values of the internal scheme are 0.03-0.45 higher than those of the external method, with an average increase of 0.23. This degree of underestimation is dependent on many factors including the heat pump usage, location, meter locations, and distribution pump settings.

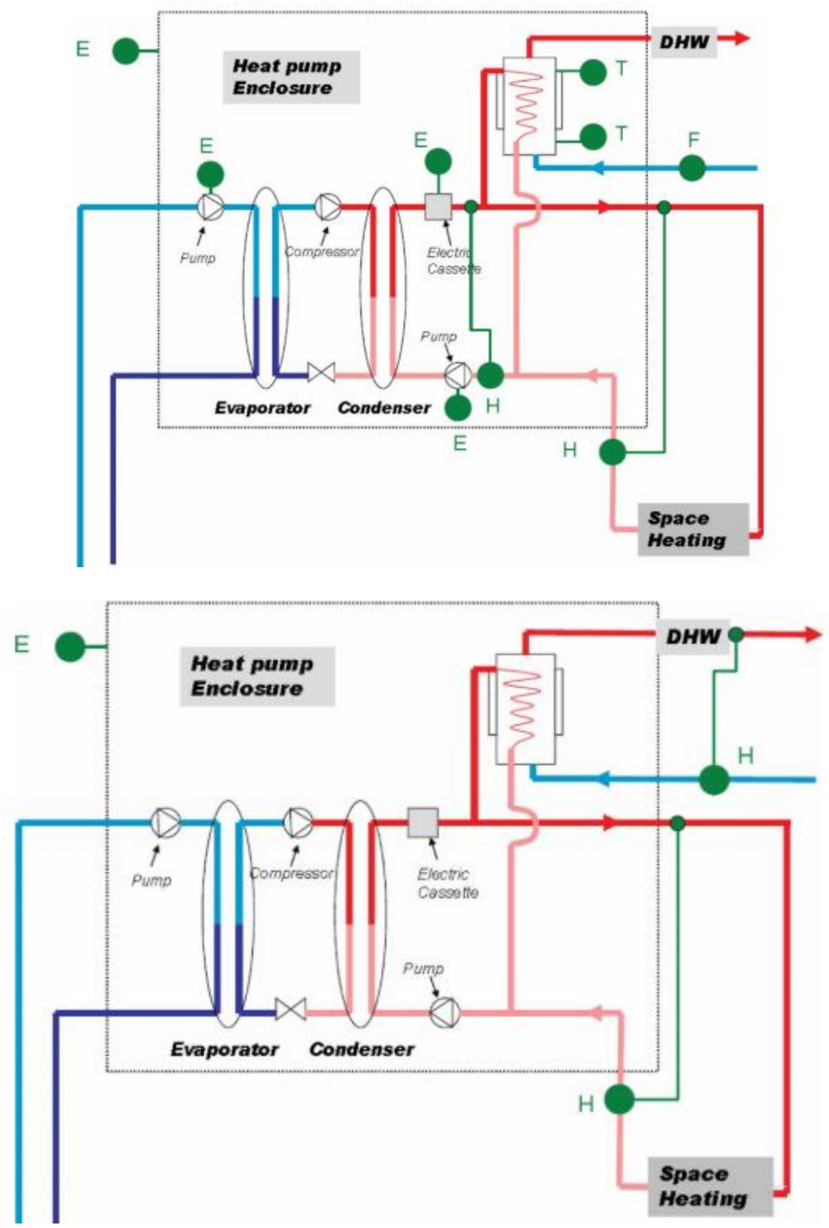


Figure 6a - Internal Monitoring Scheme, Figure 6b External Monitoring Scheme (Stafford, 2011)

2.4 System Boundaries

Various system boundaries can be applied when calculating the COP, SPF, or SEI, allowing for the inclusion or exclusion of various system components such as auxiliary heating/cooling sources, buffer tanks, circulation pumps etc. This will inevitably affect the efficiency value calculated. For example, if circulation pumps were included within the system boundary, little-to-no useful heat output would be provided but the electricity demand within the specified boundary would be greater, thus the value of the chosen performance measure would decrease.

This means that the use of different system boundaries in different studies makes it difficult to compare the findings with one another.

The Seasonal Performance Factor and Monitoring for Heat Pump Systems in the Building Sector (SEPEMO) project was undertaken in an attempt to provide some clarification and consistency between the values reported (Nordman *et al.*, 2012). This project produced the following boundary definitions and allows for the simple comparison of SPF values produced for various systems in various studies worldwide.

- SPF H1: Heat Pump Only
- SPF H2: H1 + Source Side Circulation Pumps
- SPF H3: H2 + Back Up Heater
- SPF H4: H3 + Load Side Circulation Pumps

The cold equivalents of these measures were also introduced, namely SPF C1-C4.

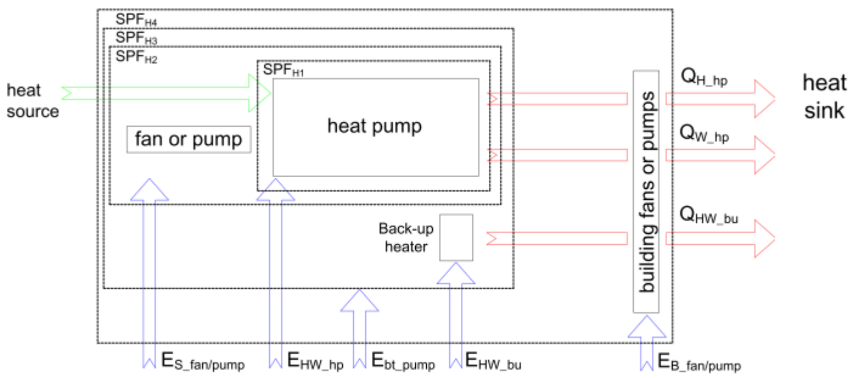


Figure 7 - SEPEMO SPF Boundaries (Nordman et al., 2012)

These definitions have been accepted by the EU for defining the renewable energy delivered by a heat pump system (The European Commision, 2013) and SPF H2 corresponds to the SPF used in evaluating the minimum performance standards and renewable energy contributions (The European Parliment and the Council of the European Union, 2009). This states that for a heat pump to be declared as 'Renewable' it has to satisfy the conditions in Equation 6, where η is the ratio of total gross production of electricity to primary energy consumption for electricity consumption and is given as an EU average.

$$SPF\ H2 > \frac{1.15}{\eta} \tag{6}$$

SPF H4 as defined by the SEPEMO boundaries can be used to compare the efficiencies of heat pump systems and their corresponding emissions to more traditional heating systems (Gleeson and Lowe, 2013; Rees and Curtis, 2014).

These definitions were compared with other boundary definitions used in major European field trials, as discussed below, in a meta-analysis of heat pump performance in Europe, highlighting the similarities and redundancies in a number of the performance indicator boundaries (Gleeson and Lowe, 2013). This work extended the SEPEMO boundaries to include tapped hot water rather than the heat into the hot water cylinder, defining this as SPF H5. This allowed for the inclusion of the results termed “System Efficiency” in the original EST UK field trials (Roy, Caird and Potter, 2010).

In the German field trials that were investigated, the JAZ boundaries were used and are defined as below.

- JAZ 1: Includes the Ground Loop, Heat Pump, Controls, Compressor, & Header Pumps
- JAZ 2: JAZ 1 + Space Heating Buffer Storage Losses
- JAZ 3: JAZ 2 + Auxiliary heating + Space Heating Circulation Pump
- JAZ 4: JAZ 2 + Auxiliary heating

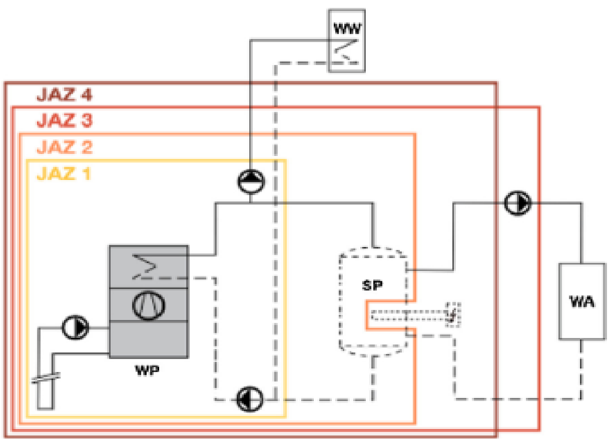


Figure 8 - German JAZ SPF Boundaries (Gleeson and Lowe, 2013)

Early Swedish trials reported seasonal efficiencies according to the two following boundaries as proposed by the SP Technical Research Institute:

- SPF_{hps} - Heat Pump System including source pump and central heating sink pump at boundary A
- SPF_{hs} – Whole Heating System including back up heating at boundary E

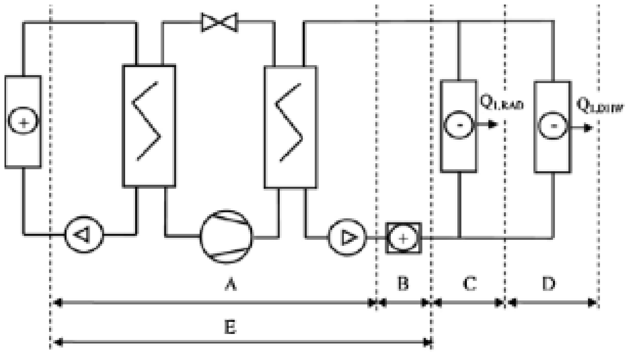


Figure 9 - SPTRI Season Efficiency Boundaries (Gleeson and Lowe, 2013)

The results of the European heat pump field trials highlighted in this study will be revisited in Section 2.7, however the paper clearly demonstrated the effects of the system boundaries on the reported SPF values for heat pump systems and the need to ensure the appropriate measures are being used when comparing systems to one another.

The SEI calculations and the sub efficiencies within the heat pump system, as per Section 2.3.3, were based on the boundaries developed in the SEPEMO project with a few changes. These include the isolation of the refrigerant circuit in the first SEI boundary, in comparison with the first SEPEMO boundary which includes the heat pumps' internal circulation pumps. The second SEI boundary includes the building circulation pumps, differing from the second SEPEMO boundary which just includes the ground loop side. These boundaries are shown in Figure 10.

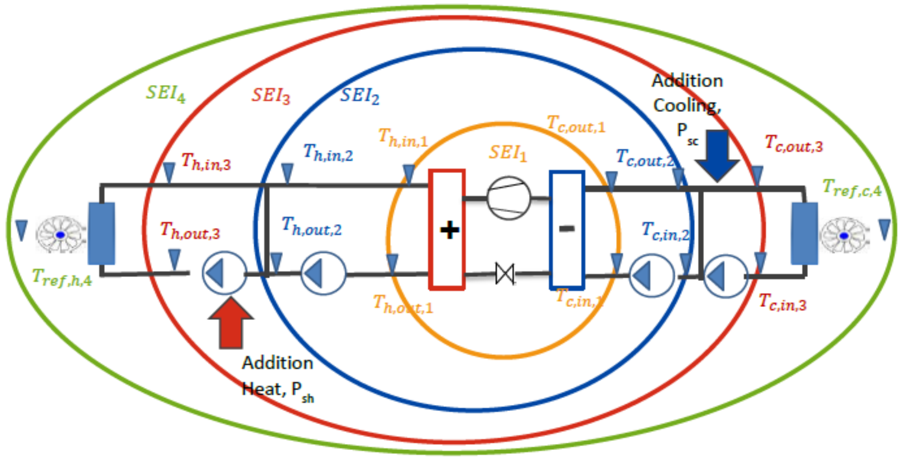


Figure 10 - SEI System Boundaries (Lane et al., 2014)

- SEI1 – Refrigeration circuit only, i.e. the load from compressor. This is not the same as the HP as it doesn't include HP internal circulation pumps
- SEI2 – Includes source & sink circulation pumps i.e. the ground loop and the building
- SEI3 – Includes the auxiliary heating and/or cooling systems
- SEI4 – Covers the whole process to deliver heating and/or cooling to the end user, including auxiliary systems of the heat sink and heat source system

As part of the IEA Annex 52 work into "Long Term Performance Measurement of GSHP Systems Serving Commercial, Institutional and Multi-Family Buildings", it became clear that the boundary definitions in place were not robust enough for the case studies being analysed. As such, the revised system boundaries summarised in Figure 11 and Table 2 have been proposed as an output of the Annex (IEA HPT Annex 52, 2019).

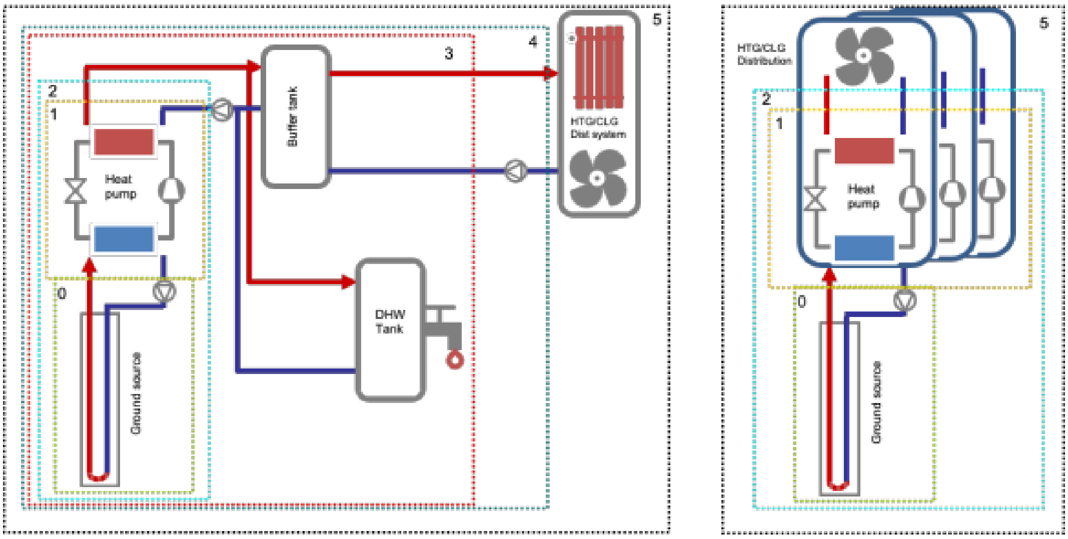


Figure 11 - IEA Annex 52 SPF Boundaries (IEA HPT Annex 52, 2019)

The left-hand side of Figure 11 shows the boundaries for a centralised system, with the boundaries for a distributed system on the right. It is worth noting that the distributed system boundaries are based on water-to-air heat pumps and so some modifications to these boundaries may be required for distributed water-to-water heat pumps.

The new boundaries proposed by Annex 52 will be the boundaries carried forward in this thesis, however, the following section investigating existing case studies will report the performance according to the measures used in the original report.

Table 2 - IEA Annex 52 SPF Boundaries

Boundary Description	Boundary Levels											
	0	0+	1	1+	2	2+	3	3+	4	4+	5	5+
Ground source (circulation pump & ground heat exchanger)	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓
HP unit inc. internal energy use, exc. internal circulation pump			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Buffer tank inc. circulation pumps between heat pump & buffer tank							✓	✓	✓	✓	✓	✓
Circulation pump between buffer tank & building distribution system									✓	✓	✓	✓
Building heating/cooling distribution system											✓	✓
Auxiliary heating/cooling		✓		✓		✓		✓		✓		✓
SEPEMO Equivalent			H1		H2	H3			C3		H4	C4

2.5 Long Term Heat Pump Performance in the UK

Investigations into the performance of heat pumps can generally be categorised as either simulation studies, in which modelling methods and software are used to simulate the heat pump operation, or experimental and field trials, in which systems operating in real world conditions are monitored. The following section describes the various field trials conducted in the UK along with the key performance figures as per the specified system boundary schema in the original report. A summary table of these studies is provided at the end of this section.

2.5.1 Energy Savings Trust Field Trial (EST) – Phase 1

One of the largest scale field trials to have been conducted in the UK was the two stage trial ran by the Energy Savings Trust (Roy, Caird and Potter, 2010; Energy Savings Trust, 2013) Phase one of the trial was based on a sample of 83 heat pumps. These systems were chosen to be broadly representative of the market and as such include ASHPs and GSHPs, installations in both private and social housing, new and retrofit installations, and different heat delivery systems such as radiators or underfloor heating. The results of this study have been analysed by many sources. Table 3 contains a brief summary of the first phase of the study, which ran for one year from spring 2009 to spring 2010, as reported by the EST and the Department of Energy and Climate Change (DECC). As mentioned in Section 2.4, the “System Efficiency” referred to here is an extension of the SEPEMO system to SPFH5, considering useful heat as heat delivered for space heating and heat delivered to the taps for domestic hot water.

The results presented by the DECC differ from those originally produced by the EST as the data set was reduced from 83 systems to 71 due to data quality issues found upon deeper inspection.

Table 3 - Summary of EST Phase 1 Findings (Roy, Caird and Potter, 2010)

Source	**No. of Systems**		**COP Range**		**System Efficiency Range (SPF H5)**		**Median System Efficiency**	
	ASHP	**GSHP**	**ASHP**	**GSHP**	**ASHP**	**GSHP**	**ASHP**	**GSHP**
EST (Roy, Caird and Potter, 2010)	29	54	1.2-3.3	1.3-3.6	1.2-3.2	1.3-3.3	-	-
DECC (Energy Savings Trust, 2013)	22	49	-	-	1.2-2.2	1.55-3.47	1.83	2.31

This trial was conducted to investigate the factors affecting the performance of heat pumps, including factors such as building efficiency, user behaviour, system sizing, types of heat sources and sinks, and installation practices. It is important to note that the first phase of these trials began before the current UK standard supporting the installation of heat pumps (Microgeneration Certification Scheme, 2019), was in place and as such the heat pumps were not installed to these recommendations. In fact, many systems were found to have been installed incorrectly and it is suggested that this may have been due to the complexity of having multiple contractors installing each system, leaving no single point of responsibility.

As can be seen in Table 3, this study found a range of performance throughout the UK. The report also suggested that the results were worse than similar trials conducted in Europe; this is investigated in Section 2.7. It is suggested that this ‘poor performance’ could be attributed to the UK’s old and inefficient housing stock, cold and damp climate, and less developed market, leading to relative inexperience (Roy, Caird and Potter, 2010; Energy Savings Trust, 2013).

Despite the underperformance relative to European studies, the EST study found user satisfaction to be high with the installed systems, with a reduction in heating bill for some customers, especially those not previously connected to the gas grid.

Many users did express difficulty in understanding the operating instructions for the system along with the control system, and as such one of the key outcomes of this study was a call for clearer and simpler consumer advice, along with a review of the heating controls. As such, following Phase 1 the EST worked to improve the heat pump installation guidelines and training, along with the DECC and the MCS (Microgeneration Certification Scheme), a standards organisation that certifies low carbon energy technologies and contractors.

2.5.2 Energy Savings Trust Field Trial (EST) – Phase 2

Phase 2 of the field trial involved monitoring 44 of the systems from phase 1 and as such the systems were not installed using the now updated MCS guidelines (Energy Savings Trust, 2013). Prior to selection, each of the installations in phase 1 was analysed to understand what factors affected the system performance and manufacturers and installers carried out a number of modifications to 32 of the sites. The 44 systems chosen were typically the lower performing systems in phase 1 to allow for monitoring the effect of the interventions, but with the inclusion of a few well performing sites to act as benchmarks. Where interventions had occurred, they followed the updated MCS guidelines where possible.

The breakdown of these systems can be seen in Table 4.

Following the interventions noted below, the systems were monitored for a further year, from spring 2011 to spring 2012, and it was expected that the performance of the systems would increase. This phase of the study adopted the SEPEMO SPF H2 and SPF H4 to monitor the performance of the systems, but also recorded the “System Efficiency” again to compare the results directly to phase 1.

Table 4 - Breakdown of EST Phase 2 Field Trial Systems

Classification	No. of Sites	Example of Intervention	Comments
Major Intervention	12	Replace heat pump Repair a leak Recharge refrigerant	Requires input from HP expert & specific manufacturer
Medium Intervention	9	Adding variable speed circulation pumps Installing low temperature emitters Decontaminating ground loops	Carried out by competent plumber
Minor Intervention	11	Improvement to control regime Extra insulation to pipes Disable auxiliary heater	Overseen by householder
No Change	6	-	
New Site	6	-	All ASHPs – installed to MCS guidelines

Table 5 summarises the results from this trial, and Figure 12 shows the effect of the interventions on the system efficiencies.

Table 5 - EST Field Trial Phase 2 Results (Energy Savings Trust, 2013)

No. of Systems (Total)		Mean SPF H2 (No of Systems)		Mean SPF H4 (No of Systems)		Mean System Efficiency - SPF H5 (No of Systems)	
ASHP	GSHP	ASHP (15)	GSHP (21)	ASHP (15)	GSHP (22)	ASHP (17)	GSHP (27)
17	27	2.68	3.1	2.45	2.82	2.11	2.3

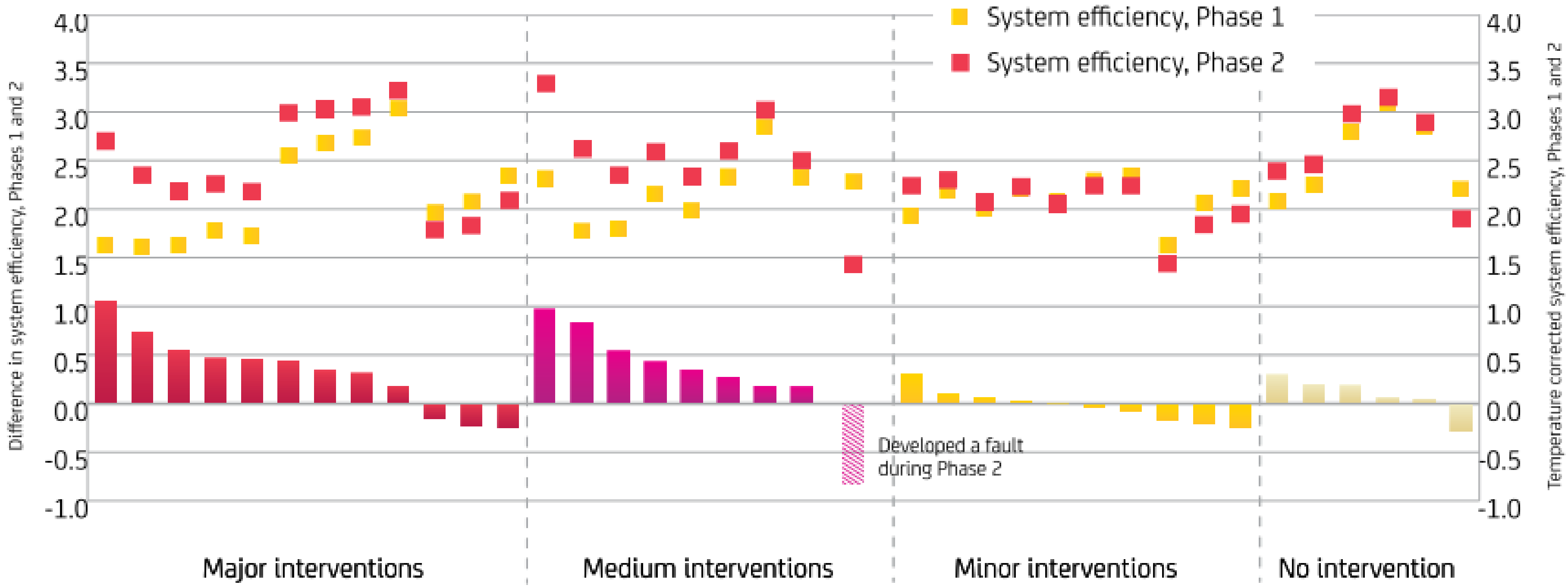


Figure 12 - EST Field Trial Change in System Efficiency from Phase 1 to Phase 2 (Energy Savings Trust, 2013)

It can be seen that the majority of the interventions led to an improvement in performance, though this was only small in the case of minor interventions. This indicates that the underperformance in the first phase of the trial was at least partially understood, though the improved performance values are still relatively low. In some cases, however, the performance is shown to decrease between the two phases. This was attributed by the study's authors to a change in user behaviour to the detriment of the system efficiency. In general, the GSHPs were found to have a higher value of SPF, but also a higher distribution of reported performance than the ASHPs. Customer satisfaction was again found to be high throughout the trial, with more than 80% of the consumers satisfied or very satisfied with the hot water and the space heating produced from the heat pump.

2.5.3 Renewable Heat Premium Payment (RHPP) Trials

Another large scale field trial in the UK involved the analysis of data collected on systems installed under the Renewable Heat Premium Payment, a scheme that provided subsidies to install renewable heat systems in residential properties (Lowe *et al.*, 2017). This trial took data from over 700 heat pump sites, collecting data every two minutes for 17 months from October 2013 to March 2015. This data analysis was complimented by an analysis of compliance with MCS, and a case study looking at 21 cases in more detail. From the 700 systems analysed a number were filtered out due to having SPF values perceived to be too high or low and likely to be caused by monitoring anomalies. The results of the remaining systems are shown in Table 6.

Table 6 - RHPP Field Trial Results

	SPF H2 (SEPEMO)		**SPF H4 (SEPEMO)**	
	GSHP	**ASHP**	**GSHP**	**ASHP**
No. of Systems	92	292	92	293
Mean	2.93	2.64	2.77	2.41
Median	2.81	2.65	2.71	2.44

The report notes that missing heat meter data will have had an effect on the SPF values, but this is expected to be less than 4%. It is also noted that the heat meters used in the trial were calibrated for water not glycol and as such SPF values could be overestimated by 4-7%. Neither of these correction factors are included in the published results.

Some general observations from this report include that GSHP systems outperform ASHPs as expected, and systems with underfloor heating again outperform those with traditional radiator systems. The study conducts an investigation into the factors affecting the poor SPF values and concludes that there is no single factor accounting for the performance but a myriad of factors that all contribute, including:

- Cycling time – A very large proportion of ASHPs were found to have short on-to-on cycle times of 10 minutes, whereas GSHPs had a median cycle time of 18 minutes.
- High flow temperatures – this increases the temperature lift required by the heat pump, thus increasing the energy used and reducing the performance.
- Presence of mixing circuits – This goes against MCS guidance but could have been carried over by an installer from their gas boiler experience.
- Excessive use of immersion heater – more than half of the sites with an SPF <2 had immersion use greater than 20% of the total electricity, compared to the average of 12%.
- Poor control such as setting the hot water thermostat to a higher temperature than achievable by the heat pump alone.

The detailed case study of the 21 systems found high satisfaction with over 80% being satisfied or very satisfied with the system and with the level of training material provided. However, the notion of satisfaction was found to be a complex one, with factors such as thermal comfort, running costs, ease of use, technical integrity, noise levels, and controllability being found to affect it. The control strategies implemented in these 21 systems varied widely, and some home-owners were found to have been deliberately experimenting with different operating strategies.

Despite the high levels of satisfaction, 10 of the 21 systems experienced a significant problem of one form or another following installation indicating that follow up visits after installation would be useful and could help maintain the system performance over the long term. The investigation into MCS compliance found that it was not possible to determine which version of MCS was applied to each installation but showed that heat pump sizing and radiator sizing were both either poorly understood or poorly expressed at the point of installation. The annual energy use estimate from the installers was also found to have a poor correlation to the actual measured energy usage which could be due to the complex nature of the calculations, or the unpredictably mild winters during the monitoring period. Weather compensation was found to be used in 64% of the installations, as per the recommendations in MCS version 4.0, but it is suggested that in some circumstances this may not be the most effective strategy.

The overriding conclusions of this study were that the performance of the heat pumps is sensitive to the dwelling with factors such as the specified heating system, controls, commissioning, and the operational and lifestyle decisions of the occupants all having an impact. It is also recommended that the controls should be optimised to ensure resistance heating is not used excessively, but still used for sterilisation of the DHW.

2.5.4 Harrogate

Another UK based trial involved monitoring 10 domestic GSHP systems supplying space heating and DHW to 10 similar small, social housing bungalows in Harrogate (Stafford, 2011). In this study each GSHP system was identical and included an IVT Greenline C6 GSHP fed by a single borehole heat exchanger (BHE), a 165-litre storage tank, and was connected to conventional radiator systems that were oversized by 30% to compensate for the lower flow temperatures. They also included a cassette back up heater that could run at 3kW or 6kW depending on the heat demand. The bungalows themselves were all small one or two storey buildings with approximately 60-

70m^2 floor area, and had all had cavity wall insulation, double glazing, and increased loft insulation prior to installation of the heat pumps. These systems had been in operation for at least one year before monitoring began but were monitored from January to December 2010.

The results show an average SPF H3 of the 10 properties of 2.38 with monthly values ranging from around 1.9 to close to 3. These SPF values do not include the distribution pump power. When it is included, becoming SPF4, the value reduces by 0.08-0.28. The highest monthly SPF values were found in the spring and autumn as expected, as the output during these periods is still dominated by space heating where there is a relatively low temperature lift required, whereas in the summer up to 90% of the output is for the DHW which requires a higher temperature lift and caused significant part loading issues.

The heat pumps were found to be operating at part load for the majority of the time, even in buildings with high temperature demands, suggesting that they were oversized for the dwellings, and the back-up cassettes were generally only used for the pasteurisation cycle, that is, the routine heating of the water in the storage tank to 60°C to avoid legionella growth. This practice was recommended from the MCS Heat Pump Installer Standard MIS 3005 version 3.1a onwards(Microgeneration Certification Scheme, 2019).

Despite the fact that the heat pump systems were identical, and the bungalows in which the systems were installed were similar, a range in performance was found. The differences between the different properties were attributed to various factors including variation in internal temperatures, the combinations of settings modified to achieve this temperature, the DHW temperature set points, the different emitter areas, and the difference in user behaviour, for example opening a window or using Thermostatic Radiator Valves (TRVs). The total electricity used by the systems was found to vary significantly between the households, though the electricity used by the heat pump compressor was found to account for 76-85% of this.

A further paper investigated one of these systems in greater detail, comparing its performance and operating behaviour in the context of the whole group of 10 (Stafford and Lilley, 2012). This system, known as System A, was found to have an SPF4 of 2.2, compared to 1.99-2.54 for the other nine systems during the monitoring period of March 2010 to Feb 2011, a slightly different 1-year period from the original study. The monthly SPF values ranged between 2 and 2.5. System A was found to have relatively poor performance in the winter and good performance in the summer, despite an average temperature lift required of this system. This behaviour was found to be readily explained by the DHW temperature set point and compressor cycling behaviour. The DHW set point temperature was found to be relatively low, meaning that when DHW dominated the heat demand in summer, this system operated at a high efficiency compared to the remaining systems.

In System A, the DHW tank was also located within the thermal envelope of the building and as such the tank losses were minimised. Additionally, this system was found to have a significantly high number of cycles when providing space heating compared to the other systems. It is understood that excessive cycling increases the electrical consumption of the system, in part due to the high start-up currents drawn by the compressor, and thus drives a reduction in SPF value. Stafford and Lilley (2012) propose that the cycling behaviour in this case could have been caused by behavioural practices such as opening windows for fresh air, and building fabric issues, both of which could cause significant heat losses. Excessive cycling could also be due to a system control with too small a temperature difference between start up and shut off temperature, called the hysteresis setting, though it is not thought this played a part in System A’s performance issues.

2.5.5 Wales

A year-long monitoring study of Exhaust Air Source Heat Pumps (EASHP) was carried out for a micro community of low carbon dwellings in Wales (Littlewood and Smallwood, 2017). Exhaust air source heat pumps are used extensively in Scandinavia and essentially use the exhaust heat from inside the building that would otherwise be lost to the outside environment as the source of heat to the heat pump. The low carbon development being monitored consisted of a combination of residential properties including houses with two, three, or four bedrooms, a first-floor maisonette with one bedroom, and eight flats with one bedroom either at ground level or first floor level, however the report details the COP of only one flat. The COP was found to have a range from 0.37 to 1.733 over the monitoring period (July 2013 to June 2014), which is dramatically lower than the manufacturer's provided value of 3.15. This poor performance was attributed to a number of factors including building fabric issues, and incorrect testing and commissioning of the installed heating and ventilation systems. The knowledge gap with end users was again highlighted as a key failing, with users developing inefficient heating strategies due to unfamiliarity with the system control.

2.5.6 Northern Ireland

One of the perceived limitations of heat pumps are the low temperatures of the heat produced, leading to a requirement for well insulated buildings and often larger heat emitters to be installed. A cascade heat pump addresses this and allows for high temperatures through the implementation of a secondary refrigerant loop, as in Figure 13.

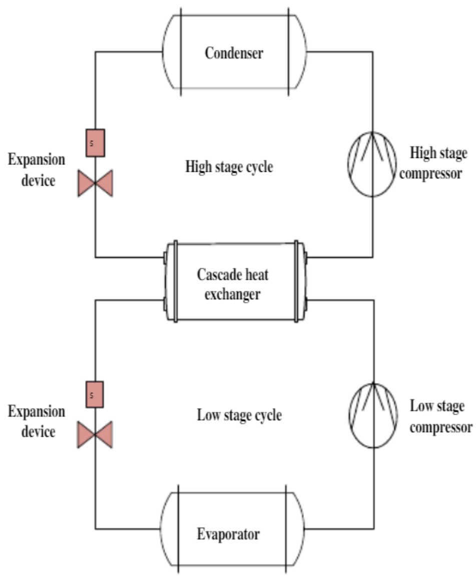


Figure 13 - Schematic of Cascade Heat Pump (Boahen, Amoabeng and Mensah, 2016)

A case study in Ulster, Northern Ireland investigated a system with an 11kW cascade ASHP with a 600-litre buffer tank that had been retrofitted to a small two storey house with approximately 96m^2 floor area. This was directly compared to the neighbouring house, also a two storey with 96m^2 floor area, using a traditional gas boiler (Shah *et al.*, 2018). These houses were monitored for a period of one year from December 2014 to December 2015.

The buffer tank was installed to shift the heat peak demand from first thing in the morning, allowing the water in the tank to be charged overnight with a lower demand, lower cost electricity, and then discharged first thing in the morning rather than having the heat pump directly heat the house. This tank was capable of meeting 8kWh of heat demand and the inclusion of the buffer tank meant the system had three operating modes as shown with the corresponding SPFs in Table 7.

Table 7 - Operation Modes and Performance for High Temperature Cascade Heat Pump with Buffer Tank

Mode of Operation	Description	COP Range	COP Average
Direct Heating	The heat pump directly provides heating	1.76-2.61	2.2
Storage	The heat pump charges the water in the buffer tank, adding heat during times of low demand	1.11-1.65	-
Combined	Combination of direct and storage, with charging and de-charging of the buffer tank	1.7-2.43	-

Naturally the storage and combined modes are less efficient due to the losses incurred in the storage tank and it was determined that the low COP of the system in storage mode made it inefficient for continuous operation, but useful in quickly providing the initial heat required first thing in the morning. A number of factors were found to affect the performance of this system including the air temperature and humidity as this drives the need for defrost cycles during which no heat is being provided to the building. The high flow temperatures requested, which were 75°C in direct mode and 80°C in storage mode, also affected the heat pumps' performance. To increase the efficiency of the system it was suggested that the charging and discharging time of the storage tank should be as close as possible, avoiding heat losses from the tank. It is also thought that a lower storage tank temperature would also improve the COP and reduce heat losses. This would require balancing with the need for larger heat emitters though as it was found that a flow temperature of 45°C would save 25% on running costs and CO_2 emissions compared to the 75-degree systems but would only emit 50% of the heat, thus driving the need for larger more expensive heat emitters.

2.5.7 Non-Domestic Renewable Heat Incentive

For domestic properties, the RHPP was superseded by the Renewable Heat Incentive (RHI) in April 2014, a scheme in which quarterly payments are given to people who have installed renewable heating systems, for up to seven years. The size of these payments is dependent on how much renewable heat the system has produced (Ofgem, 2020a). The non-domestic RHI is similar but for commercial, public, or industrial premises. This began in 2011 and payments can continue for up to 20 years (Ofgem, 2020b). 28 GSHPs and Water Source Heat Pumps (WSHPs) installed in non-domestic applications under the non-domestic RHI scheme were monitored to provide an insight into their performance (Hughes, 2018a). 21 of these systems were monitored from mid-2014 to June 2016, and an additional seven from March 2015 to June 2016. However, of these 28, nine systems have been omitted due to data issues. The systems studied varied widely in complexity, application, and design and of the 19 systems, six are WSHPs and 13 are GSHPs. Five of the ground source systems have vertical BH ground loops and the remaining eight have horizontal ground loops. Of all the systems, 15 achieved an SPF H2 of 2.5 or greater, and six of these reached a value of 3 or greater. The SPF H4 figures for these systems over a one-year period can be seen in Figure 14.

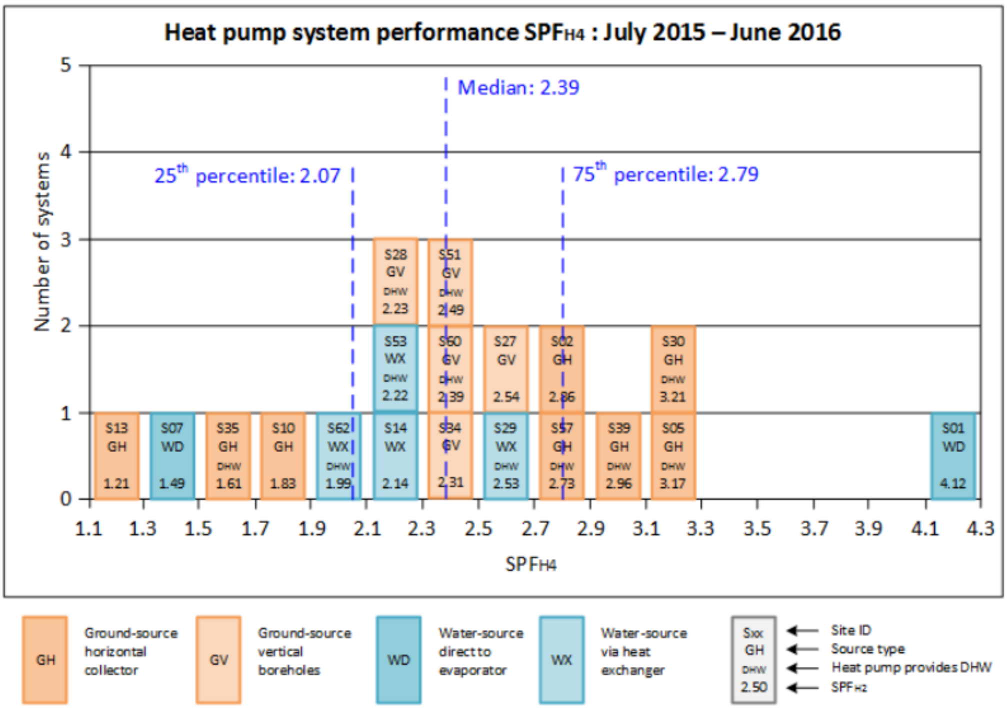


Figure 14 - System Performance of 19 systems for 12 months July 2015 to June 2016(Hughes, 2018a)

Investigations by Hughes (2018a) into the performance of these systems found a number of interesting conclusions including:

- Systems with underfloor heating did not necessarily have a higher performance than those with radiators, even when those radiators had not been oversized to account for the low flow temperatures from the heat pumps
- The hours of operation of the heating system was shown not to have a significant impact on system performance, though longer than necessary operating hours will potentially cause undesirable energy wastage
- No significant difference was found between heat pumps from different manufacturers

The report highlighted the need to look at each system individually as each application will require bespoke system design, integration, and control. However, it also suggested that the following points would be universally beneficial to a system’s performance:

- Maximising the source temperature at the heat pump evaporator inlet

- Minimising the sink temperature at the heat pump condenser outlet
- Minimising the energy usage of the auxiliary equipment
- Avoiding exceptional heat losses
- Using the correct configurations of system controls

2.5.8 Croydon

A study with a slightly longer monitoring period analysed data from a three storey industrial building in Croydon, collected over three years from September 2000 to July 2003, at which point the building was vacated and the system hibernated (Witte and Van Gelder, 2007). This building heated approximately 2,310m^2 of office space using 85 water-to-air heat pumps, and 690m^2 of warehouse facilities with a 26kW water-to-water heat pump through and underfloor heating system. The system was fed by 30 single U-tube loops buried in 100m deep boreholes. A dry cooler was incorporated in this system with the intention of storing cold in the ground during times where this can be done with high efficiency, to then be released to accommodate the higher cooling loads of the building. However, this system was expected to become operational in 2004/2005 season and as such no data for the system operation is available. It was also found that the actual cooling load was 20% higher than predicted, and the heating load was 30% lower than modelled, likely to be in part due to higher occupancy levels than was input into the simulations.

The analysis found that the fluid temperatures of the system remained within the required operating temperatures during the three years of operation but had a higher amplitude than predicted. This was due to the horizontal connecting pipes experiencing a seasonal temperature effect larger than predicted, thus, to improve the performance of the system additional insulation was proposed by the study’s authors. As the analysis of the system data focussed on the comparison of BHE and ambient temperatures and the thermal loads on the ground rather than the system performance, no COP or SPF data is available. A paper reporting on the first year of operation highlights a COP of 3.0 in heating mode and 3.4 in cooling mode, though this does not include any data from the warehouse underfloor heating system (Witte, van Gelder and Serrão, 2002).

2.5.9 Leicester

One of the longer term case studies of GSHP performance within the UK is the performance monitoring of a large system at De Montfort University in Leicester (Naicker and Rees, 2018). This system provides heating and cooling to a 5-7 storey building with a variety of rooms and a net floor area of 16,647m^2. The GSHP system comprised of x4 water-to-water heat pumps with a heat capacity of 110kW and a cool capacity of 120kW each and the system was fed from x56 borehole, single U-tube, heat exchangers buried to 100m deep. Table 8 shows performance of the system using the SEPEMO SPF definitions.

Table 8 - SPF Values for different periods of operation

Period	SPF H1	SPF C1	SPF 1	SPF 2	SPF 4
May 2010 to April 2011	2.89	3.99	3.31	2.69	2.22
May 2011 to April 2012	3.55	3.87	3.67	3.16	2.61
Feb 2010 to July 2012	3.19	4.06	3.54	2.97	2.49

It was concluded in this study that the borehole heat exchangers were underused but performing within capacity and not the cause of any detrimental performance. To assess the heat pump's performance in isolation the measured temperatures were compared to predicted outlet temperatures calculated from a parametric model derived from the supplied manufacturer's data. This comparison showed a consistent ~7% underperformance of the heat pump compared to the manufacturer's data. It was assumed that this difference was due to factors such as variations in hydraulic conditions, fluid properties, and variation in refrigerant charge etc. compared to the manufacturer's conditions. This is to be expected and does not explain the perceived underperformance of the system. Instead, this was attributed, at least in part, to the system operating frequently with short cycle times. It was shown that the predicted heating and cooling loads for the building were overestimated, and this led to an oversized system operating at part load conditions for a large proportion of the time. A high frequency of small loads coupled with a simple on-off system caused an increase in short cycle operation which induces significant losses in efficiency when compared to the steady state. This is in part due to the increase in time during which the circulating pumps will be running and demanding power whilst producing no useful heat or cool output as the compressor was designed to run for 180 seconds prior to the compressor starting and similarly run for an additional 180 seconds after compressor shut down. The authors have made many suggestions for how to better deal with part load than frequent cycling of the heat pump, including an incorporation of buffer tanks to help decouple the heat pump from the building, incorporation of a smaller capacity lead heat pump, and the use of variable speed compressors to reduce dynamic losses and excessive circulation pump usage. It was suggested that a reduction in the temperature for the heating circuit would have also been beneficial to the efficiencies obtained, though the feasibility of this measure is entirely dependent on the heat emitters available.

2.5.10 Grangetown Nursery - Cardiff

Another GSHP system monitored over a period of three years in the UK is the open loop system retrofitted to a school in Cardiff and monitored from 2015 to 2018 (Boon *et al.*, 2019). This system provided heating only and involved x2 11kW GSHPs with a well doublet source. The abstraction well was at a depth of 22m, the rejection well 18m, and the system was set up to allow the production and rejection wells to be switched should any intolerable thermal interference occur. This paper also suggested a 100-litre buffer tank was incorporated into the system and connected to the school’s existing system of radiators. This system was found to have a very high SPF H4 of 4.5 over the monitoring period. This is an impressive value, but it is suggested that the heat pumps’ performance was negatively impacted by the variability of the source temperature, which was seen to decrease as heat was abstracted over the heating seasons and was unable to fully recover during the summer periods. The reduction in source temperature of around 2°C over the three years is theorised to have caused a performance reduction of 4% in the heat pumps (Boon *et al.*, 2019). As such, to further improve the system's efficiency it is suggested that a larger spacing value between boreholes would be implemented where possible to negate thermal interference and allow for better recovery. It is also recommended that the GSHP plant room and pipework should be maintained in a more thermally insulated building to reduce losses. Overall, the high performance of this system demonstrates that heat pumps are capable of performing to a high efficiency within the UK though it is hard to isolate the successful criterion for this system to apply elsewhere without more detailed analysis.

2.6 Case Study Summary

Table 9 summarises the performance of the long-term case studies identified in the literature, though due to the different performance indicators used, a direct comparison between each of them is difficult. The expected trends of GSHPs outperforming ASHPs due to the more stable, higher temperature heat source is shown to be true of these studies. The GSHP systems typically have an SPF H2 of close to 3, and an SPF H4 of between 2 and 2.9, but can perform to much greater efficiencies within the UK climate, as shown by the Cardiff case study, reaching an SPF H4 of 4.5.

A number of factors affecting the performance of the heat pump systems can be seen to be recurring through the case studies identified, including among others:

- Control methods
- System design and installation
- Cyclic behaviour of heat pumps
- User behaviour, perhaps due to lack of understanding of the system
- Type of heat emitters
- Excessive auxiliary heating usage

It is noticeable that when these issues are addressed, as in phase 2 of the EST trials, an increase in system performance is achievable, in this case up to an additional 1.07 on the SPF. However, it would be preferable if these factors could be resolved during the commissioning of the system rather than revisiting the system after, requiring additional time and resources, and leaving the system to underperform in the meantime. The alternative would be a smart control system that would be able to monitor some of these conditions and automatically adapt, allowing for passive optimization and ultimately further carbon savings for heating in the UK.

It is also apparent that there is limited number of multi-year case studies monitoring the performance of heat pump systems in the UK, particularly for energy pile systems, and as such it is difficult to draw any conclusions on their long-term performance. The research in this thesis aims to go some way to filling this gap.

The performance of the systems in Table 9 will be compared to field trials conducted throughout Europe in the following section.

Table 9 - Summary of Long-Term UK Heat Pump Performance

Trial/Study	Heat Pump Type	Domestic / Commercial / Multi-Occupancy	Monitoring Duration	No of Systems	Heat Pumps Per System	Heat Source	Average Performance Factor (as per SEPEMO unless stated)			
							COP *Range*	SPF 2 *Range*	SPF 4 *Range*	SPF 5 *Range*
EST UK Field Trials Phase 1	ASHP	Domestic	12 Months	22	1	Various	-	-	-	1.83 *1.2 - 2.2*
	GSHP	Domestic	12 Months	49	1	Various	-	-	-	2.31 *1.55 - 3.47*
EST UK Field Trials Phase 2	ASHP	Domestic	12 Months	17	1	Various	-	2.68	2.45	2.11
	GSHP	Domestic	12 Months	27	1	Various	-	3.1	2.82	2.3
RHPP Field Trials	ASHP	Domestic	17 Months	292	1	Various	-	2.64	2.41	-
	GSHP	Domestic	17 Months	92	1	Various	-	2.93	2.77	-

RHI Non-Domestic Trials	GSHP	Non - Domestic	12 Months	13	1	Various	-	2.88 *2.24-3.89*	2.43 *1.21-3.21*	
	WSHP	Non - Domestic	12 Months	6	1	Various	-	2.96 *2.43-4.49*	2.42 *1.49-4.12*	
Harrogate	GSHP	Domestic	12 Months (Jan 10-Dec 10)	10	1	1 BH per system	-	2.38 (SPF 3)	-	
	GSHP	Domestic	12 Months (Mar 10-Feb 11)	10	1	1 BH per system	-	-	*1.99-2.54*	-
De Montfort University	GSHP	Non - Domestic	29 Months	1	4	56 Boreholes	-	2.97	2.49	-
Croydon	GSHP	Non - Domestic	14 Months	1	85	30 Boreholes	3*-heating	-	-	-

							3.4*– cooling *Boundaries not specified			
Cardiff	GSHP (Open Loop)	Non - Domestic	36 Months	1	2	X1 Well Doublet	-	-	4.5	-
Wales	EASHP	Domestic & Multi-Occupancy	12 Months			Air	*0.37-1.733* **SPF 4 Boundary*	-	-	-
Ulster	Cascade ASHP	Domestic	12 Months	1	1	Air	2.2* *1.11-2.61** **SPF 4 Boundary*	-	-	-

2.7 Comparison of UK trials to European trials

To understand what is achievable in terms of performance improvements in the UK systems, a number of studies have compared the results of the UK field trials to those reported in Europe.

The EST field trials themselves, report that performance figures observed in the UK are low when compared to similar field trials across Europe, particularly for GSHP systems (Roy, Caird and Potter, 2010). The report suggests that the underperformance is in part due to the damp British climate and the inefficient housing stock in the UK, but also points towards the quality of installations and user behaviours as less predictable factors affecting performance. It is noted that the UK heat pump market was not as mature as the European market at the time, and this could lead to quality issues with the installations due to installer inexperience.

The results published in the first phase of the EST trial were also directly compared against trials run by the Swiss Federal Office for Energy in Switzerland, and the Fraunhofer Institute ISE in Germany. The comparison can be seen in Figure 15 and Figure 16 (Delta Energy & Environment Ltd, 2011). This report shows that whilst some of the UK heat pumps were matching or exceeding the European equivalents, typically they are underperforming.

Similar conclusions were drawn from this study to that produced by Roy, Caird and Potter (2010), advocating that the lower quality of insulation in the UK housing stock was a key factor in this perceived underperformance. It is also suggested that the German and Swiss heating systems are better quality than those in the UK, and that the UK and German installations provide a higher percentage of DHW than the Swiss systems. It is supposed that a combination of these factors is causing the poor performance relative to the European systems.

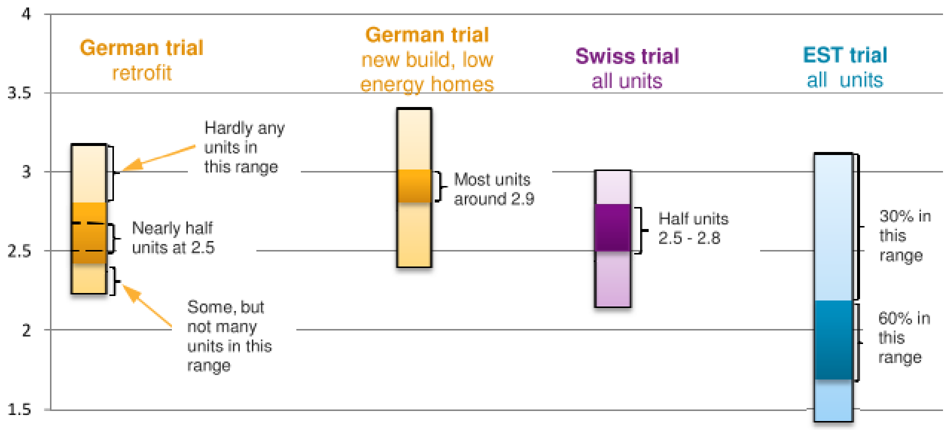


Figure 15 – SPF Comparison of ASHPs in UK and European Trials (Delta Energy & Environment Ltd, 2011)

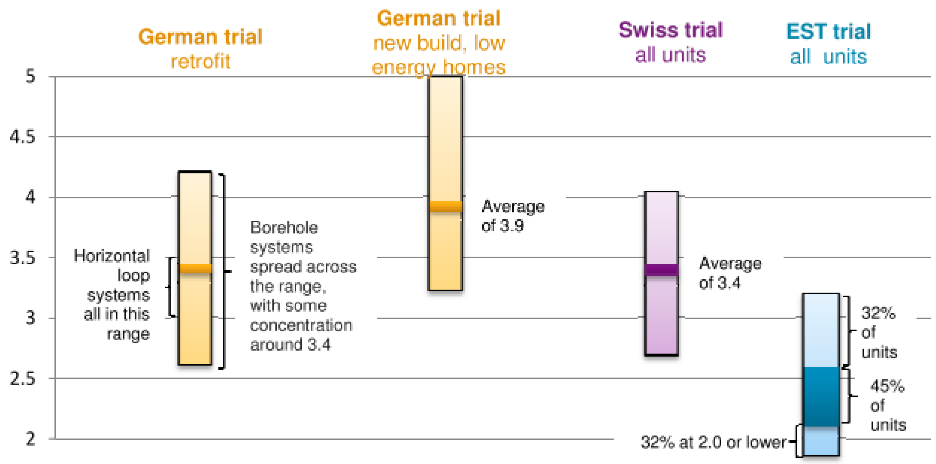


Figure 16 - SPF Comparison of GSHPs in UK and European Trials (Delta Energy & Environment Ltd, 2011)

As such, a number of potential improvements to the UK heat pump industry & installation process are suggested by Delta Energy & Environment Ltd (2011) as ways of closing this gap to the European systems, including:

- Sizing the heat pump correctly – it was noted that under sizing of the heat pump was the most common problem and resulted in extensive use of the auxiliary heating systems.
- Correct set up of automatic control settings to avoid unnecessary heating.
- Correct specification of the ground loop
- Correct set up of the whole integrated system to operate coherently and efficiently.

- Using low flow temperature heat distribution systems such as underfloor heating or using oversized radiators for retrofit properties.
- Maximising building insulation to allow the heat pump to run for long periods at low temperatures.
- Educating end users to not use heat pumps as they would traditional boilers.

However, it is noted in this analysis that different system boundaries were involved in the reporting of performance through these studies, and as such the wider boundary used in the UK trials inevitably mean the reported SPF values will be lower than the other trials.

To address this, a further study undertook an exercise to consolidate the system boundaries used in various European field trials and compare the performances like for like (Gleeson and Lowe, 2013). This study compared the UK EST data to field trials in Germany, Switzerland, Sweden, and Denmark, and the comparison can be seen in Table 10 and Table 11.

This comparison was used to address the supposed reasons for underperformance proposed in the study by Delta Energy & Environment Ltd (2011).

Gleeson and Lowe (2013) suggested that if the DHW had a significant impact as originally suggested, the UK results should fall between the Swiss and German results to reflect the number of heat pumps providing DHW in each case. It is also stated that the market conditions in the contrasting countries are the same, which should lead to similar use of materials and components in the heat pumps themselves, negating the argument of the heat pumps themselves playing a factor. In fact, this study reveals that some of the heat pump manufacturers used in the EST trials were also used in the Swiss and German trials. It is put forward instead, that the difference between these systems is that both weather compensation control of heat pump systems, and variable speed heat pumps, have a far higher market penetration in Europe than in UK. Finally, it is suggested that high envelope losses do not explain the poor performance in the UK. A comparison on existing buildings within the

Fraunhofer study shows the German systems to still have the greater performance, despite having higher heat losses.

The authors of this study propose that if the heat pump model, envelope losses, and emitters are not the cause of this disparity, then the quality of the installation could be the source of underachievement.

Table 10 - Comparison of European Field Trials – GSHP Performance (Gleeson and Lowe, 2013)

GSHP	JAZ 2			SPF $_{H2}$			SPF$_{H3}$			SPF$_{H4}$		
Trial	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range
FAWA	100	3.4	2.3-5.3									
LAHR	25	3.1	2.3-4.2									
SPTRI 2007	5	2.9	2.4-2.9							5	2.6	2.4-2.9
EST	10	2.4	2.4-3.5							17	2.5	1.4-3.3
SPTRI 2010							6	3.26	2.6-3.6			
Fraunhofer Existing							36	3.3	2.2-4.8			
Fraunhofer New				56	3.93		56	3.88	3.1-5.1	56	3.75	
DTI										138	3.03	3.1-5.1
No, Mean, Range	140	3.3	2.3-5.3	56	3.93		98	3.6	2.2-5.1	216	3.2	1.4-5.1

Table 11 - Comparison of European Field Trials - ASHP Performance (Gleeson and Lowe, 2013)

ASHP	JAZ 2			SPF $_{H2}$			SPF$_{H3}$			SPF$_{H4}$		
Trial	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range
FAWA	100	2.6	1.5-4.0									
LAHR	25	2.3	1.7-3.0									
EST	9	2.3	1.9-2.6						7	1.9	1.2-2.3	
Fraunhofer Existing							34	2.6	2.1-3.4			
Fraunhofer New				18	2.95		18	2.89	2.3-3.4	18	2.74	
DTI										12	2.33	2.3-3.4
No, Mean, Range	134	2.5	1.5-4.2	18	3		52	2.7	2.1-3.4	37	2.4	1.2-3.4

As previously shown in Figure 12, the performance of the EST systems improved somewhat in the second phase after a number of interventions. Comparing these results to the comparison in Table 10 and Table 11.

, the SPFs at boundary 4 for the ASHPs are found to fall between the results from the DTI study and the Fraunhofer study of new buildings, with the GSHPs still found to be underperforming compared to both of these studies. The same can be said of the results from the RHPP trials, with GSHPs in particular still struggling to match the levels of performance in Europe. Similarly, the Harrogate trial, with an average SPF 3 value of 2.38, also falls short of the values in both of the Fraunhofer studies and the SPTRI 2010 study. In this case, the highest performing Harrogate system has an SPF value lower than the worst performing system in both the Fraunhofer study of new builds, and the SPTRI study. The outlier in the identified literature is the open loop system in Cardiff, operating at an SPF higher than the average for each of the European studies.

As summarised by Rees and Curtis (2014), the series of large scale trials in the UK indicate that too many of the systems installed are performing poorly compared to installations in European countries, and even the increase in the performance shown in the more recent reports leaves the average seasonal performance short of the European standards. As shown by case studies such as the open loop system in Cardiff, UK systems are capable of reaching high SPFs, so investigation is required into why the majority of GSHP systems installed are not reaching their potential and how to mitigate this.

2.8 Annex 52 – Long-term performance of Commercial and Multi-Family GSHPs

This lack of long-term performance data for ground source heat pumps supplying commercial buildings or multi-family residential buildings was noted, and in 2019 a group of international researchers formed the International Energy Agency Heat Pumping Technologies Annex 52 (herein referred to as Annex 52) to address this gap. An initial literature review (Gehlin and Spitler,

2019) summarised the performance of 32 case studies, some of which have been touched on previously in this review. A table detailing the individual performance of these systems was presented by Spitler and Gehlin (2020) and is shown in Figure 17.

ID	Reference	Year	Location	Tot. m of Borehole	System Type [1]	Uncer-Tainty Analysis	Nom. Cap. [2] (kW)	Nom W/m	UGT[3] (°C)	SPF H1	SPF H2	SPF H3	SPF H4	SPF C1	SPF C2	SPF C3	SPF C4	SPF HC4	Annual	Monthly	Daily	Hourly	Binned
1	[58]	2017	USA, Fairbanks, AK	Horizontal–1463 m	C	N	21	14	2.4	3.5*										X			
2	[59]	2017	USA, Kalispell, MT	Ground-water	C	N	280		7.7				2.7						X				
3	[59]	2017	USA, Cedarville, AR	11,948	D	N	812	68	16.9				3.3				3.1		X		X		
4	[59]	2017	USA, Raleigh, NC	6126	D	N	300	49	16.4				4.0				4.3		X				
5	[59]	2017	USA, Albany, NY	20,574	D	N	1253	61	10.0				2.5				3.0		X				
6	[59]	2017	USA, Rochester, MI	24,969	D	N	1540	62	11.2				2.7				4.2		X				
7	[59]	2017	USA, Butte, MT	Mine water	C	N	175		8.1				3.7				3.6		X				
8	[59]	2017	USA, Greenville, SC	30,480	D	N	2153	71	19.5				4.4				5.2		X				
9	[59]	2017	USA, Denver, CO	Waste water	C	N	754		11.6									3.7	X				
10	[59]	2017	USA, Lincoln, NE	60,990	C	N	4900	80	11.6				3.6				5.3		X				
11	[59]	2017	USA, Muncie, IN	219,822	C	N	17,500	80	12.4									3.7	X				
12	[43]	2016	Greece, Athens	1200	C	N	55	46	20.0	6.4	5.6		2.9	6.3	5.5		2.7		X				
13	[43]	2016	Spain, Barcelona	1400	C	N	60	43	18.0	6.4	5.9		3.7	7.4	6.8		3.3		X				
14	[43]	2016	Slovenia, Benedikt	390	C	N	20	52	11.1	5.6	5.3		4.7		9.8		7.0		X				
15	[43]	2016	Portugal, Coimbra	875	C	N	70.4	80	17.5	5.4	5.2		4.3	6.8	6.0		4.0		X				
16	[43]	2016	France, Septèmes les Vallons	600	C	N	26	43	17.0	4.6	4.0		3.1		10.5		4.2		X				
17	[43]	2016	Romania, Oradea	1300	C	N	37	28	12.0	5.4	5.0		4.4	7.3	6.7		5.1		X				
18	[43]	2016	Italy, Padova	320	C	N	14	45	15.0	4.1	3.6		3.2	5.6	5.1		4.2		X				
19	[43]	2016	Spain, Valencia	300	C	N	18	60	17.7	4.7	4.5		2.9	5.3	4.8		2.9		X				

ID	Reference	Year	Location	Tot. m of Borehole	System Type [1]	Uncer-Tainty Analysis	Nom. Cap. [2] (kW)	Nom W/m	UGT[3] (°C)	SPF H1	SPF H2	SPF H3	SPF H4	SPF C1	SPF C2	SPF C3	SPF C4	SPF HC4	Annual	Monthly	Daily	Hourly	Binned
20	[48]	2014	Switzerland, Geneva	2700	C	N	240	89	11.7			3.1	3.0						X				
21	[46]	2013	Greece, Pylaia	1680	C	N	276	164	16.5	4.9				4.5					X				
22	[60]	2018	United Kingdom, Leicester	5600	C	N	480	86	10.6	4.1				3.2				2.5	X		X	X	
23	[57]	2017	Poland, Cracow	210	C	N	10	48	9.9			3.6*							X				
24	[56]	2016	Italy, Venice	720	C	N	50	69	14.9	4.0	3.7			4.3	4.0				X	X			
25	[36]	2004	Germany, Rostock	ATES	C	N			9.8	4.3									X				
26	[49–51]	2014	USA, Atlanta, GA	1464	D	Y	111	76	17.1				3.3				4.3		X	X			X
27	[37]	2008	Spain, Valencia	300	C	Y	17	57	17.1		3.5			4.3					X		X		
28	[45]	2011	Belgium, Brasschaat	ATES	C	N	195		11.4	5.6	5.9			6.0	26.1				X				
29	[33]	2017	Switzerland, Uster	869	C	N	33	38	10.8		3.9								X		X		
30	[42]	2013	Germany			N	270			3.5	3.0								X				
31	[42]	2013	Germany			N	54			4.9	3.6								X				
32	[42]	2013	Germany			N	57			5.2	3.6								X				
33	[42]	2013	Germany			N	122			5.7									X				
34	[42]	2013	Germany			N	68			4.4	4.1								X				
35	[42]	2013	Germany			N	75			6.2	5.7								X				
36	[44]	2011	China, Shanghai	22,400	C	N	1000	45	18.5	4.6				4.7					X				
37	[40]	2018	United Kingdom	Ground-water	C	Y	26			4.64	4.49		4.12						X		X		
38	[40]	2018	United Kingdom	Horizontal 2400 m	C	Y	93	38.75		3.76	3.44		2.86						X		X		
39	[40]	2018	United Kingdom	Horizontal 1200 m	C	Y	21.4	17.8		3.98	3.42		3.17						X		X		
40	[40]	2018	United Kingdom	Water	C	Y	96			3.11	2.72		1.49						X		X		
41	[40]	2018	United Kingdom	Horizontal 800 m	C	Y	22	27.5		2.36	2.24		1.83						X		X		
42	[40]	2018	United Kingdom	Horizontal 4000 m	C	Y	144	36		2.55	2.24		1.21						X		X		

ID	Reference	Year	Location	Tot. m of Borehole	System Type [1]	Uncer-Tainty Analysis	Nom. Cap. [2] (kW)	Nom W/m	UGT[3] (°C)	SPF H1	SPF H2	SPF H3	SPF H4	SPF C1	SPF C2	SPF C3	SPF C4	SPF HC4	Annual	Monthly	Daily	Hourly	Binned
43	[40]	2018	United Kingdom	Ground-water	C	Y	60			3.46	2.43		2.14						X		X		
44	[40]	2018	United Kingdom	1500	C	Y	54	36		2.88	2.76		2.54						X		X		
45	[40]	2018	United Kingdom	1500	C	Y	70.8	47.2		2.95	2.73		2.23						X		X		
46	[40]	2018	United Kingdom	Coils in river	C	Y	126			3.14	2.88		2.53						X		X		
47	[40]	2018	United Kingdom	Horizontal	C	Y	14			4.11	3.89		3.21						X		X		
48	[40]	2018	United Kingdom		C	Y	64			3.2	2.56		2.31						X		X		
49	[40]	2018	United Kingdom	575	C	Y	19.8	34.4		2.7	2.38		1.61						X		X		
50	[40]	2018	United Kingdom	Horizontal 1200 m	C	Y	22.9	19.1		3.22	3.95		2.96						X		X		
51	[40]	2018	United Kingdom		C	Y	38.3			2.85	2.69		2.49						X		X		
52	[40]	2018	United Kingdom	River water	C	Y	30			3.15	2.61		2.22						X		X		
53	[40]	2018	United Kingdom	Horizontal 1500 m	C	Y	40	26.7		3.21	2.88		2.73						X		X		
54	[40]	2018	United Kingdom	800	C	Y	40	50		3.48	3.15		2.39						X		X		
55	[40]	2018	United Kingdom	Open water	C	Y	268			3.1	2.62		1.99						X		X		

1 Centralized (C) or distributed (D). 2 Nominal heat pump capacities for either heating or cooling. In a number of cases, the heat pump capacity is not given and is estimated from the floor area and the specific heating or cooling load. 3 Undisturbed ground temperatures (UGT) are taken from the nearest location found in a world-wide database [62]. These values do not include local disturbances due to urbanization. Table entries with UGT left blank correspond to references for which specific locations are not given. * SPF values have been estimated from the authors' presented results.

Figure 17 - Performance of GSHP Systems in Commercial and Multi Family Buildings (Spitler and Gehlin, 2020)

Additionally, the annex, comprising members from Germany, Sweden, Finland, Netherlands, Norway, UK, and USA, compiled further case studies over the three-year working period that fell into this category. The final report for Annex 52 (Gehlin and Spitler, 2022) summarises these case studies, as shown in Figure 18 and the performance figures as per the Annex 52 boundary schema as shown in Figure 11 (Section 2.4).

	Sweden	Germany	Norway	UK	Finland	USA	Netherlands
Residential	4	1	1	-	-	-	-
Commercial	9	5	4	3	1	1	2
Industrial	1	-	-	-	-	-	-
Boreholes	12	3	5	1	1	1	-
Groundwater	2	-	-	1	-	-	2
Energy Piles	-	3	-	1	-	-	-

Figure 18 - Summary of Case Studies Covered in IEA HPT Annex 52 (Gehlin and Spitler, 2022)

It is to be noted that two of the three case studies contributed to Annex 52 by the UK are covered in this thesis.

A summary of the performances of these systems and which boundary levels they reported is provided by Gehlin and Spitler (2022). These performance figures highlight the range of performance factors achievable, indicating the difficulty in maintaining high efficiencies, but they also provide a useful benchmark for comparing the UK case to at each of the system boundaries.

Table 12 - Reported Performance for IEA HPT Annex 52 Case Studies - (Gehlin and Spitler, 2022)

System Boundary	Number of Reporting Projects	Measured Years	SPF Range	Years with an SPF of 3 or more	Mean SPF	Median SPF
SPFHC0	6	39	10.9-65*	100%	33*	33.9*
SPFHC1	14	66	1.5-7.2	88%	4	3.8
SPFHC2	11	62	1.4-13.0	80%	4.7	3.5
SPFHC3	3	26	0.8-12.0	62%	5	5.5
SPFHC4	12	57	1.2-8.8	44%	3.3	2.7
SPFHC5	4	21	1.1-3.7	10%	1.9	1.8
SPFH0	9	50	3.1-171*	100%	37*	32*
SPFH1	18	71	1.7-7.2	72%	4	3.8
SPFH2	15	71	1.5-6	72%	3.7	3.6
SPFH3	8	41	0.4-5.5	53%	3.3	3
SPFH4	12	55	1-4.4	49%	2.8	2.9
SPFH5	6	27	1-136*	30%	21*	2.4
SPFC0	8	45	13.5-173*	100%	60*	51*
SPFC1	9	41	1.1-13.2**	76%	4.4	3.9
SPFC2	11	58	1.6-128*	89%	22*	5.2
SPFC3	2	12	0.6-4.3	67%	2.9	3.2
SPFC4	5	27	0.6-5.8	28%	2.5	2.5
SPFC5	5	26	0.5-145*	35%	23.6*	2.4

Investigation into the performance of UK based heat pumps has highlighted an underperformance compared to European field trials (Delta Energy & Environment Ltd, 2011; Gleeson and Lowe, 2013). However, many of the studies and trials conducted monitor the systems for a short period of time, with longer term studies generally assessing data over a year-long period. Whilst the monitoring of such systems over a year allows for inter-seasonal effects to become present, multi-year monitoring allows for an examination of the longevity of the performance of these systems. This is important for GSHPs as the response of the ground will directly affect emissions savings possible when compared to traditional fossil fuel-based systems. It will also affect the financial payback period of the system due to the high capital cost associated with drilling boreholes. This is one of the primary limitations holding back deployment in the UK (EGEC, 2014; Karytsas and Choropanitis, 2017). The case study with the longest monitoring period was found to be the borehole based system installed at De Montfort University (Naicker and Rees, 2020) which was monitored for 38 months, however no such equivalent has been identified for energy pile installations, which are in theory more cost effective than their borehole counterparts. As such, these systems are of great interest, and through analysis the long-term performance can not only be determined, but understood, with factors causing potential underperformance investigated and addressed to allow for increased efficiencies moving forward. This will not only help increase their sustainability credentials, but also improve their business case, making them more attractive as an alternative to gas boilers. Furthermore, through comparison with additional non-energy pile case studies, parallels between borehole-based systems and energy pile-based systems can be drawn, potentially allowing for generalized conclusions to be drawn for ground source heat pump systems in the UK.

Upon investigating GSHP performance, it was also noted that a large number of the case studies conducted in the UK are focused on domestic installations for a single household (Roy, Caird and Potter, 2010; Energy Savings Trust, 2013; Lowe *et al.*, 2017). The systems installed for commercial buildings or centralized plants supplying heat to multiple buildings, are often much more complex, with many more component and/or control interaction points with the potential to introduce losses and reduce performance. As such any learning that can be achieved on these systems would be invaluable.

Additionally, none of the systems identified in this literature review utilise shared ground heat exchangers. As part of a separate body of work developing a policy brief on such systems, see Appendix A, a rapid evidence assessment was conducted, investigating systems that share a ground loop and have distributed heat pumps. This highlighted the potential benefits of such systems, including the opportunity to reduce the size of the ground heat exchangers due to the unlikelihood of all the users requiring peak output from their heat pumps at the same time (Bale, Barns and Turner, 2022). This is called the diversity of the shared ground arrays. The rapid evidence assessment also highlighted the absence of monitoring data for these systems and so investigations into their real-world performance, along with understanding the utilisation levels of these shared arrays would be incredibly useful.

3 Case Study #1 – The Crystal

The following chapter details the long-term performance of the ground source heat pump system installed at The Crystal Building in East London. This is a modified version of the report produced for the IEA Annex 52 (Turner, Loveridge and Rees, 2021),with some additional analysis included.

The objectives for this chapter are to:

- Evaluate the long-term performance of the ground source heat pump system at multiple system boundaries.
- Draw out any performance issues with associated causes and potential solutions.
- Investigate the long-term thermal performance of the energy piles, as an uncommon ground heat exchanger.

The chapter will be set out with an introduction to the system followed by an explanation of the methodology for the analysis, including the data cleaning required and KPIs used. The results of the analyses are then presented, firstly investigating the building and ground heat exchanger loads, moving on to the calculated performance factors, and then interrogating the temperature of the instrumented energy pile. Finally, the performances are compared to systems found in the literature and both conclusions on the systems performance and recommendations for improvements are collated.

3.1 System & Instrumentation

3.1.1 The building

The Crystal Building in London, Figure 19, opened in September 2012, was built for Siemens as an exhibition of sustainable technologies as well as an office space and conference facility. The heating, cooling, and domestic hot water demand of the building was designed to be met primarily from ground source heat pumps, with the addition of solar thermal and immersion sources for hot water and an auxiliary chiller for extremely hot days.

Figure 19 – The Crystal Building (Wilkinson, 2020)

Table 13 - Summary of the Building Features

Location	London, United Kingdom
Year of building construction	2012
Ground source system operation start date	2012
Building Type	Office & Exhibition building
Building floor area (net, gross)	6,920 m^2 gross
Monitoring start date	2013 – March – 24th
Monitoring end date	2021 – March – 23rd

Table 14 - Summary of the system configuration

Heat distribution	Underfloor, trench heating
Cooling distribution	Passive chilled beams, VAV, Low velocity displacement ventilation
Domestic hot water (DHW) production by system	Heat pump
Supplementary heat for DHW	Solar thermal & Immersion
Supplementary cooling	Air cooled Chiller – 400kW
Nominal capacity of supplementary heating for DHW	Immersion – 40kW
Design load for supplementary heating for DHW	Solar Thermal – 13 MWh/yr, Immersion – 13MWh/yr
Heating load (Predicted Building Demand)	307.20 MWh/year (44.39 kWh/m^2,yr)
Cooling load (Predicted Building Demand)	172.65 MWh/year (24.95 kWh/m^2,yr)
Heating load (Used for GL Design)	1293.56 MWh/year (186.93 kWh/m^2,yr)
Cooling load (Used for GL Design)	843.41 MWh/year (121.88 kWh/m^2,yr)
DHW	72.2 MWh/year (10.43 kWh/m^2,yr)
Heat pump type	Water-to-Water
Reversible	Yes
Compressor type	4 x Hermetic scroll
Speeds	Single Speed
Heat pump system	Centralized
Number of heat pumps	2
Nominal total heat pump heating capacity	814 kW_{th} (2x 407 kW)
Nominal total heat pump cooling capacity [kW_{th}]	780 kW_{th} (2x 385 kW) (Cooling only) 628 kW_{th} (2x 314 kW) (Cooling & Heating Simultaneously)
Refrigerant	R410a

Table 13 and Table 14 give the main characteristics of the building and the GSHP system. It should be noted that the information has been collated from a number of sources, as follows.

The heating and cooling loads shown include both the assumed thermal profile of the building, and the thermal profile used in the design of the ground loop system. The predicted building demands has come from a performance report by the system designers (GI Energy, 2015) whereas the loads used in the ground loop design have come from a scope of works document for the project (Unknown Author, 2012). It is unclear why the assumed load profile was not used for the ground loop design.

The DHW load has been calculated from figures suggesting that the 13MWh/yr to be produced by the solar thermal system would account for 18% of the total DHW load (Alexander and Kiauk, 2014).

There are 4 compressors and 4 capacity control steps for each heat pump, suggesting that each compressor is single speed only, with the activation of each compressor allowing for an additional capacity control step.

3.1.2 The ground source system

The system has been designed to meet the ‘worst case’ scenario of providing up to 614kW of heating, which is expected to occur in January, and 614kW of cooling, which is anticipated to be in August, simultaneously and as such the ground loop has been designed for significantly larger loads than are expected, as shown in Table 14.

These loads were designed to be met by two centralised WSHF-SXC 115D Clivet heat pumps, referred to herein as heat pump A and heat pump B, capable of simultaneous heating and cooling at all times. This is achieved through heat recovery, avoiding the need for cycle inversion. If the heat pump is operating in heating mode, a three-point modulating valve is opened to allow for the ground loop fluid to mix with the fluid in the chilled water (CHW) loop. This allows the CHW set point temperature to be achieved, with the remainder of the heat needed to achieve the low temperature hot water (LTHW) set point coming from the ground loop. Similarly, if the heat pump operates in cooling mode, another three-point modulating valve can be opened to allow the heat generated to be discharged to the LTHW loop until the LTHW set point temperature is achieved. The remaining heat is then discharged to the ground loop. The heat pumps were designed to operate in a duty-assist manner and have a heating capacity of 407kW, and a cooling capacity of 385kW when operating to provide cooling only, or a cooling capacity of 314kW, when providing heat and cool simultaneously.

Three 11 kW Grundfos TP80-330/2 single head pumps are used to circulate the fluid within the ground loop. The circulation pumps internal to the heat pumps move the fluid between the heat pumps and the low loss header. A 750-litre buffer vessel is installed between the heat pumps and each of the CHW and LTHW distribution loops, to reduce the short cycling of the compressors. Two 7.5kW single head Grundfos TP100-200/4 circulation pumps are installed after the buffer vessel, circulating the fluid to the plate frame heat exchanger which transfers energy to the building distribution system. This is shown diagrammatically in Figure 20.

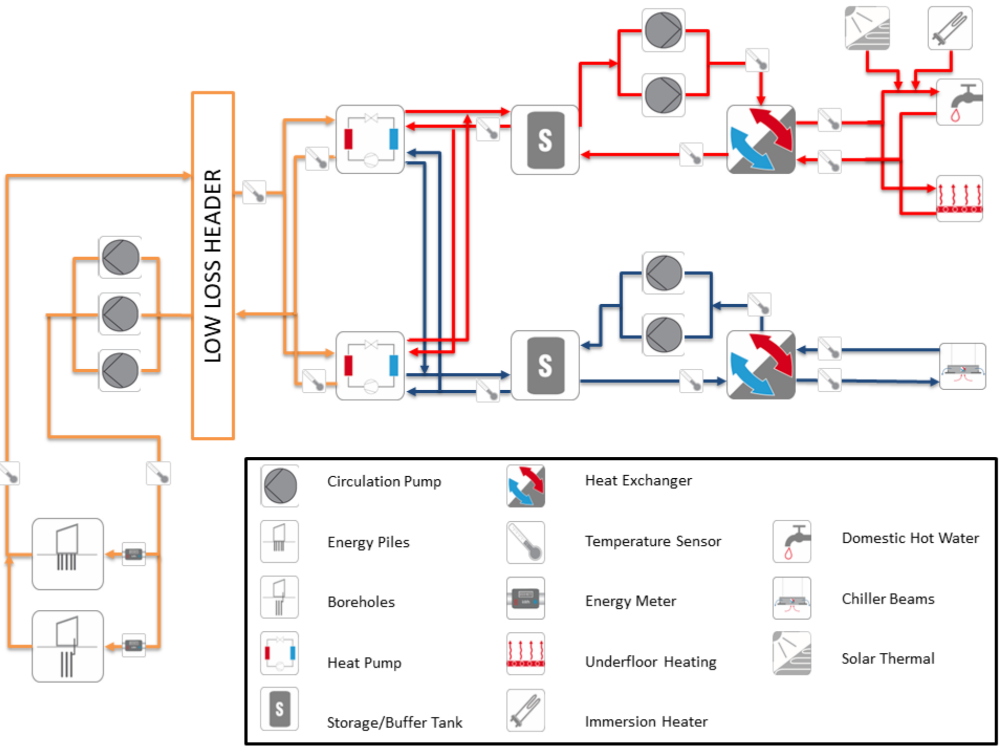


Figure 20 - Crystal Heat Pump System Schematic: Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52.

The ground source heat pumps are connected to a system of 36 boreholes and 160 pile heat exchangers as shown in Figure 21. It is understood that two of the 38 boreholes shown in Figure 21 were not connected, leaving 36 active boreholes.

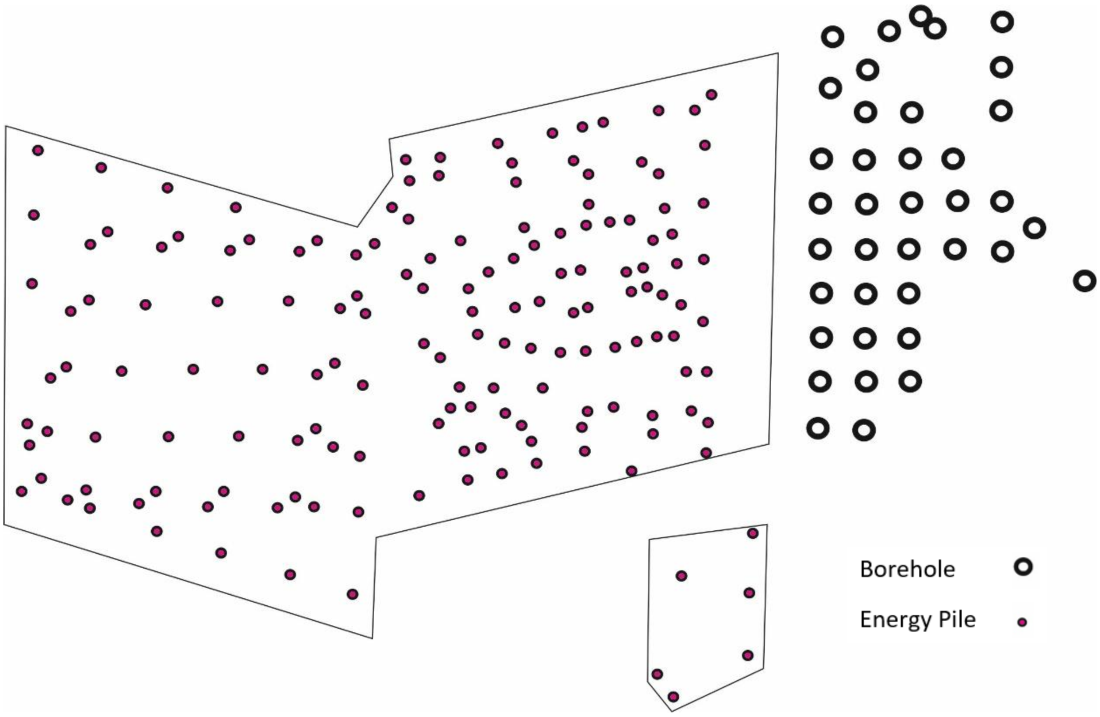


Figure 21 - The Crystal Energy Piles and Boreholes Layout – Top View

Each borehole is 150m deep and contains a single U-tube made from HDPE for circulation of the heat transfer fluid. They pass through the full sequence of London Basin geology with the lower two thirds of each ground heat exchanger being in contact with the Thanet Sands and Chalk aquifers, see Figure 22. Details of the BHEs are provided in Table 15.

Table 15 - Summary of the ground heat exchanger – Boreholes

Number of boreholes	36
Borehole length	150 m
Total borehole length	5400 m
Borehole diameter	150 mm
Borehole filling material	Gravel for lower 2 thirds, grout upper third
Borehole heat exchanger type	Single U-tube
Design Effective thermal resistance per unit length	0.085 Km/W
Source side pipe characteristics	HDPE (40/63/90/125/160mm)

Each energy pile was constructed using Continuous Flight Auger (CFA) techniques, to an approximate depth of 21m, and founded in the London Clay. Above this, the upper half of the piles pass through made ground, alluvial clays, and river terrace deposits. The piles are either 600, 750, or 1200 mm in diameter. Each pile each contains two HDPE U-tubes, located centrally within the pile. Details of the piles can be found in Table 16.

Table 16 - Summary of the ground heat exchanger – Energy Piles

Number of piles	160
Pile length	21 m
Total pile length	3360 m
Pile diameter	600/750/1200 mm
Pile material	Concrete pile with steel cage
Pile type	2 U-tube, 32mm diam pipes, centralised in pile
Source side pipe characteristics	HDPE (40/63/90/125/160mm)

Initial measurements conducted have also shown that though the maximum groundwater level is around 2 m below ground level, there are likely to be three aquifers; the river terrace deposits, perched water within the Lambeth Group sand lenses, and the major aquifer of the Thanet Sands and the Chalk. The water table from the deeper layers is between 8 m and 11 m below ground level. These values have come from piezometer measurements at various depths as shown in Figure 22 with additional details in Table 18 and Table 17.

Table 17 - Summary of the ground source and sink

Ground source	160 Energy Piles & 36 Boreholes
Loop type	Closed loop
Ground composition	See table 18
Maximum Groundwater level [m]	2 m
Annual mean air temperature (measured)	12.25°C
Undisturbed ground temperature	12.8°C for Piles – 13.4°C over depth for boreholes
Measured ground thermal conductivity (boreholes)	1.95 W/m.K for heat injection 2.07 for recovery
Assumed Volumetric ground heat capacity	2.69 MJ/m^{3}K

The value given for the ground thermal conductivity has been derived through an on-site thermal response test (TRT) and is applicable for the 150m depth of the boreholes; no such value for the energy piles is currently available. During this TRT, the assumed ground volumetric heat capacity was given as 2.69MJ/m^3.K and so this has been presented rather than the specific heat capacity. Similarly, the value of the borehole thermal resistance had been derived through the initial on-site TRT. The details for the TRT can be found in Loveridge et al. (2013). Pile thermal resistance has not been determined at this stage.

Strata	Description	Depth
Made Ground	Fine to coarse brick and concrete gravel; soft to firm black sandy gravelly clay.	3.3m
Alluvium	Very soft clayey silt, sandy clay, and peat	6.3m
River Terrace Deposits	Medium dense silty fine to coarse sand and fine to coarse gravel (mainly flint)	11.2m
London Clay	Stiff thinly laminated fissured silty clay with silt partings	23.5m
Lambeth Group	Silty fine sand and fissured silty clay	43.3m
Thanet Sands	Very dense, slightly silty fine sand	56.1m
Chalk	Medium density (Grade B3) chalk	>150m

Table 18 - Summary of the ground layers

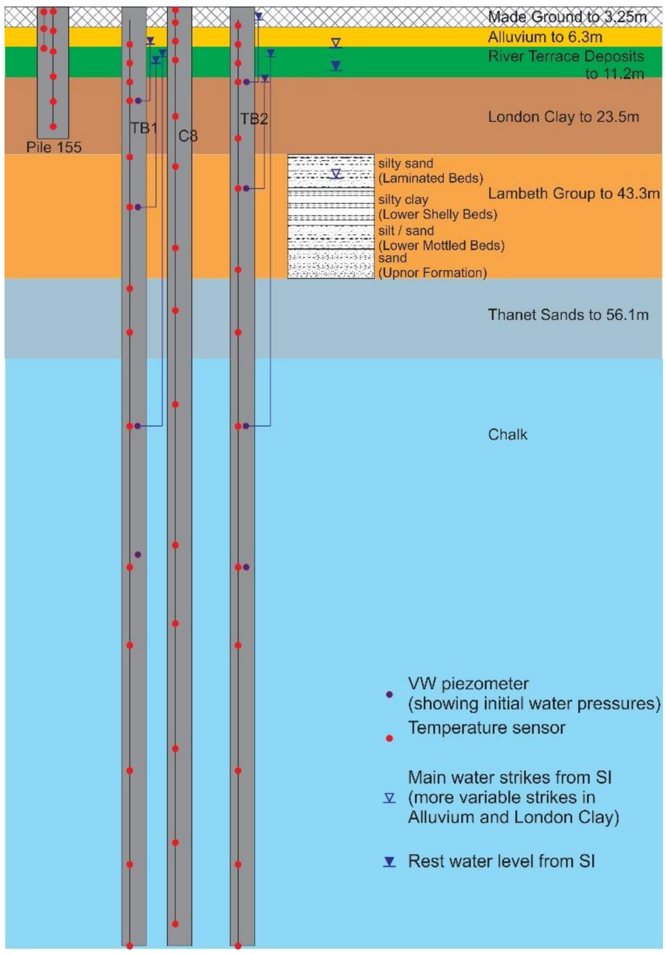


Figure 22 - Summary of the ground layers

3.1.3 Instrumentation & Monitoring

The energy being delivered to the Crystal Building has been monitored and recorded via a series of heat and electricity meters connected to the Building

Energy Management System (BEMS). The BEMS has also monitored the heat exchanged with the ground via two additional heat meters, one for the energy pile ground loop, and one for the borehole ground loop. Unfortunately, the heat meters for both the energy pile and the borehole ground loops cannot differentiate the direction of heat transfer, either to or from the ground. As such, assumptions have been made to allow the calculation of energy extracted from and rejected to the ground. The data collected from the BEMS dates back to the spring of 2013; however, the borehole ground loop data has been included from 2015 onwards as prior to this the heat meters were not communicating correctly with the BEMS.

Additionally, a single 1200 mm diameter energy pile was fitted with five thermistor strings to allow the temperature evolution of the pile to be monitored. The first thermistor string was attached to the central bundle of the two U-tubes down to a depth of 19 m. The remaining four thermistor strings were attached to the steel cage of the same energy pile, at equal spaces around its circumference, facing approximately North, East, South and West, down to a depth of 6.6m. The depth of each of the measurement points can be found in Table 19 below and is illustrated in Figure 22. The outer strings extended to a lesser depth since the steel cage was not required over the full depth of the pile.

Table 19 - Depth of Thermistors

Thermistor Level	Depth Below Pile Cut Off Level (m)	
	Central String	Outer Strings
1	0.7	0.75
2	3.6	3.25
3	7.1	6.6
4	11.1	-
5	15.1	-
6	19.1	-

Temperature data from this pile has been collected since the summer of 2012, however the central thermistors at levels five and six have been malfunctioning for large periods and as such only the first four thermistor levels have been included in this analysis. Gaps in the temperature data are also present due to data logger malfunctions.

The data from both the temperature sensors and the BEMS has been analysed up to the 23rd of March 2021.

Table 20 details the measurements available either through the BEMS or the instrumented energy pile. Unfortunately, there is no information regarding which sensors were used for the data collection and as such the information on calibration and uncertainties in these values is also unavailable.

Table 20 - Summary of the system monitoring

Measurement	Recorded Unit	Typical Interval	Comments
GSHP Heat Generated	kWh	30 min	
GSHP Cool Generated	kWh	30 min	
GSHP A Elec Used	Wh	15 min	
GSHP B Elec Used	Wh	15 min	
Solar Thermal Heat	kWh	30 min	
Chiller Cool Generated	kWh	30 min	
Chiller Elec Used	Wh	15 min	
Immersion Elec Used	Wh	15 min	
Energy Pile Energy	kWh	30 min	
Borehole Energy	kWh	30 min	Data from 2015-2021
Ground Loop Pumps & Primary Circulating Pumps Elec Used	Wh	15 min	Primary circulating pumps are located after the buffer tanks
Secondary Circulating Pumps Elec Used	Wh	15 min	Secondary circulating pumps are located in the distribution system
Pile Temperatures	°C	60 mins	
Outdoor Temperature	°C	15 min	
Outdoor Humidity	%	15 min	
Heat Used for Domestic Hot Water	kWh	30 min	Calculated from other measurements

3.2 Data Analysis & KPIs

3.2.1 Performance metrics

Of the available system boundaries defined by the original Annex 52 schema, only the boundaries shown in Table 21 are available to be reported. This is due to many of the measurements available in the BEMS being a combination of data sets. For example, the electricity to the ground loop circulation pumps is presented jointly with the primary load side circulation pumps thus preventing the analysis at boundary 0.

Similarly, the internal circulation pumps for the heat pumps cannot be separated from the heat pump compressor electricity consumption. As such, H1/C1 and H1+/C1+ as per the original schema cannot be presented. In this instance the heat pumps' internal circulation pumps are used to pump the flow to the buffer tanks, replacing the stand-alone circulation pumps in boundary level 3, however as the ground loop circulation pumps cannot be separated from the primary circulation pumps, this boundary is also not applicable. As boundary level 2 is a combination of boundary 0 and 1, this is also not available for this case study.

Table 21 - Calculated system boundaries for the system according to the Annex 52 boundary schema.

	HPT Annex 52 Boundary levels					
Boundary description	**H1*/C1***	**H1+*/C1+***	**H4/C4**	**H4+/C4+**	**H5/C5**	**H5+/C5+**
Ground Source (circulation pumps+ ground source)			✓	✓	✓	✓
Heat pump unit including internal energy use, excluding internal circulation pump	✓	✓	✓	✓	✓	✓
Buffer tank (including circulation pumps between heat pump and buffer tank)			✓	✓	✓	✓
Circulation pump on load-side (between buffer tank & building Heating/Cooling distribution system)			✓	✓	✓	✓
Building Heating/Cooling distribution system					✓	✓
Auxiliary Heating/Cooling System		✓		✓		✓
Equivalent in the SEPEMO boundary schema	H1/C1				C3	H4/C4

Despite this, there is value to evaluating the heat pump performance without the inclusion of the external circulation pumps, and as such a modified boundary level 1 has been reported. This is as per the Annex 52 schema, but with the inclusion of the heat pumps' internal circulation pumps and is denoted as PF1* and PF 1+* throughout this report. This will allow an assessment of the impact of the external circulation pumps energy demands.

Whilst the power for the building heating/cooling distribution pumps is also provided along with power for the sewage water treatment pump as a single value, it has been assumed that the sewage pump was not used over the monitoring period, thus allowing the calculation of the heat pump system at boundary level 5 and 5 plus. This is a reasonable assumption as data collected from the BEMS shows that the sewage plant did not use any electricity over the eight-year monitoring period, suggesting it was not used. It follows then, that the pump to this system would also not be operating.

In the case of auxiliary boundaries, the immersion heater is assumed to be 100% efficient, and so the measurement of the electricity to the immersion is also used as the measurement of heat provided. No electricity information is provided for the solar thermal system, and as the contribution from the solar thermal system to the heat produced is relatively insignificant, comprising only 0.1% of the total heat produced, this has been neglected from the performance factor (PF) calculations.

As it is not known where in the system the immersion heater is physically located, it has been included at each of the available system boundaries to provide a comparison.

These system boundaries are shown diagrammatically in Figure 23, with the key consistent with that in Figure 21Figure 20, and the system performance factors were calculated using the Equations (7) to (12), where:

A = GSHP A, *B* = GSHP B, *Im* = Immersion, *CP* = Circulation Pumps, *GL* = Ground Loop, *P* = Primary, *S* = Secondary (not shown in Figure 23)

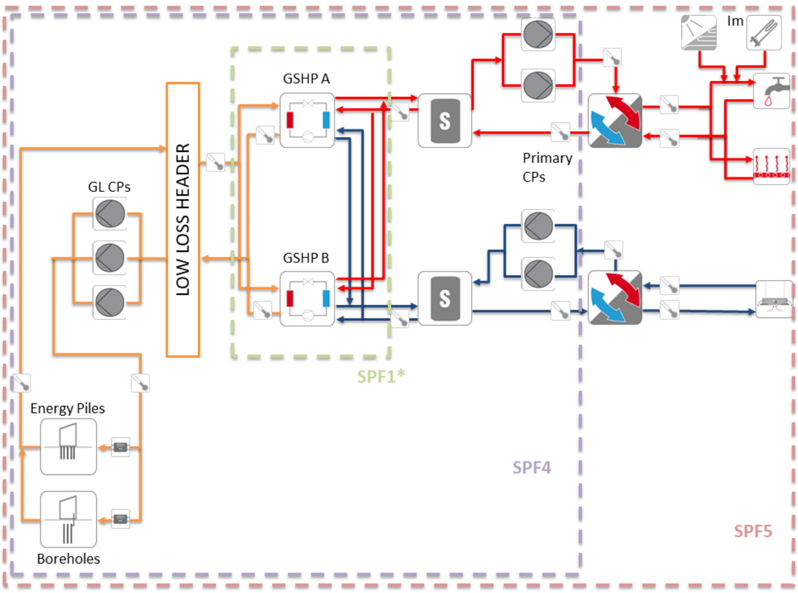


Figure 23 - Crystal Heat Pump System Schematic with reported system boundaries: Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52.

$$PF1^* = \frac{Heat_{GSHP}+Cool_{GSHP}}{Elec_A+Elec_B} \quad (7)$$

$$PF1+^* = \frac{Heat_{GSHP}+Cool_{GSHP}+Elec_{Im}}{Elec_{GSHP\ A}+Elec_B+Elec_{Im}} \quad (8)$$

$$PF4 = \frac{Heat_{GSHP}+Cool_{GSHP}}{Elec_A+Elec_B+Elec_{GL\ CP}+Elec_{Primary\ CP}} \quad (9)$$

$$PF4+ = \frac{Heat_{GSHP}+Cool_{GSHP}+Elec_{Im}}{Elec_A+Elec_B+Elec_{GL\ CP}+Elec_{Primary\ CP}+Elec_{Im}} \quad (10)$$

$$PF5 = \frac{Heat_{GSHP}+Cool_{GSHP}}{Elec_A+Elec_B+Elec_{GL\ CP}+Elec_{Primary\ CP}+Elec_{Secondary\ CP}} \quad (11)$$

$$PF5+ = \frac{Heat_{GSHP}+Cool_{GSHP}+Elec_{Im}}{Elec_A+Elec_B+Elec_{GL\ CP}+Elec_{Primary\ CP}+Elec_{Secondary\ CP}+Elec_{Im}} \quad (12)$$

3.2.2 Building heating and cooling loads

The BEMS reports the GSHP cooling generation and GSHP heating generation values directly from the corresponding heat meters. The heat provided from the GSHP for domestic hot water is calculated via Equation (13), which subtracts the heat consumption used for space heating in the various rooms in the corporate area of the building from the overall heat to that area. It is assumed that this value is not additional to the value of heat generated from the heat pumps in the BEMS but constitutes a proportion of this heat. However, little information is available on the building distribution loop and as such the reliability of the values produced from this calculation is unknown. This can sometimes produce erroneous values where the energy to the DHW from the GSHP is greater than the total heat energy the GSHP has produced.

$$DWH_{GSHP} =$$

$$Corporate\ Heating\ Consumption - AHU1\ Heating\ (Offices\ \&\ Meeting\ Rooms) - AHU2\ \&\ 3\ Heating\ (Auditorium) - Trench\ \&\ Underfloor\ Heating \quad (13)$$

The energy exchanged within the energy pile and borehole ground heat exchangers is reported by the BEMS as positive values only. It is assumed that the BEMS is recording both extraction and rejection and as such assumptions have been made to allow for interpretation of this data. In the following analysis for each 15-minute interval, which is the smallest typical data increment available for this system, the larger of the two loads defines the operating mode for the whole of that interval. For example, if the heat generated during the 15-minute interval exceeds the cool generated plus the work from the compressors, it is assumed that the heat pump operated solely in heating mode for the 15-minute period and all energy recorded for the energy piles and boreholes, was energy extracted from the ground. In this case the cool provided to the building is generated through recovery. The opposite situation is true if the cooling load plus the compressor work is larger for the 15-minute interval, and the energy exchanged with the ground is assumed to be heat rejected to the piles and boreholes. This is summarised in Equations (14) and (15).

$$Heating\ Mode: GSHP\ Heat\ Generated > GSHP\ Cool\ Generated + GSHP\ Elec\ Used \quad (14)$$

$$Cooling\ Mode: GSHP\ Heat\ Generated < GSHP\ Cool\ Generated + GSHP\ Elec\ Used \quad (15)$$

The values reported in Table 14 (Section 3.1) show the expected total heat and cool demands of the building. As per the assumptions detailed, this means that the space heating load was calculated as the total heat from the GSHP as reported by the BEMS minus the contribution to the DHW calculated by the BEMS using Equation (13).

Table 22 shows the recorded heating and cooling demands, and the DHW load is the resulting value of Equation (13), plus the heat from the auxiliary systems i.e., the immersion and the solar thermal. Similarly, the cooling load includes the cool generated through the auxiliary chiller.

The heating load % met by the heat pumps has been calculated using equation (16):

$$GSHP\ (\%) = \frac{Space\ Heating\ Load + DHW_{GSHP}}{Space\ Heating\ Load + DHW_{GSHP} + DHW_{Solar\ Thermal} + DHW_{Immersion}} \times 100 \quad (16)$$

This gives the percentage of thermal energy provided by the GSHP with respect to the thermal energy delivered to the building. In this case, the remaining percentage would be the heat delivered by the auxiliary systems. The corresponding equation has been used for the cooling equivalent.

3.3 Results

Table 22 details the load characteristics of the monitored data from The Crystal.

Table 22 - Overall load characteristics

Start of evaluation period	March 23rd 2013
End of evaluation period	March 23rd 2021
Building space heating load met by system [MWh_{th}]	3720.9
Building cooling load met by system [MWh_{th}]	4187.7
DHW load met by system [MWh_{th}]	1306.5
Thermal energy extracted from the ground [MWh_{th}]	637.3
Thermal energy injected to the ground [MWh_{th}]	1482.9
Thermal balance ratio (extracted/rejected)	0.43
Heating load (incl. DHW) met by heat pumps (%)	94.57%
Cooling load met by heat pumps (%)	99.58%

Figure 24 shows the mean hourly heating/cooling load binned into the hourly average outdoor temperature bins, providing an energy signature for the building.

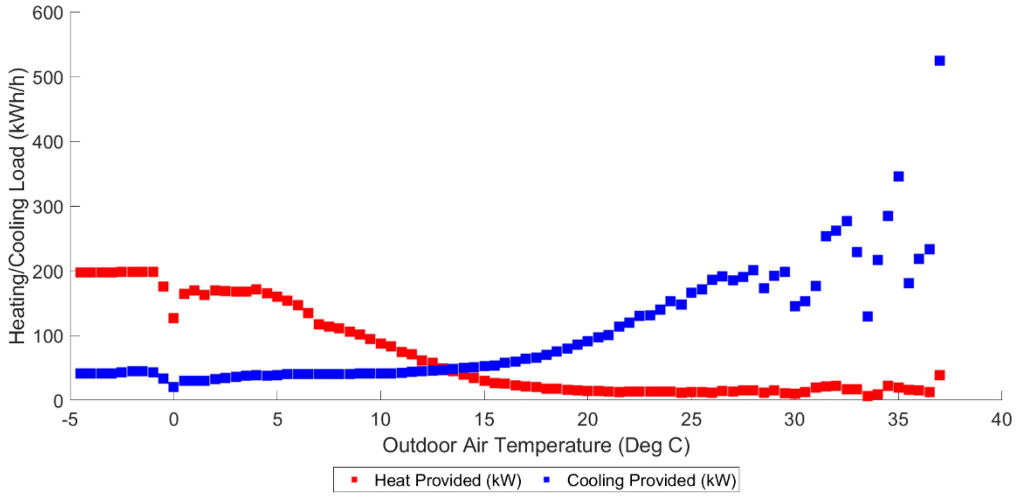


Figure 24 - Measured building energy signature for The Crystal from March 2013 to March 2021

It can be seen that there is a consistent base load of cooling required, even at temperatures below zero. This is assumed to reflect the need for cooling the IT equipment in the building. Similarly, there is a base load of heat, though it is much smaller than the base cooling. This is likely to reflect the need for domestic hot water year-round. When the outdoor air temperature is above 27°C the cooling loads deviate from the previous clearly defined trends, and the heating loads also see a slight disruption. This is likely due to the limited number of hours at these elevated temperatures; <2% of the hourly data points register an average temperature above 27°C. Thus, it is harder to generate a typical profile for such conditions. It is to be noted that with the data retimed to 15-minute intervals, ~10% of the data does not have corresponding outdoor ait temperature readings available from the BEMS. Hourly data from a nearby weather station has been used to backfill these gaps where possible. These values were then linearly interpolated to produce data points every 15 minutes. Roughly 1% of the resulting data is still without a corresponding outdoor temperature value.

Figure 25 and Figure 26 show the annual and monthly heat and cooling requirements of the building, including the heat and cool produced by the auxiliary sources. It is worth noting that each bar in Figure 25 shows one years' worth of data, with each 'season' starting in March and ending the following March. This is because data collection began in March 2013 and whilst data collection is still ongoing, it has only been analysed over an 8-year period, ending in March 2021.

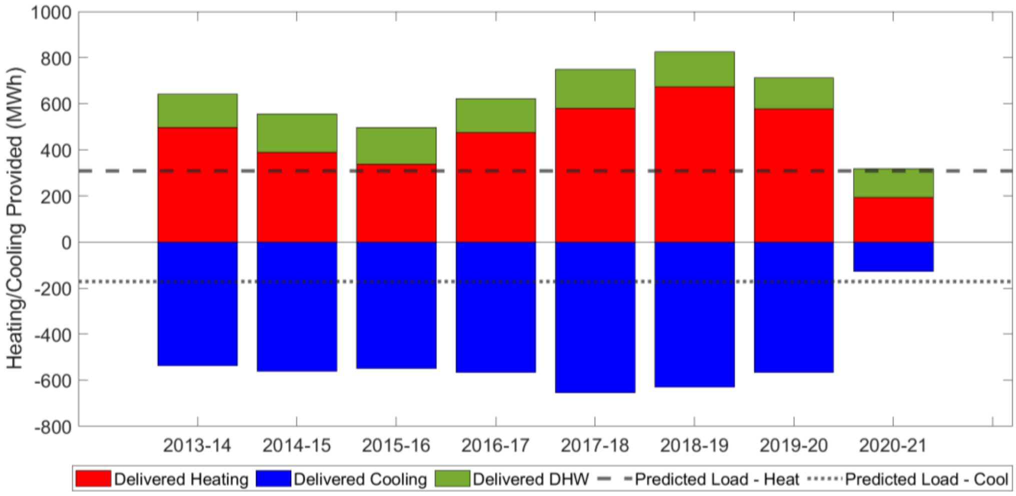


Figure 25 - Heating and cooling per season (March to March), MWh/year

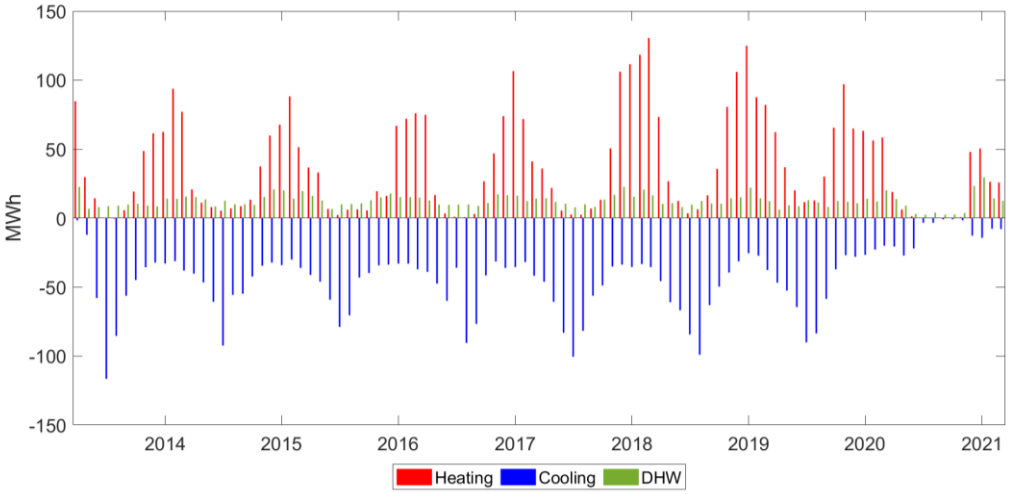


Figure 26 - Monthly heating, cooling, and DHW loads over the monitoring period

The significant reduction in demand during 2020 is likely due to the Covid pandemic, resulting in the building being left vacant, and thus the system provided only background heating and cooling. The monthly data indicates this period to be from July 2020 to December 2020. The base cooling load discernible from the building energy signature is also clearly visualised in the monthly data, typically found to be between 20 and 30 MWh per month. Interestingly, whilst the seasonal variation of heating demand is ever present, the distribution of the loads appears to change somewhat after 2019, with a less clear peak in demand. This may be due to the change of ownership of the building in the summer of 2019 leading to a change in how the system is utilised, though it is hard to say for sure as Covid has impacted the data from around March 2020, when the first UK lockdown was initiated. Similarly, any one year could be impacted by the climate in that year, so additional data collection may be required to determine whether this is an anomaly or a continuing trend.

3.3.1 Ground heat exchanger performance

The energy exchanged with the ground has been categorized as heat extracted or heat rejected depending on the assumed mode of operation of the heat pump defined as per Equations (14) and (15). This means that during each 15-minute period, all energy exchanged with the ground will be solely attributed as heat extracted when in heating mode, and heat rejected when in cooling mode. In reality, it is likely that this was not always the case and the heat pumps switched between the operating modes during the 15-minute interval.

Figure 27 and Figure 28 show the annual and monthly heat extraction and rejection based on these assumptions.

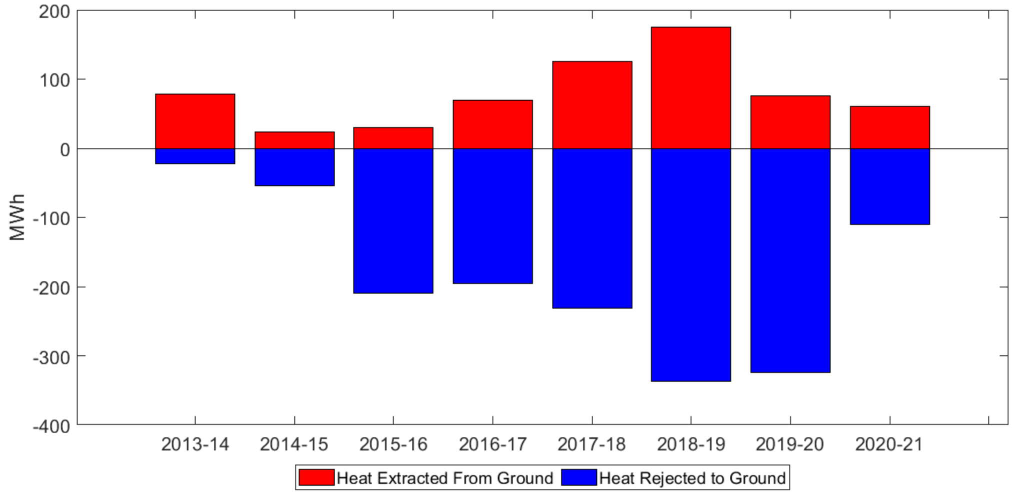


Figure 27 - Ground heat exchange per season (March to March), MWh/year

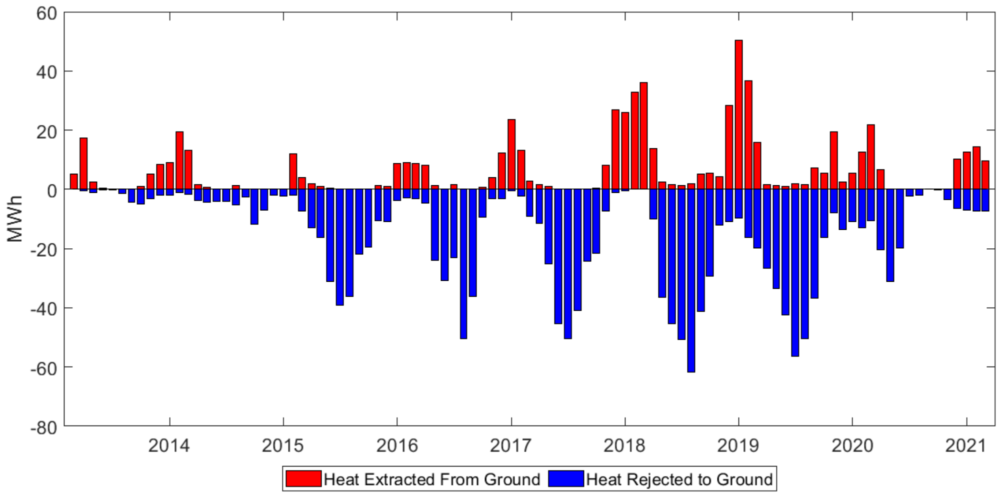


Figure 28 - Monthly ground heat exchange (extraction and rejection)

It is worth noting, as with the energy loads, each 'season' of data begins in March. It is also important to emphasise that either through sensor error or BEMS error, the data recorded from the boreholes' heat meter from March 2013 to January 2015, was erroneous and has been omitted. This absence of reliable data could explain, at least in part, the significantly lower levels of heat extraction and heat rejection in 2013 and 2014. It can be seen that each season significantly more energy is rejected to the ground that is extracted from it, and this imbalance continues throughout the monitoring period. This is likely due to the recovery mode operation of the heat pump. When at peak heating load, during the heights of winter, the building still has the base load cooling demand required to cool the IT equipment. This means that the energy extracted to provide this cooling will then be used, via the heat pumps recovery mode, to provide some of the peak heating load. The opposite case is not true, as when at peak cooling load during the summer months, there is very little heating demand, and as such the majority of the heat removed from the building is not recovered and is rejected to the ground.

Figure 29 shows the heat extraction and rejection split between the boreholes and energy piles. This figure highlights an interesting ground heat exchanger control system configuration, with the energy piles seemingly being used predominantly for heat rejection, and the boreholes being used predominantly for heat extraction. This may not have been the case originally as there is a clear change in use of the energy piles from mid-2014, with little to no energy extracted from the piles beyond this point. It stands to reason that the borehole control strategy may have also been changed at this point in time, and so no accurate conclusion as to the effects of the omitted data can be drawn. A small amount of heat is rejected to the boreholes over the monitoring period, but this is insignificant compared to the heat rejected to the energy piles. The total heat extracted and rejected from each ground heat exchanger has been included in Table 23 for reference, along with the mean heat exchange per unit length for the different heat exchangers.

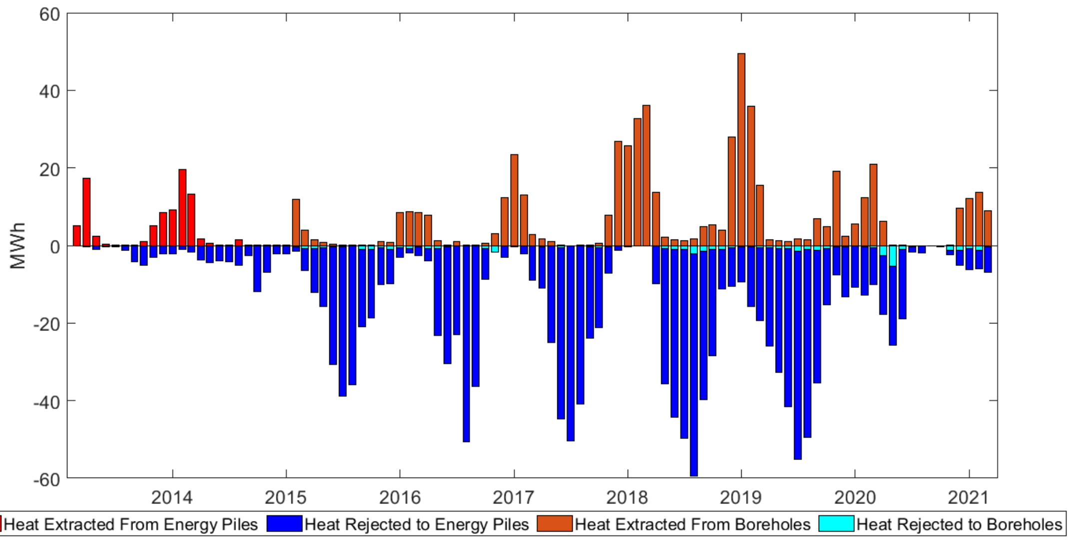


Figure 29 - Monthly borehole and energy pile heat exchange (extraction and rejection)

As the assumptions made for the mode of operation of the heat pumps is based on 15-minute intervals, to calculate the mean heat exchange per unit length of the two heat exchangers, Equation (17) was used.

$$Mean\ Heat\ Exchange\ Per\ Unit\ Length_{Heating} = \frac{Mean\ heat\ extraction\ in\ 15\ minute\ interval \times 4}{Total\ Depth\ of\ Heat\ Exchanger} \quad (17)$$

The peak heat extraction per unit length was calculated in the same way except with the peak heat extraction/rejection in a 15-minute period. These values are calculated using the total drilled depth rather than total length of heat exchangers. These are shown in Table 23.

Table 23 - Ground Heat Exchanger Summaries

	Boreholes	Energy Piles
Total Heat Extracted (MWh)	536.6	100.7
Total Heat Rejected (MWh)	50.2	1432.7
Mean heat extraction per unit length (heating) [W/m]	6.8	2.8
Mean heat rejection per unit length (cooling) [W/m]	1.0	5.48
Peak heat extraction per unit length (heating) [W/m]	42.5	40.2
Peak heat rejection per unit length (cooling) [W/m]	18.0	64.6

Whilst the peak values for the heat extraction/rejection per heat exchanger length are close to or within the expected values suggested in the literature, the mean values are much lower.

Figure 30 to Figure 33 shows the number of occurrences for the specific heat exchanged in each operating mode for each heat exchanger. These figures clearly show that despite the peaks achieving expected values, this happens very infrequently, with the ground loops underperforming for the majority of the monitoring period.

As demonstrated in (Gehlin *et al.*, 2022) the specific heat exchange is typically used as a proxy for how the ground loop is performing. The underperformance shown in these figures would suggest the system is overdesigned and underutilised. This could be due in part to the ability of the heat pumps to operate in recovery mode, minimising the heat exchanged with the ground, and also the sub-optimal control strategy noted in Figure 29.

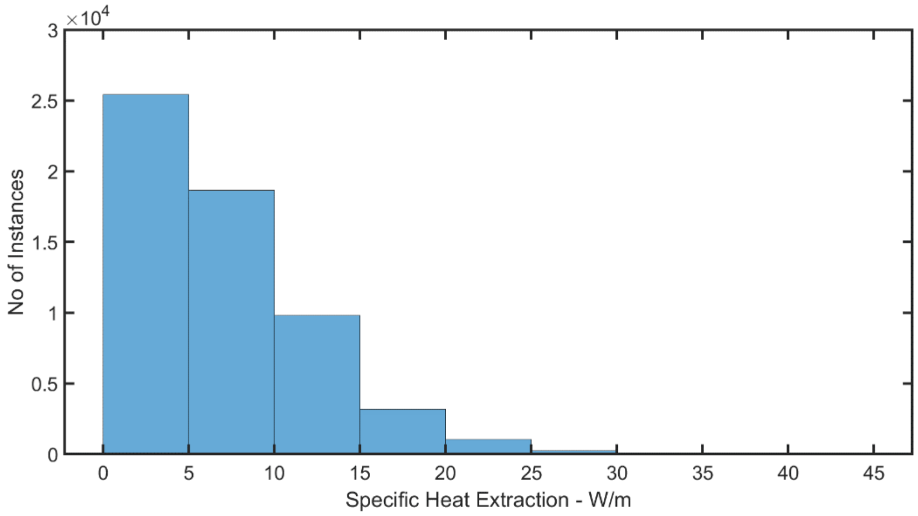


Figure 30 - Histogram of Borehole Heat Extraction Per Unit Length

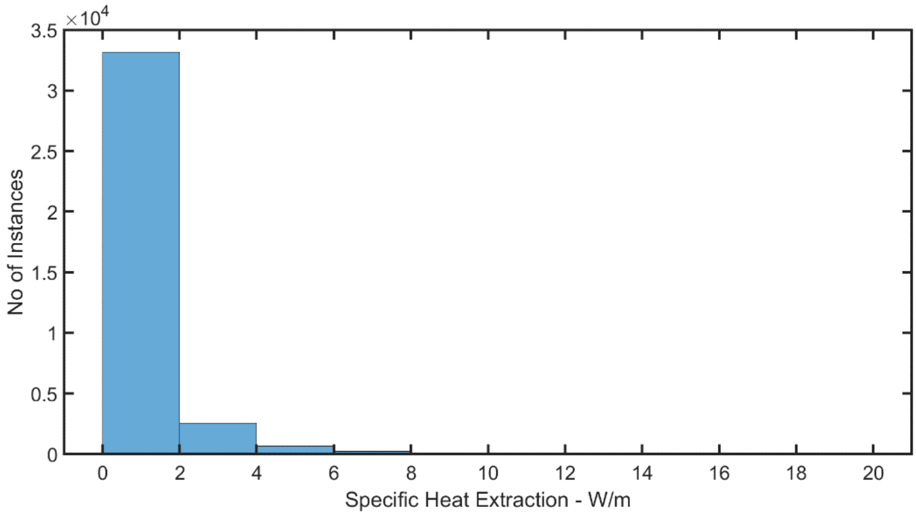


Figure 31 - Histogram of Borehole Heat Rejection Per Unit Length

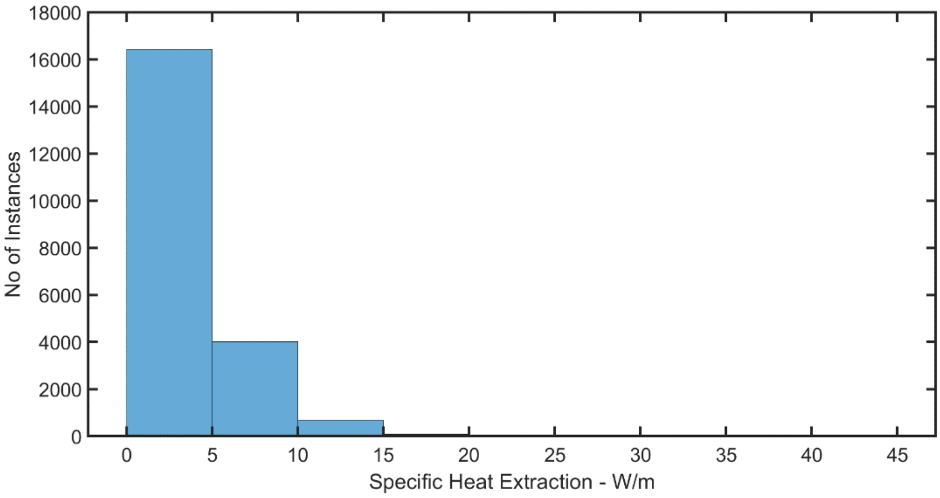


Figure 32 - Histogram of Energy Pile Heat Extraction Per Unit Length

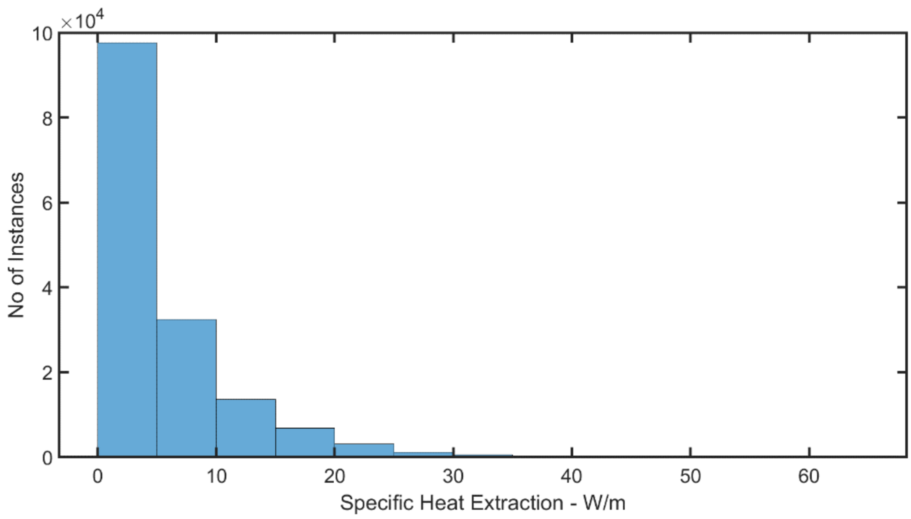


Figure 33 - Histogram of Energy Pile Heat Rejection Per Unit Length

3.3.2 Overall system performance

As the solar thermal system only produced 0.1% of the total heat, has no available electricity data and hasn't provided any heat since 2015, it has been ignored in the calculations of all performance factors. Similarly, from comparison of the data for the air-cooled chiller, Figure 34, it can be seen that the electricity data is not reliable across the monitoring period, suggesting the electricity meter is likely experiencing issues. The cool provided by the chiller accounted for only 0.4% of the total cool, and the electricity recorded for the chiller only amounts to 6% of the total electricity for the heat pumps and chiller in cooling mode. This is just 4.1% of the total electricity used by the heat pumps and chiller.

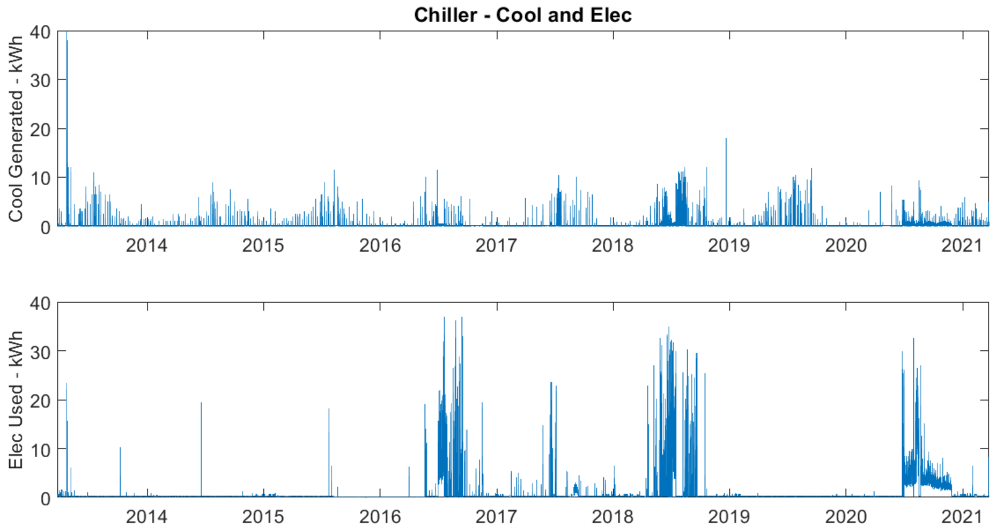


Figure 34 - Comparison of cool produced and electricity used by the air cooled chiller

Inclusion of these variables in the performance calculations would provide some large, likely inaccurate, differences between the boundaries and their '+' counterparts such as with the Monthly Performance Factor at system boundary 1* (MPF1*) and the Monthly Performance Factor at system boundary 1*+ (MPF1*+) in July 2016, Figure 35. As such, the chiller has also been omitted from these calculations, meaning the only auxiliary heat/cool source included in the PF values is the immersion heater, which has been assumed to be 100% efficient.

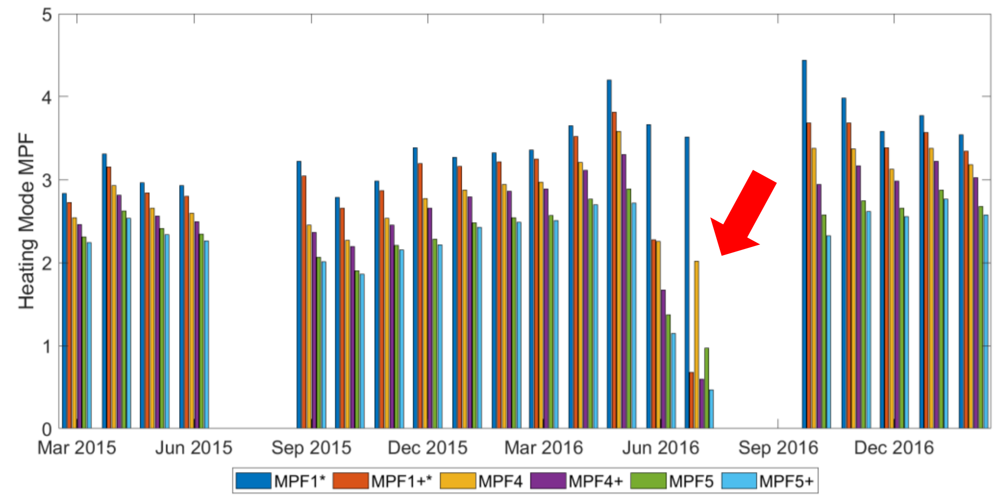


Figure 35 - Effect of erroneous auxiliary data - heating mode monthly performance factor (MPF)

The data from the immersion heater is also somewhat fragmented. Looking at Figure 36, the BEMS had trouble recording the data for the immersion heater before September 2017. At this point a single large value was recorded, possibly being entered manually. When comparing this value to the following years it seems a reasonable cumulative total for the operating time and so has been averaged back to the previous reading so as not to lose that information. This does mean however, that there is no granular data for this time period and actual usage patterns cannot be determined. From 2017 onwards the values were recorded appropriately by the BEMS, roughly every 15 minutes.

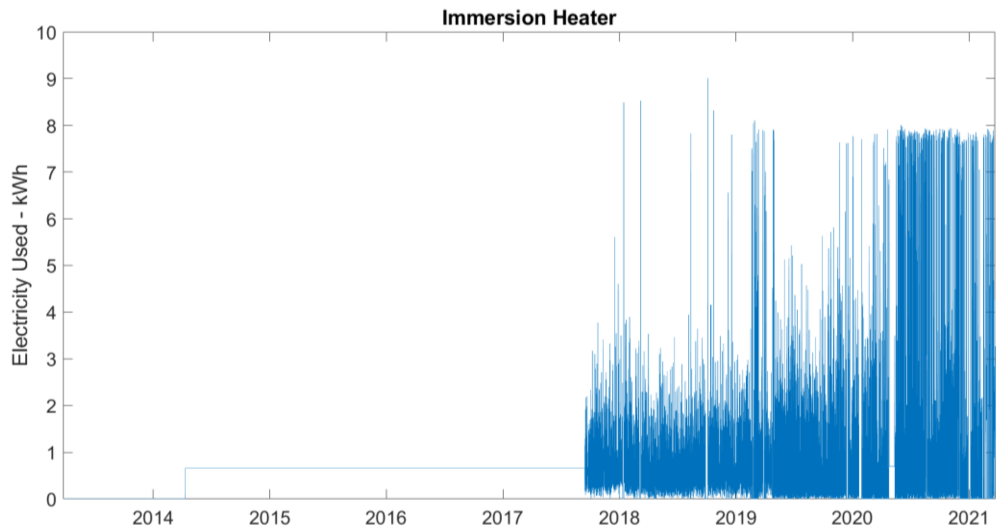


Figure 36 - 15 minutely data for immersion heater

As the GSHP system continually produces both heat and cool, the heating mode performance factors do not account for all of the heat delivered to the building. Instead, the heating mode performance factors give an indication as to the performance of the system delivering both heating and cooling, when the heating load is dominant. In this case the cooling is produced via recovery. Similarly, the cooling mode performance factors account for the cool and heat provided simultaneously to the building, whilst the heat pumps are in cooling mode.

Equations (18) to (21) show an example of the calculations for the heating mode and cooling mode performance factors at system boundary level 4 and 4+, where the subscript denotes the operating mode of the heat pump (e.g. H=Heating Mode):

$$Cooling\ PF4 = \frac{Active\ Cool_C + Recovered\ Heat_C}{HPA\ and\ HPB\ Elec_C + Ground\ Loop\ \&\ Primary\ Circulation\ Pumps\ Elec_C} \tag{18}$$

$$Cooling\ PF4+ = \frac{Active\ Cool_C + Recovered\ Heat_C + Immersion\ Elec_C}{HPA\ and\ HPB\ Elec_C + Ground\ Loop\ \&\ Primary\ Circulation\ Pumps\ Elec_C + Immersion\ Elec_C} \tag{19}$$

$$Heating\ PF4 = \frac{Active\ Heat_H + Recovered\ Cool_H}{HPA\ and\ HPB\ Elec_H + Ground\ Loop\ \&\ Primary\ Circulation\ Pumps\ Elec_H} \tag{20}$$

$$Heating\ PF4+ = \frac{Active\ Heat_H + Recovered\ Cool_H + Immersion\ Elec_H}{HPA\ and\ HPB\ Elec_H + Ground\ Loop\ \&\ Primary\ Circulation\ Pumps\ Elec_H + Immersion\ Elec_H} \tag{21}$$

Figure 38 to Figure 41 show the monthly heating mode performance factors at the varying system boundary levels.

Where the system was not in the corresponding mode for at least 1% of the operational time over the month, the MPF has been omitted. This is because on such a small sample, one erroneous data point has the ability to skew the MPF value, as can be seen in September 2016 in Figure 37. During the summer months of July 2017, and July, August, and September 2020 the system actually operated solely in cooling mode.

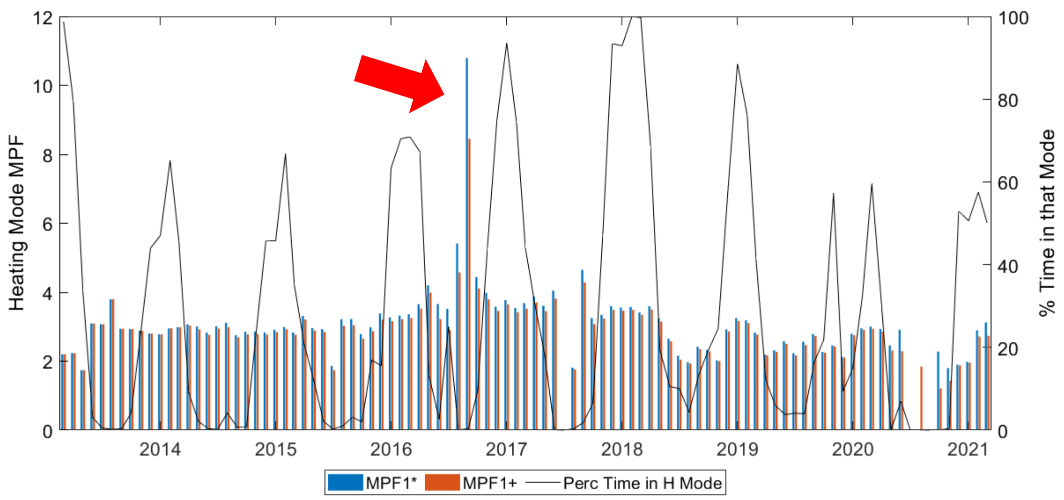


Figure 37 - Effect of erroneous data in small sample - heating mode MPFs

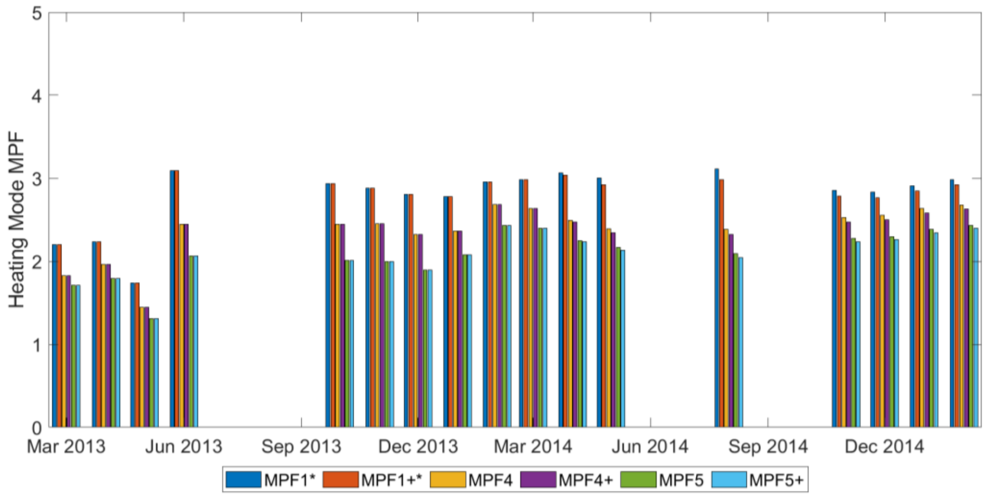


Figure 38 - Monthly performance factors in heating mode for different system boundaries 2013-15

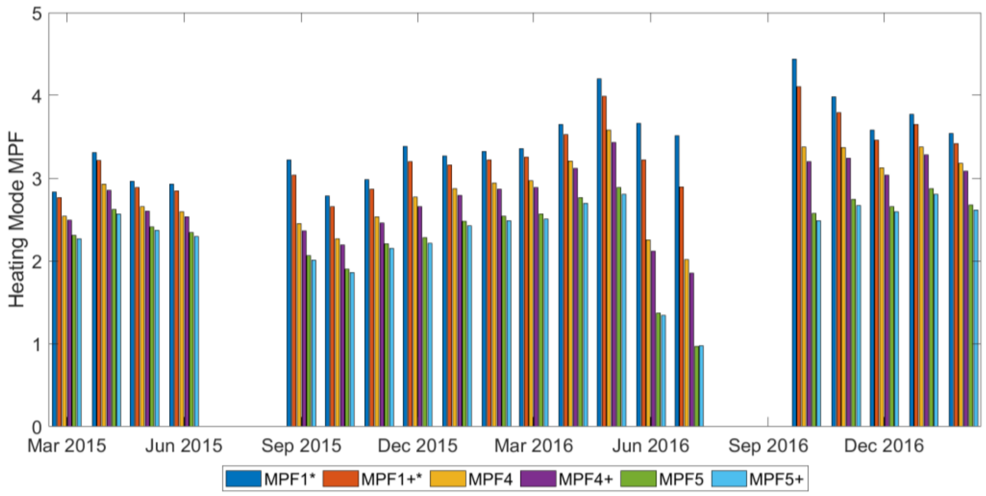


Figure 39 - Monthly performance factors in heating mode for different system boundaries 2015-17

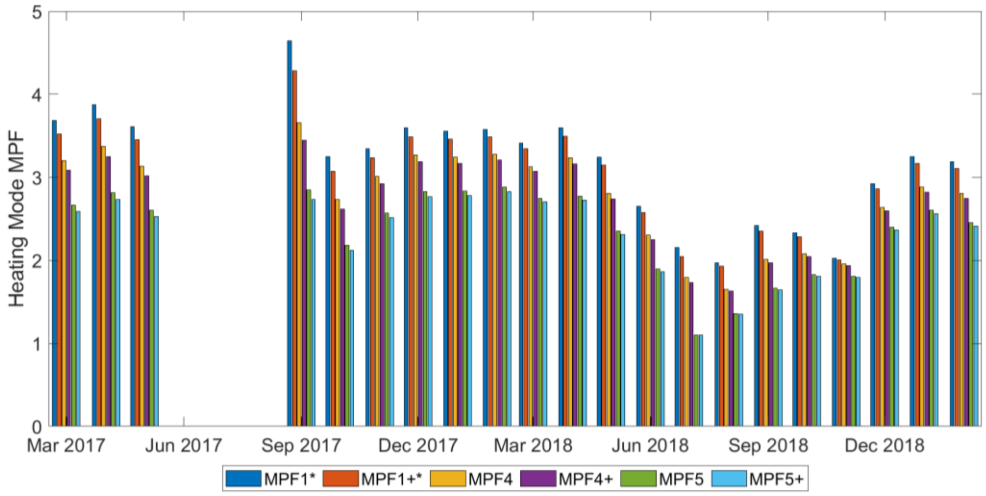


Figure 40 - Monthly performance factors in heating mode for different system boundaries 2017-19

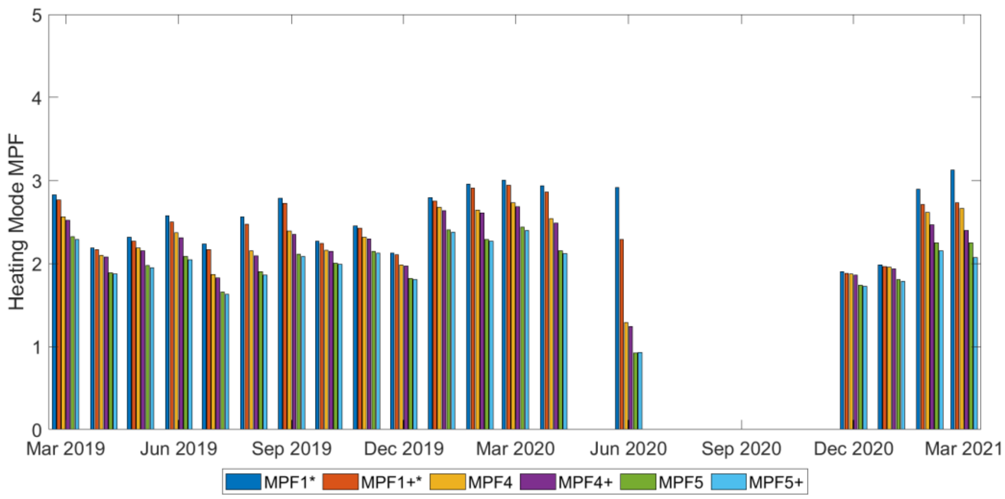


Figure 41 - Monthly performance factors in heating mode for different system boundaries 2019-21

The heating mode Monthly Performance Factors (MPFs) remain at a fairly consistent level throughout the winter months during the monitoring period, with lower performance factors typically occurring in the height of summer. As expected, the values of the MPFs decrease with increasing boundaries as more ancillary pumps are accounted for in the calculations.

Figure 42 to Figure 45 show the equivalent MPFs for the system in cooling mode, and again, if the system was in cooling mode for less than 1% of the operating time that month, the MPF values have been omitted.

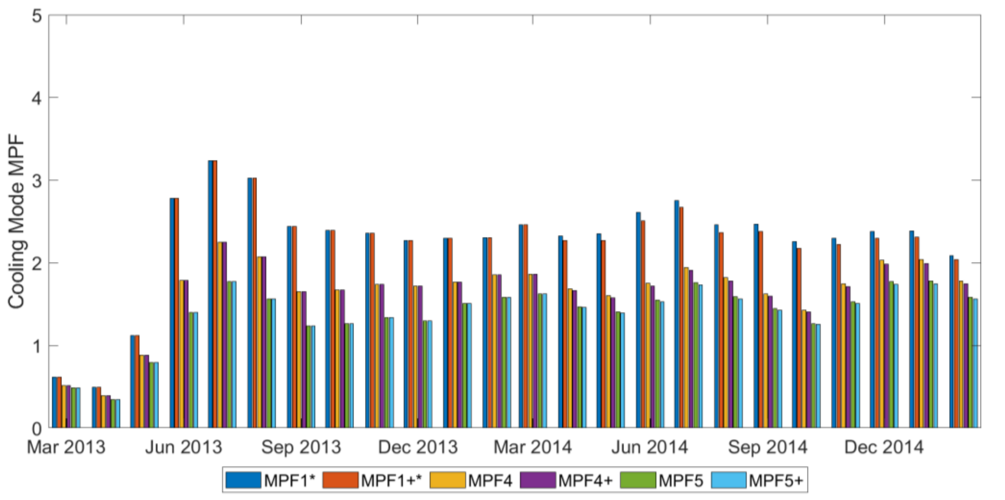


Figure 42 - Monthly performance factors in cooling mode for different system boundaries 2013-15

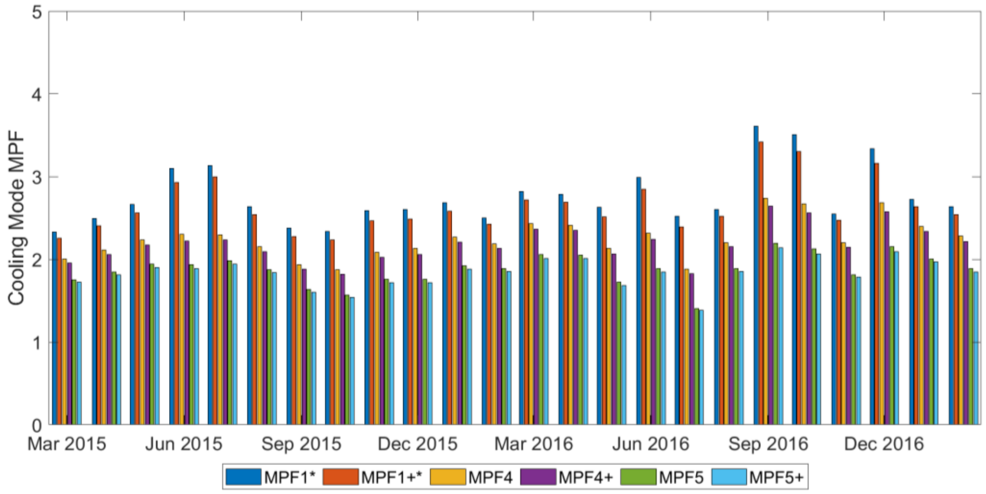


Figure 43 - Monthly performance factors in cooling mode for different system boundaries 2015-17

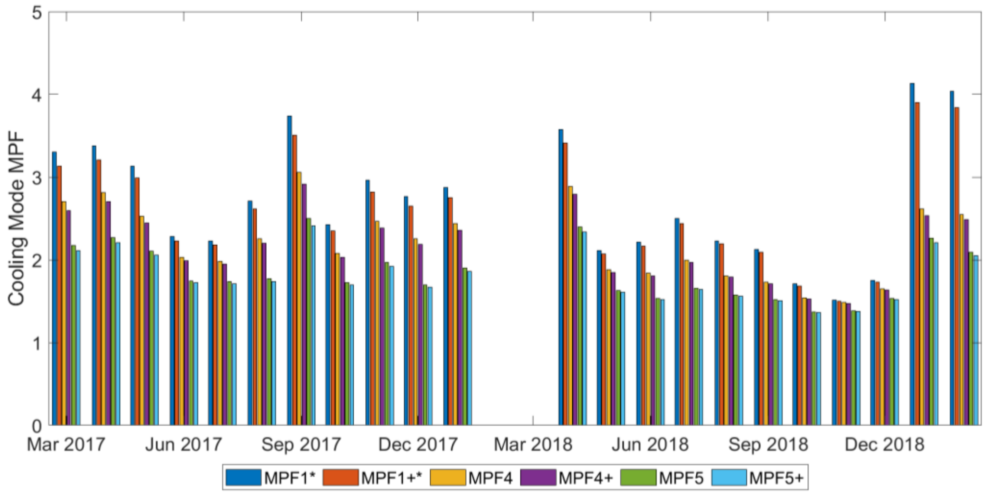


Figure 44 - Monthly performance factors in cooling mode for different system boundaries 2017-19

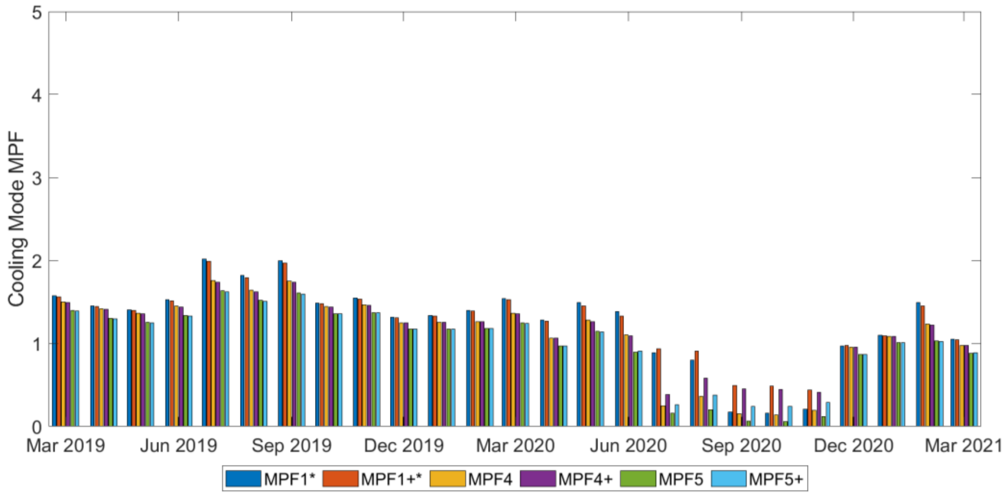


Figure 45 - Monthly performance factors in cooling mode for different system boundaries 2019-21

The cooling mode MPFs are typically lower than in heating mode by a value of 0.5-1. The performance factors remain at a fairly consistent level throughout the first 5 seasons of the monitoring period, though a noticeable drop off occurs from mid-2018. Excluding the two well performing months in early 2019, the system struggles to reach a performance factor above 2 from October 2018 onwards, a significant underperformance for the system.

Initial investigations appear to show an increase in the use of heat pump B during this period, as in Figure 46. In heating mode, the effect of this on the performance of the system is somewhat offset by a reduction in the use of heat pump A, however in cooling mode, heat pump A continues to have a significant electricity footprint. This could indicate a change in control regimen, as the overall heat and cool provided to the building over the 2019-2020 period does not appear to deviate greatly from the preceding years. This is perhaps supported by the decrease in cool provided whilst in heating mode, and the increase in heat provided in cooling mode, suggesting that from mid-2018 onwards the system spent significantly more time in cooling mode, despite no obvious change demand from the building. In this case it is hard to separate cause and effect as there is no indication of the mode of operation of the heat pumps other than calculations using the electricity used. Thus, it is impossible to determine if the additional electricity is due to additional time in cooling mode, or if the additional electricity is caused by a separate factor and this then suggests the system is in cooling mode as per Equations (14) and (15). It is again worth noting that the data from 2020 to 2021, particularly July to December, will have been significantly impacted by Covid, with drastically reduced demand.

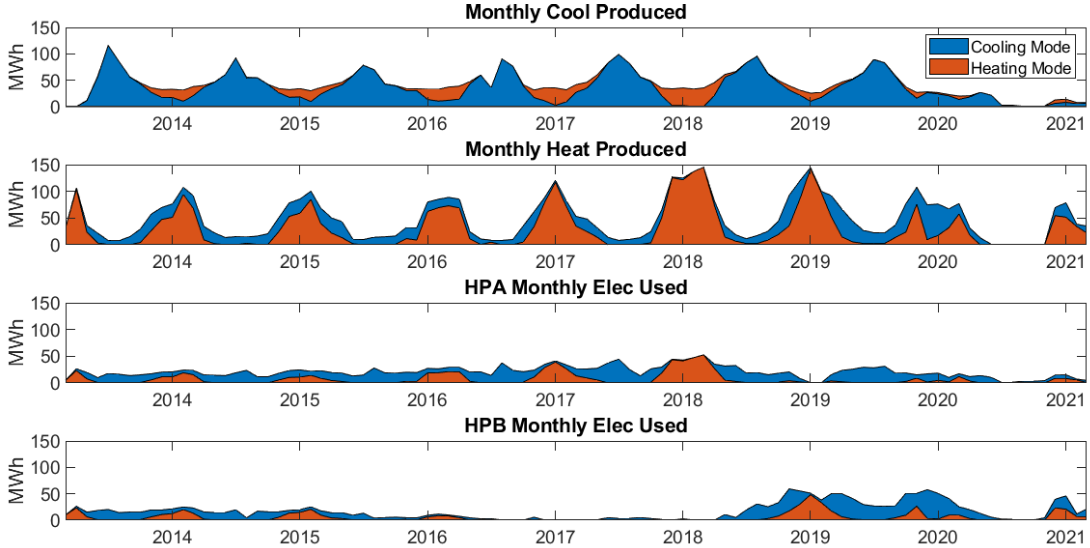


Figure 46 - Monthly heat pump heat & cool produced, and heat pump electricity used

Through comparison of the different boundary levels in Figure 42 to Figure 45, one can see the significant impact of the peripheral circulation pumps to the overall system performance. Cooling mode MPF1*, covering the heat pump energy use including its internal circulation pump, has a peak greater than 4. This peak reduces to ~3 at system boundary 4, which includes the ground loop and primary circulation pumps, and ~2.5 when the distribution system circulation pumps are included at boundary level 5.

The very low performance factors produced in cooling mode in the summer of 2020 show that despite the reduced demand due to Covid, the system was not completely shut down, producing very small amounts of cooling. Upon further investigation it was found that the circulation pumps were still using small amounts of power consistently through this period. From Figure 47, both heat pump A and heat pump B were likely in standby mode for the majority of this period, with heat pump A drawing slighter more power than heat pump B from September to December. With the heat pumps dormant, there is no need for the primary and ground loop circulation pumps to be in operation, and so these were also dormant from September through to December though it is worth noting that these pumps were not turned off for large parts of the period from July to September, when there was minimal use of the heat pumps. This could constitute wasted electricity. Figure 48 shows that the minimal heating required by the building during this period was produced primarily by the immersion heater, and that is likely the reason that the distribution side pumps were never switched off; to allow the circulation of this energy.

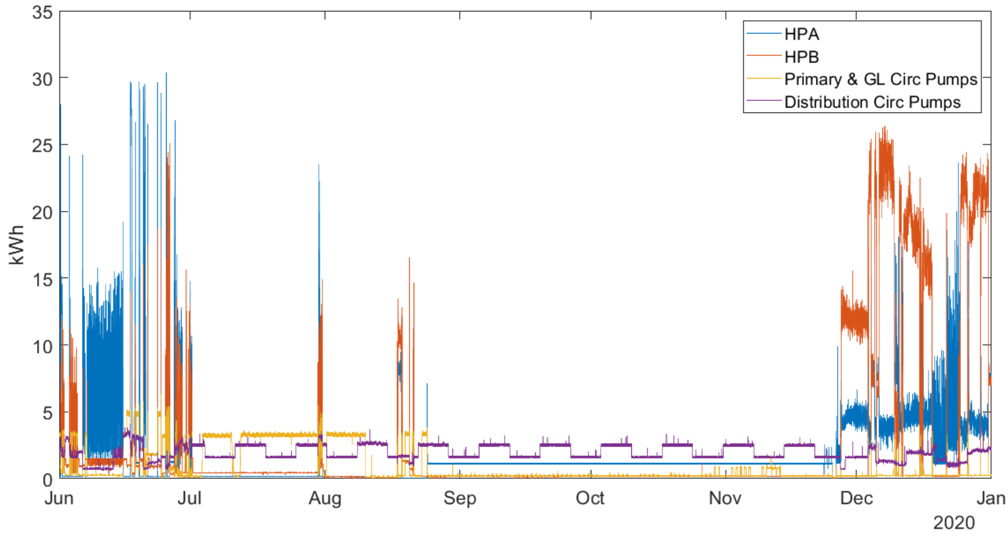


Figure 47 - 15 Minutely electricity use during covid shutdown – Jun 2020 to Jan 2021

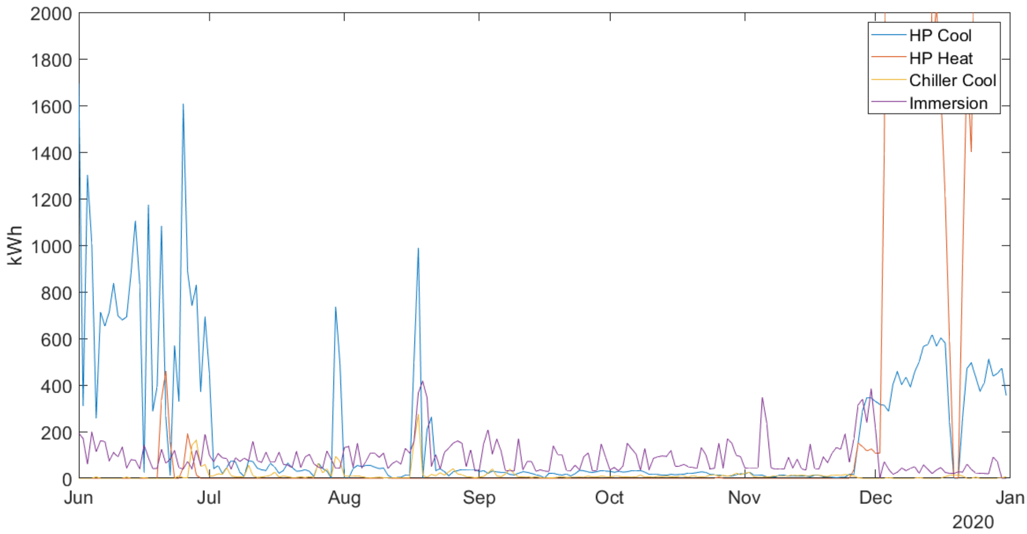


Figure 48 - Daily heat & cool during covid shutdown – Jun 2020 to Jan 2021

The overall monthly performance factors calculated as per Equations (7) to (13) have been presented in Figure 49 to Figure 52. In this case, the total heat and cool, including both recovered heat and cool is accounted for.

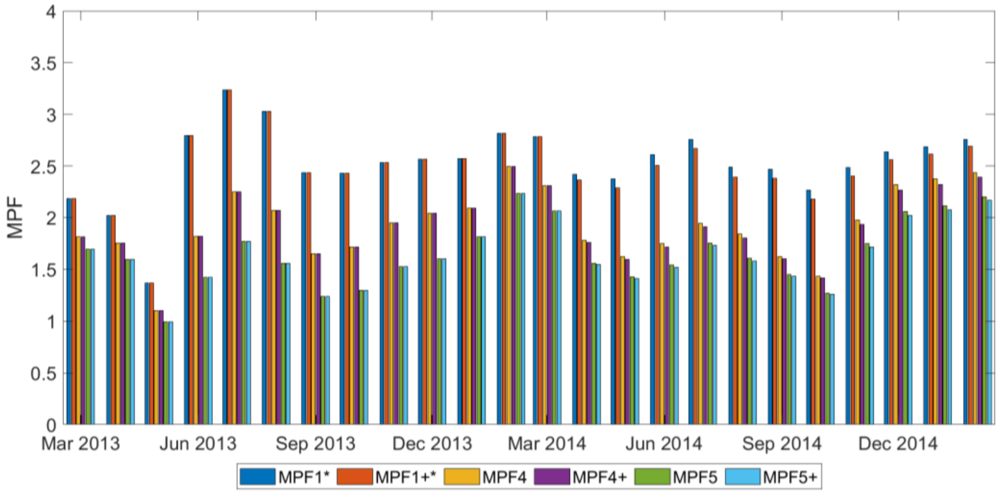


Figure 49 - Monthly performance factors for different system boundaries 2013-15

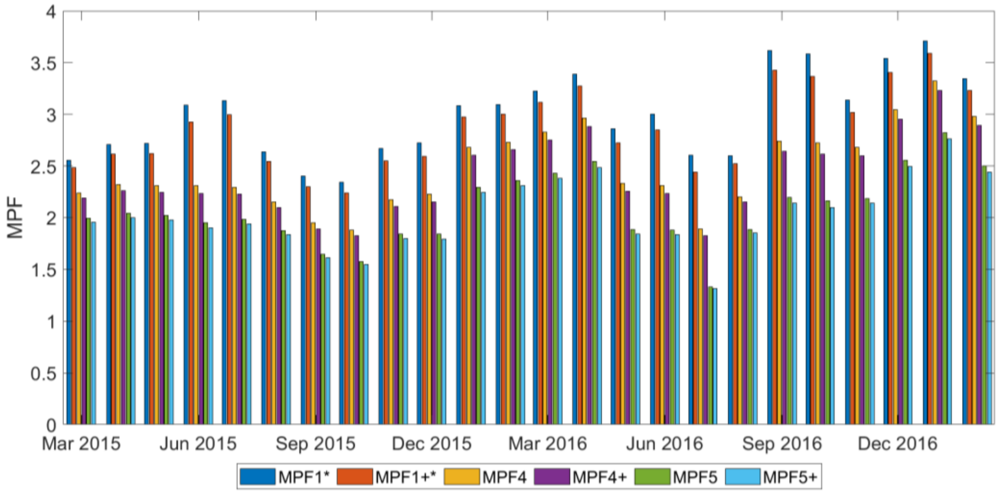


Figure 50 - Monthly performance factors for different system boundaries 2015-17

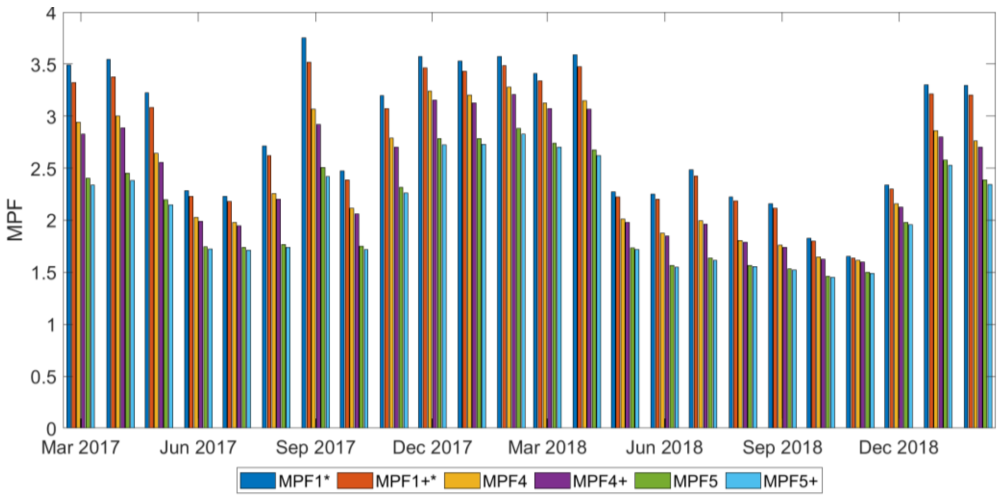


Figure 51 - Monthly performance factors for different system boundaries 2017-19

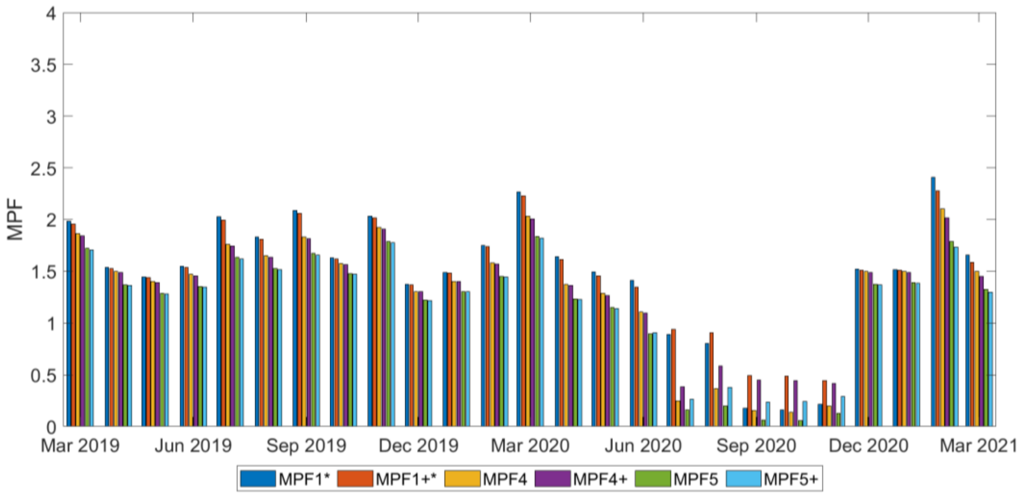


Figure 52 - Monthly performance factors for different system boundaries 2019-21

Again, a drop off in performance from mid-2018 can be seen across all system boundaries from these figures, supporting the theory that the system has spent an increasing amount of time in cooling mode from this point.

The monthly electricity for the various system components has been displayed in Figure 53 and Figure 54.

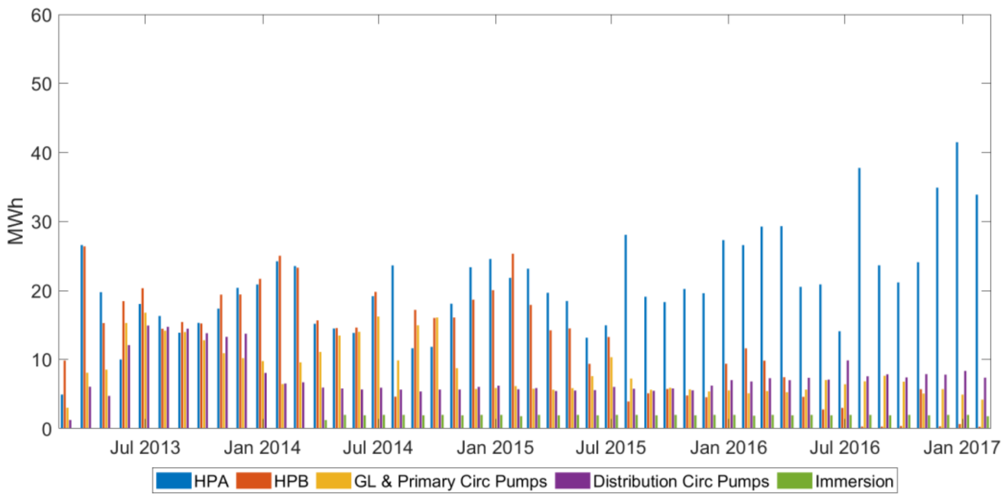


Figure 53 - Breakdown of electricity contributions 2013-17

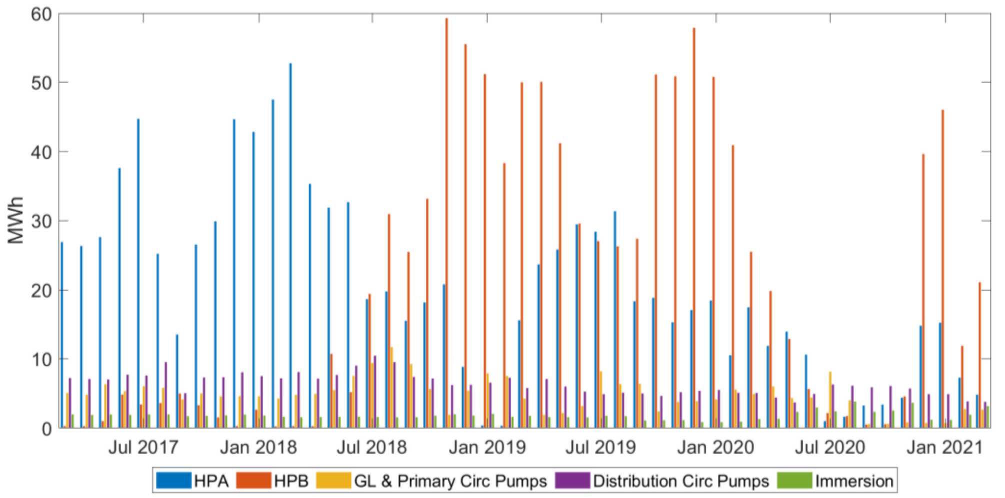


Figure 54 - Breakdown of electricity contributions 2017-21

These figures show that the ground loop, primary circulation pumps and distribution side circulation pumps were optimized around January 2014, reducing their monthly electricity usage from a peak of around 15 MWh to less than 10MWh, where they remained for the monitoring period. It can also be seen that the control strategy for the system is likely to have changed a couple of times. From the start of the monitoring period, both heat pumps are operating for similar periods or time, up until mid-2015. This matches the original design intention of switching the duty heat pump every 7 days. From mid-2015 onwards Heat Pump A appears to become the duty heat pump with minimal switching and little contribution from Heat Pump B until mid-2018. This corresponds with the period of increasing system performance. From mid-

2018 onwards, it appears that the control strategy is switched again, with Heat Pump B becoming the duty heat pump, but Heat Pump A still providing a significant contribution. This corresponds to the decrease in performance to its current levels.

Figure 55 shows the percentage of total electrical consumption for each of these groups of components over the whole monitoring period.

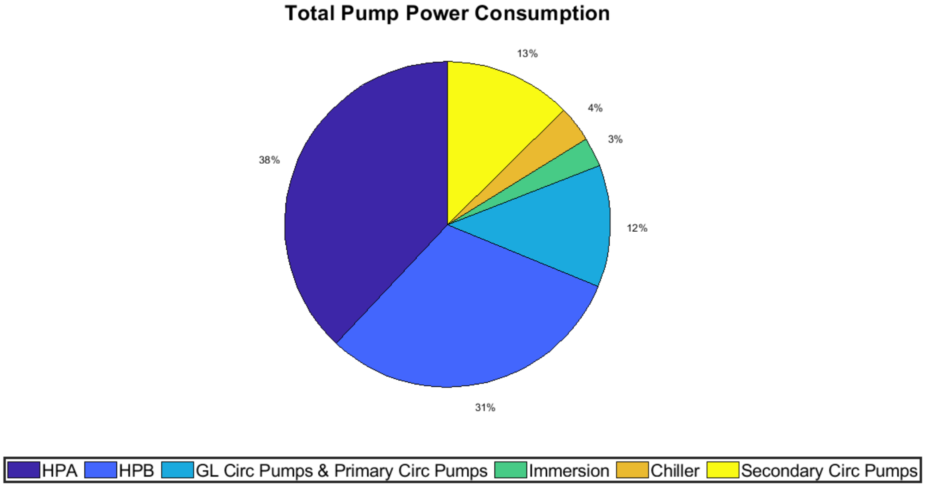


Figure 55 - Electrical Consumption Breakdown

This shows a high percentage of the energy being consumed is being used by the circulation pumps, which will affect the performance factors at the higher system boundaries.

The system performance has also been compared to the quantity of heat actively produced (i.e. heat produced in heating mode rather than recovered whilst in cooling mode) in Figure 56, and similarly the amount of cool actively produced in Figure 57. In these figures the performance factor (PF) is for the whole system and so does include recovered heat and cool.

The PF of the system appears to increase roughly linearly with an increase in hourly active heating load, up to a value of around 175 kWh. At this point the PF appears to stabilize across all system boundaries, until a value of heat generation above ~ 320kWh, at which point the correlation disappears. The cause of this is yet unknown and requires further investigation, though it may be down to a small sample size for each bin; the system only spent 0.25% of the time actively producing 320kWh or more of hourly heat generation. The increase in PF noted is likely due to the increased cycle times required for the larger loads. The longer the cycle time, the more the efficiency achieved negates the adverse efficiencies of the heat pump start up periods. Additionally, as the loads increase, the power used for the fixed speed circulation pumps become smaller relative to the compressor power. This can be seen in the steeper increase of PF at system boundaries 4 and 5 compared to system boundary 1 in Figure 56.

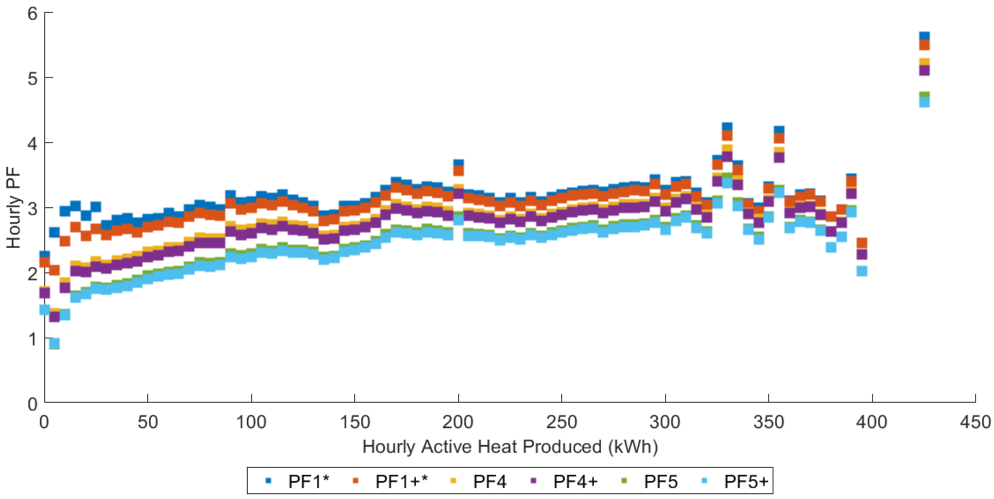


Figure 56 - Binned hourly performance factor vs quantity of active heating provided

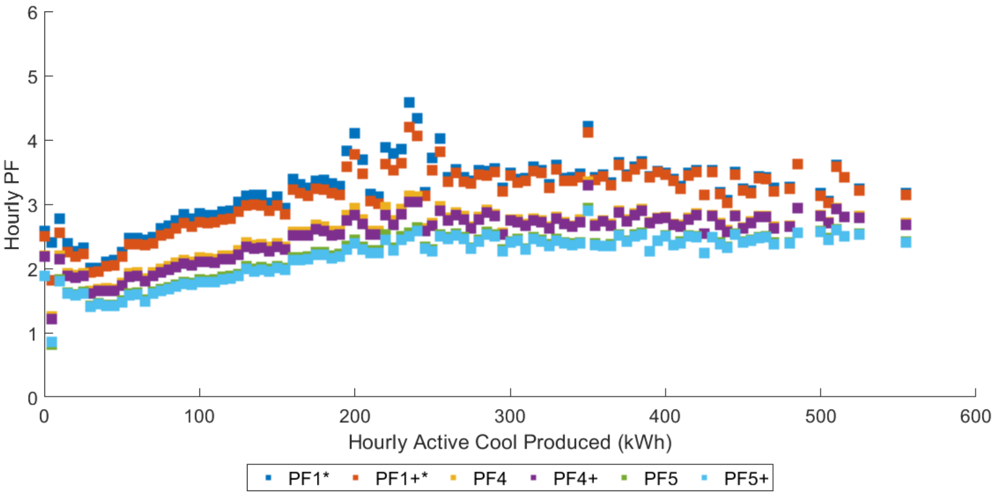


Figure 57 - Binned hourly performance factor vs quantity of active cooling provided

Similarly, the PF increases initially with an increase in cool produced, likely due to the increased cycle times, before plateauing at around 290 kWh. Despite the peak hourly cooling load being above 500 kWh, less than 0.6% of the total monitoring period was spent actively providing more than 290 kWh/h of cooling.

Figure 58 shows the daily system PF as per Equations (7) to (13), against the daily mean outdoor air temperature.

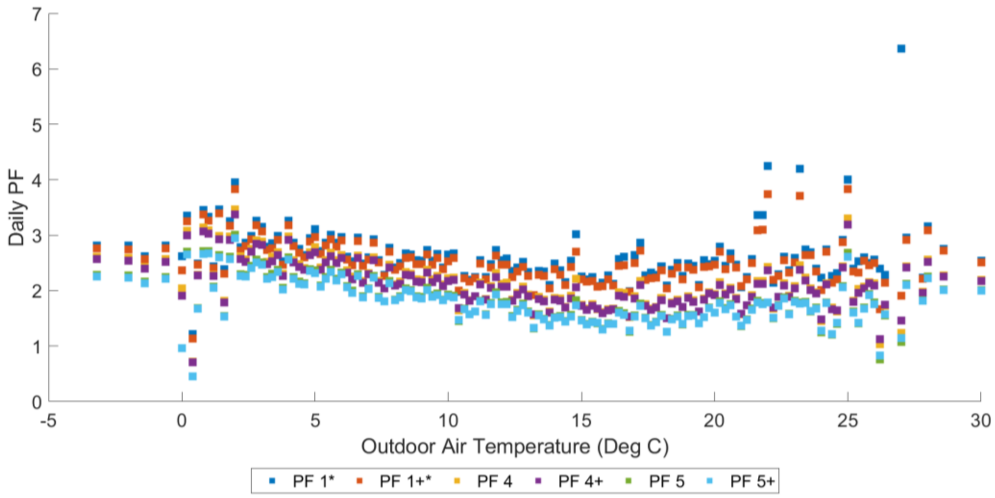


Figure 58 - Binned daily performance factor vs daily mean outdoor air temperature

There appears to be a slight negative correlation between the air temperature and system performance, supporting the conclusion that the heat pumps are performing less favourably in cooling dominated loads. The remaining anomalies require further investigation to identify the cause of the high PF values.

Table 24 provides a summary of the heating, cooling, and electricity usage for the system, including both the active heat/cool generated by the heat pumps as well as with the total heat/cool generated by the heat pumps. The electricity measurements for the load side circulation pumps are grouped with the ground loop (source side) circulation pumps as presented in the BEMS. Similarly, the load side distribution circulating pumps are grouped together and so cannot be split into heating distribution and cooling distribution, so only the total value for heating and cooling distribution pumps whilst in either heating or cooling mode has been included here. It is also not currently possible to separate the electricity used by the heat pumps circulation pumps from the electricity used by the compressors, as such only the total electricity used is shown.

Table 24 - Provided heating and cooling and used electricity

Start of evaluation period	March 25th 2013
End of evaluation period	March 24th 2021
Heat output from the ground source, used by heat pump for heating [kWh]	637,337
Heat output from the heat pump [kWh]	4,754,220
Active heating provided [kWh]	3,034,754
Heat output from supplementary heating between boundary 4 & 5 [kWh]	163,081
Cooling output from the ground source [kWh]	1,482,879
Cool Output from the heat pump [kWh]	4,170,117
Active cooling provided [kWh]	3,474,843
Cooling output from supplementary cooling between boundary 4 & 5 [kWh]	17,547
Electricity used by source side circulation pumps and load side circulation pump between buffer tank and distribution system in heating mode [kWh]	144,076
Electricity used by the heat pump compressor, including internal control system and internal circulation pump in heating mode [kWh]	1,226,647
Electricity used by the supplementary heating btw boundary 4 & 5 [kWh]	156,260
Electricity used for load side building heating & cooling distribution in heating mode [kWh]	189,286
Electricity used by source side circulation pump and load side circulation pump between buffer tank and distribution system in cooling mode [kWh]	499,149
Electricity used by the compressor in cooling mode, including internal control system and internal circulation pump in heating mode [kWh]	2,420,598
Electricity used for load side building heating & cooling distribution in cooling mode [kWh]	480,200

Table 25 - Performance factors over the monitoring period

Start of evaluation period	March 25th 2013	March 25th 2014	March 25th 2015	March 25th 2016	March 25th 2017	March 25th 2018	March 25th 2019	March 25th 2020	March 25th 2013
End of evaluation period	March 25th 2014	March 25th 2015	March 25th 2016	March 25th 2017	March 25th 2018	March 25th 2019	March 25th 2020	March 25th 2021	March 25th 2021
SPFH1*	2.61	2.91	3.23	3.70	3.53	3.02	2.55	2.31	3.04
SPFH1+*	2.61	2.85	3.13	3.56	3.44	2.95	2.51	2.25	2.97
SPFC1*	2.47	2.43	2.65	2.93	2.69	2.05	1.55	1.12	2.15
SPFC1+*	2.47	2.35	2.54	2.80	2.60	2.02	1.54	1.10	2.09
SPFHC1*	2.53	2.57	2.82	3.27	3.10	2.41	1.69	1.54	2.45
SPFHC1+*	2.53	2.49	2.71	3.13	3.00	2.34	1.68	1.49	2.39
SPFH4	2.25	2.59	2.84	3.24	3.21	2.71	2.36	2.19	2.72
SPFH4+	2.25	2.55	2.77	3.14	3.13	2.66	2.33	2.13	2.67
SPFC4	1.76	1.76	2.15	2.36	2.30	1.78	1.45	0.95	1.78
SPFC4+	1.76	1.73	2.08	2.29	2.23	1.76	1.44	0.95	1.75
SPFHC4	1.95	1.97	2.34	2.73	2.72	2.12	1.58	1.36	2.08
SPFHC4+	1.95	1.93	2.27	2.64	2.65	2.09	1.57	1.32	2.04
SPFH5	2.00	2.35	2.47	2.70	2.78	2.40	2.14	1.96	2.39
SPFH5+	2.00	2.31	2.42	2.64	2.73	2.36	2.12	1.92	2.35
SPFC5	1.39	1.55	1.83	1.92	1.91	1.56	1.34	0.76	1.53
SPFC5+	1.39	1.53	1.79	1.88	1.87	1.55	1.34	0.78	1.51
SPFHC5	1.61	1.75	2.00	2.24	2.31	1.87	1.46	1.13	1.80
SPFHC5+	1.61	1.72	1.96	2.19	2.26	1.85	1.46	1.12	1.77

* heat pump internal electricity use is included - not strictly boundary 1 as per Annex definition.

Finally, Table 26 displays some additional key performance indicators for the system.

Table 26 - Additional performance indicators

Start of evaluation period	Month Day Year
End of evaluation period	Month Day Year
Heating mode ratio of source & load side pumping electricity to heat pump electricity [%]	27.18%
Cooling mode ratio of source & load side pumping electricity to heat pump electricity [%]	40.46%
Ratio of supplementary heating provided to heat pump heating provided [%]	3.43%
Ratio of supplementary cooling provided to heat pump cooling provided [%]	0.42%

3.3.3 Energy Pile Temperatures

Figure 59 shows the evolution of the temperature of the instrumented energy pile, with the measurements averaged over the thermistor depth. This removes the axial variation from the pile temperatures which is addressed separately in the following section.

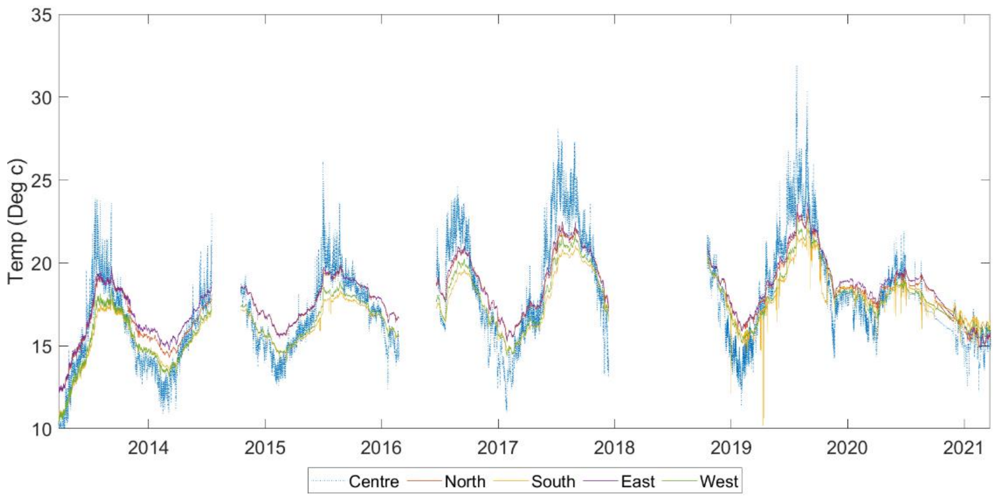


Figure 59 - Average circumferential temperature across energy pile

Overall, the pile temperature varied from just above 10°C when the pile was first thermally activated to a maximum value of close to 30°C in the hottest summer period. It can also clearly be seen that the temperature at the centre of the pile varied significantly more than at the edge of the pile, having a higher peak temperature in the summer, and a lower minimum temperature in the winter. This was due to the central temperature string being located on the heat transfer pipes. The thermal capacity of the concrete meant that the peak temperature variations were damped by the time the heat diffused out to the thermistor strings on the steel cage.

There was also a slight increase in the average temperature with time, for both the centre and the edge of the pile, which is reflective of the energy piles being used more in cooling mode, storing rejected heat. This appears to be plateauing, though this is hard to gauge due to the large gap in data from 2018 followed by the period of disuse due to Covid. This will become clearer as the data collection continues.

Conversely to Figure 59, Figure 60 shows the temperature at the pile's edge averaged between the four circumferential locations at each depth rather than averaged across its depth. This gives an indication of the axial temperature effects in the pile. It is noted that the temperature difference across the measurements typically remained less than 2°C, and that whilst initially the pile edge temperature increased with depth, this difference became smaller with time.

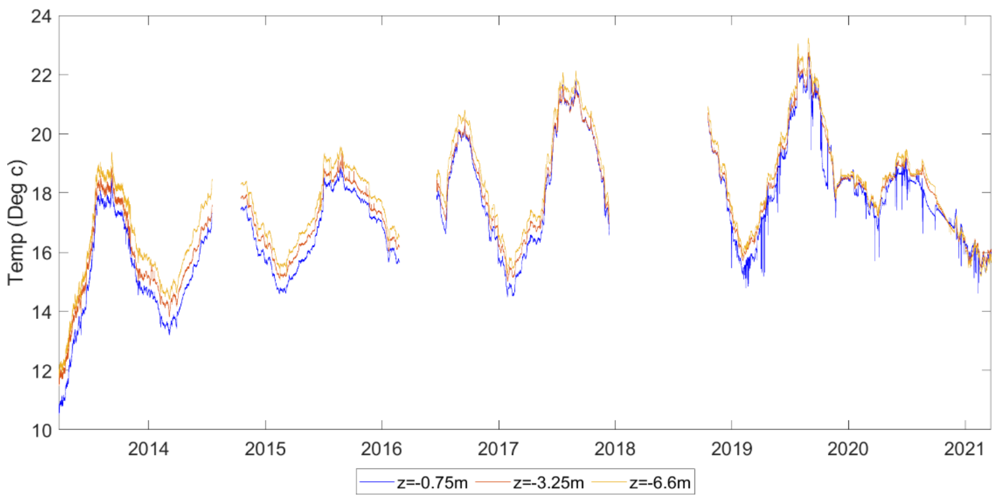


Figure 60 - Average temperature with depth across energy pile

3.4 Discussion

3.4.1 Design lessons learnt

The actual operating loads of the building are significantly higher than predicted thermal loads shown in Table 14. However, the values used in the design of the ground loop were extremely conservative and as such the ground loop is sufficient in size to be able to meet the additional demand comfortably, with the heat pump providing 100% of the space heating, and over 99% of the cooling. Even so, the low specific heat exchange rate of the heat exchangers indicate that the ground loop has been designed with a large safety factor.

The imbalance of the heating and cooling loads of the building, coupled with the ability of the heat pumps to operate in recovery mode and provide heating and cooling simultaneously, has led to more heat being rejected to the ground than being extracted from it. The peak heating load is greater than the peak cooling load, however it occurs at a time where there is also significant cooling demand. The cooling demand is kept at a fairly high level, even in the winter months, due to the need to cool the IT facilities. This means that a large portion of the heat required in the winter months can be met through recovery, taking the heat from the chilled water loop, thus simultaneously meeting the required cooling load. This results in less heat being extracted from the ground loop. Conversely, when the cooling load is at its peak, there is relatively little heat demand, resulting in the bulk of the heat energy removed from the chilled water loop being rejected back into the ground rather than being redirected to the building. This imbalance would mean that less heat extraction is required in total, leading to the steady increase in average ground temperature year on year but this expected behaviour is complicated by the sub-optimal control of the ground loop as discussed below.

The instrumented energy pile does demonstrate an increasing temperature, though this is likely to be higher than the average increase caused by the ground heat exchange imbalance alone. Figure 29 suggests that the energy piles are almost exclusively being used for energy rejection from 2014 onwards, with the heat extraction occurring in the boreholes. This approach would mean that whilst the average ground temperature would be increasing, there would be localized variances. The temperatures around the boreholes would likely be decreasing due to the continued heat extraction, and the temperatures around the energy piles would increase with the continual heat rejection, as demonstrated in Figure 59 and Figure 60.

Without the corresponding extraction from the piles and rejection to the boreholes, the efficiency of the ground heat exchange would also decrease as the surrounding ground approached the temperature of the heat exchange fluid, potentially negatively impacting the performance of the system. The increase in temperature of the energy piles would limit the efficiency of the continued heat rejection, and similarly the temperature of the energy being extracted from the boreholes would decrease, requiring more work from the system to achieve the required set point temperatures. Whilst this is hard to validate as no temperature data for the heat pumps is available, if this is the case a change in control strategy to rebalance the use of the energy piles and boreholes could see an increase in performance. This is particularly the case as the London Clay in which the energy piles sit are very good inter-seasonal energy stores due to their low diffusivity. This may be why the rejected heat is being directed primarily to the energy piles, however this benefit is not realised if they are then not used for heat extraction. It is important to restate that this interpretation is based on the assumptions used to determine operating mode in Equations 14 & 15.

It can be seen Figure 56 and Figure 57 that the performance factor is linked to load being produced by the heat pumps, with the performance improving particularly as the cooling load increases. It is possible that the low performance at low loads is due to an increase in cycling of the heat pumps, degrading the performance through the run-on time for the circulating pumps and compressors, though this cannot be confirmed as the typical data interval for this system is 15 minutes.

The period from July 2020 to December 2020, during Covid, provided a unique opportunity to monitor the recovery of the ground with little to no use of the system. It can be seen that the temperatures within the energy pile dropped by 1.5 to 3.9°C over this time. If the overall trend of rejecting more heat than is extracted continues in the long term, this could be a useful starting point for assessing how long may be required for the ground to recover.

3.4.2 Circulating pumps and operating faults

Unfortunately, as the ground loop circulation pumps are not distinguishable from the primary circulation pumps in the data, no comparisons between the two can be drawn.

The imbalance in the ground heat exchangers can explain at least in part the increase in ground loop and primary circulation pumps power consumption in cooling mode compared to heating mode noted in Table 26.

The auxiliary chiller, whilst not providing significant cooling at any point, was however in use throughout the monitoring period. This is despite the heat pump rarely if ever reaching its cooling capacity limit. This would suggest that the control strategy was not to use it as a backup but rather to assist the heat pump system and meet these peak loads. Unfortunately, as the chiller electricity data is not reliable, it is difficult to understand the impact of this on the overall efficiency.

The solar thermal system has also been severely underutilized. This was designed to meet 13 MWh per year, 18% of the designed domestic hot water demand, and whilst operational from March 2013 to August 2015 only generated 6.8MWh, which is 1.9% of the total domestic hot water in this same period. From 21st of August 2015 onwards, either the system has been taken offline completely, or the meters have not been recording the data. This may be an attempt to prevent further imbalance within the ground heat exchangers.

3.4.3 Performance

Figure 61 to Figure 63 show the performance factors for the Crystal relative to some similar systems as highlighted in the literature review. The details and references for the comparative case studies can be found in Table 27.

Figure 61 compares the SPF of the Crystal to three German systems utilising energy piles. All four of the systems are capable of providing heating and cooling, though Figure 61 only shows the performance factors in heating mode.

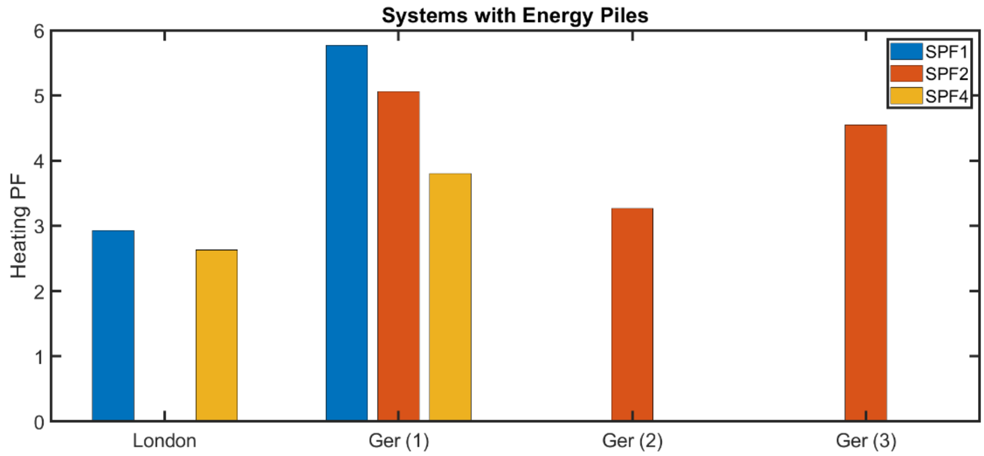


Figure 61 - Heating SPFs of Systems with Energy Piles

The Crystal system appears to be underperforming against each of these systems, though this may be partly attributable to the fact that The Crystal utilises both energy piles and boreholes, seemingly with a sub-optimal control strategy that does not utilise these heat exchangers to their full potential. Additionally, the system at the Crystal is much larger than the others, with a capacity of 814 kW compared to 82-107kW for the German counterparts, thus it likely requires larger circulating pump capacity. However, the small reduction in performance factor from boundary 1 to boundary 4 in the Crystal shows that the additional parasitic load is likely not the cause of the underperformance.

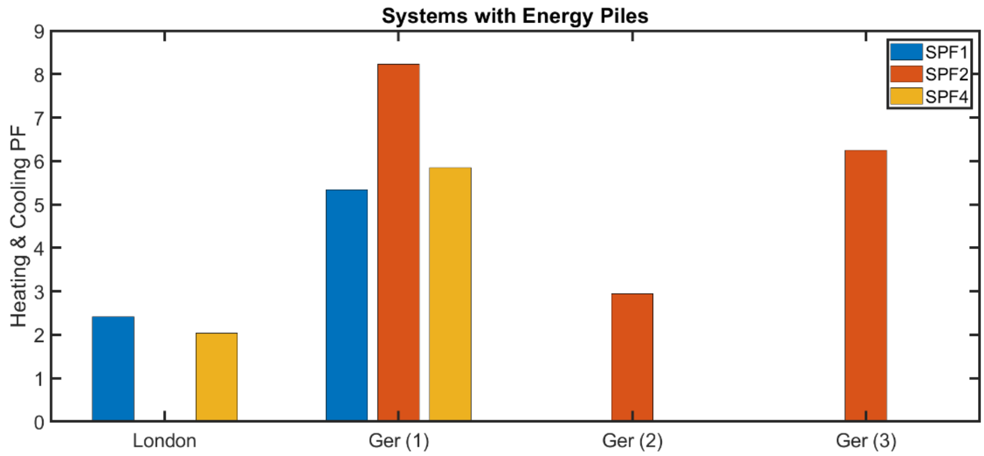


Figure 62 - Heating and Cooling SPFs of Systems with Energy Piles

Figure 62 shows the performance factor for heating and cooling for these same systems. The two German systems with significantly larger PFs at boundary 2 are utilising free cooling from the energy piles. This highlights the potential of free cooling compared to active cooling which appears to be reducing the overall PF in the other two systems.

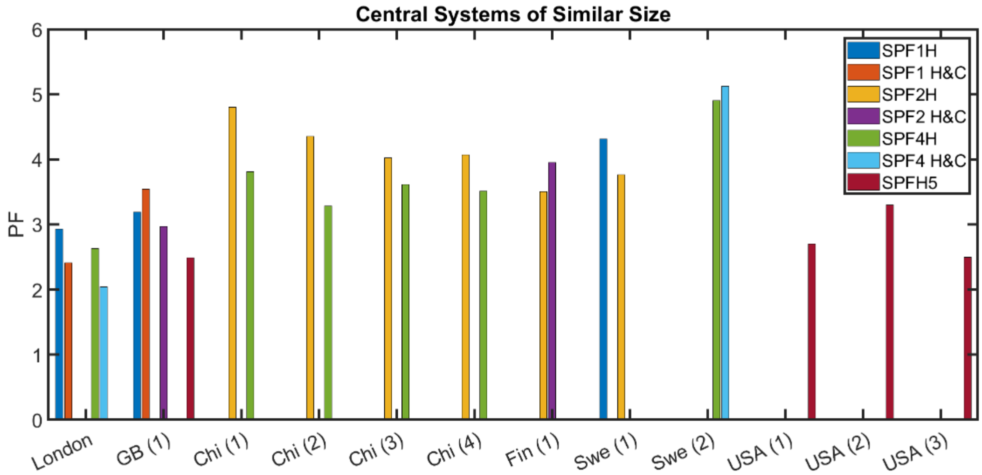


Figure 63 - SPFs of 400-1300 kW Systems

Figure 63 compares the Crystal system performance factors to other centralised systems of a similar size, between 400 and 1300 kW. Once again, the Crystal appears to underperform compared to the global counterparts, whilst performing to a similar level as the other GB based system.

Table 27 - Comparative Case Study References

Identifier	Country	System Capacity (kW)	Building Type	Citation
Ger (1)	Germany	107	Office	(Bockelmann, 2021a)
Ger (2)	Germany	82	Office	(Bockelmann, 2021c)
Ger (3)	Germany	-	School	(Bockelmann and Fisch, 2019)
GB (1)	Great Britain	480	University	(Naicker and Rees, 2018)
Chi (1)	China	1040	Residential	(Deng *et al.*, 2019a)
Chi (1)	China	1986	Residential	(Deng *et al.*, 2019a)

Chi (1)	China	2600	Residential	(Deng *et al.*, 2019a)
Chi (1)	China	2160	Residential	(Deng *et al.*, 2019a)
Fin (1)	Finland	790	University	(Todorov *et al.*, 2021)
Swe (1)	Sweden	480	Industrial	(Andersson, Rydell and Håkansson, 2021)
Swe (2)	Sweden	1400	Hospital	(Walfridson, 2022b)
USA (1)	USA	754	Museum	(Im and Liu, 2015b)
USA (2)	USA	812	High School	(Liu, Malhotra and Im, 2017)
USA (3)	USA	1253	Student Apartments	(Liu *et al.*, 2015)

It is possible that the continual switching of modes within the heat pumps, as shown by Figure 64, is driving their low performance, causing the heat pumps to run at sub-optimal temperatures. Additionally, the unbalanced nature of the loads within the boreholes and energy piles means that the benefits of using the ground as a thermal store are not being realised.

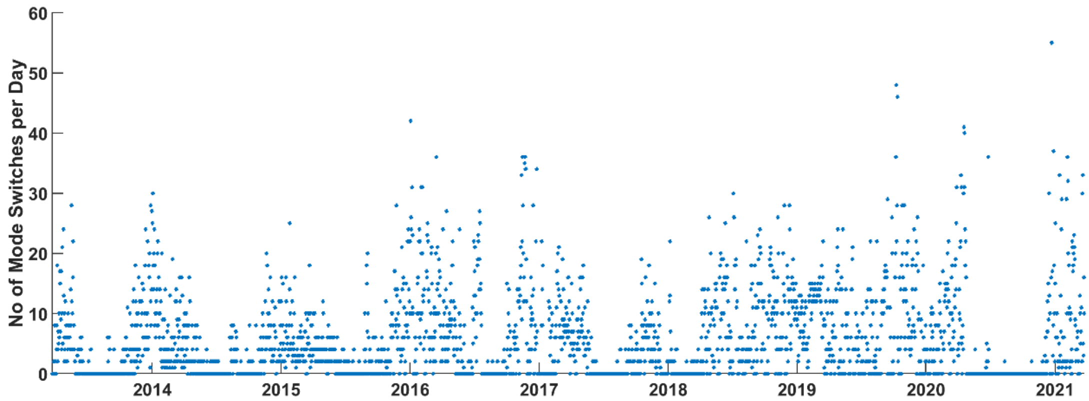


Figure 64 - Mode Switches Per Day

3.4.4 Improvement measures

Despite the apparent wealth of data available for this system, the grouping of key datasets and lack of temperature readings has prevented deeper analysis of the performance of the heat pumps. The nature of the data from several of the meters would also suggest that the meters are not being routinely monitored as several seem to indicate malfunction or present erroneous data. This detracts from the analysis possible and highlights the difficulties faced in monitoring such large systems. As the literature review suggested, there is a need for continuous monitoring, and maintenance, of the equipment used in these systems to allow for meaningful analysis and maintain high efficiencies.

Obtaining the breakdown of the grouped datasets to determine the individual contribution of each of the circulation pumps would allow a much more detailed analysis of the system. This would allow the heat pumps to be analysed in isolation for example, calculating individual performance factors to determine whether a heat pump malfunction is the cause of underperformance, or whether the control strategy is the more significant factor. Similarly, the assumptions made in the analysis of this system have implied an unusual control strategy for the ground heat exchangers, but the clear separation of the heat extracted from, and heat rejected to, the two types of ground heat exchangers would provide a more accurate understanding of this without the need for complex analysis.

Additionally, the following datasets should be available according to the documentation, and access to these would be invaluable to further understand how the system performance could be improved.

1. Heat pump operating mode
2. Fluid temperature data
    a. Entering and leaving ground loop.
    b. CHW and LTHW flow to, and return from, building loop.
    c. CHW and LTHW flow to, and return from, buffer tank.
    d. Flow to, and return from, the low loss header to the heat pumps.

The temperatures would show the temperature lift required of the heat pumps, both in recovery mode and not. This could highlight the effectiveness of the heat pumps when recovering heat compared to simply extracting and rejecting heat to the ground. This might also yield some insight into why the performance is worse in cooling mode than heating mode.

Unfortunately, the analysis of this system began in earnest at the same time as the ownership of the building changed hands. A lack of communication with the new owners has made resolving these issues impossible to date. It is also unclear how much information on this system was provided to the new owners at the handover and this may be one of the reasons that the performance of the system has deteriorated over the past few years.

A key improvement measure would entail revisiting the control strategy, to try and rebalance the use of heat pump A and heat pump B, as running them both simultaneously when the first is not at capacity appears to have caused a decrease in the system performance, seen from mid-2018 onwards. Rebalancing the use of the energy piles and boreholes may also produce an increase in heat exchanger performance and thus system performance, though this would need to be validated with temperature data not presently available.

3.5 Conclusions

The following conclusions can be gleaned from the analysis conducted on the long-term data for the system at The Crystal:

- The long-term performance of this system is relatively poor, particularly when compared to similar systems outside of the UK.
- The actual loads of the building are greater than predicted but the ground loop was designed to meet significantly higher loads than have been seen.
- The unbalanced nature of the loads means more heat is being rejected to the ground than extracted from it, causing an increase in temperature within the energy piles.
- The temperature of the energy piles can recover quickly when the system is not in use, as highlighted during the Covid period.
- The control strategy appears to have deviated or been altered from how it was originally setup. This should be addressed to increase the performance factor of the system, looking both at when heat pump A and heat pump B are in operation, and also when to extract/reject from the energy piles and boreholes.
- Despite a wealth of data available from the BEMS, performance factors at system boundaries 0, 2, and 3 cannot be calculated. Whilst the BEMS is fit for purpose, this highlights the additional benefits possible if due consideration is given when developing monitoring strategy.
- From a troubleshooting perspective, measuring the heat produced by the individual heat pumps and the fluid temperatures is more important than monitoring the energy used.
- However, to optimise the system, monitoring the energy used by each heat pump, would allow for the calculation of multiple KPIs including PFs and SEI which can then be used to compare the performance to the factory conditions.

- Additionally, measuring the heat extracted and heat rejected from/to the ground can provide an indication into the control strategy, allowing for further optimisation.
- This would also provide feedback on the ground loop design, though this is more useful from an academic perspective and to inform future designs rather than improving the performance of the existing system.

3.6 Future Work

It is hoped that through the continued collaboration with the new owners of the Crystal, additional data will be made available, allowing for further detailed analysis to be conducted.

Obtaining the breakdown of the grouped datasets to determine the individual contribution of each of the circulation pumps would allow a much more detailed analysis of the system, as discussed in Section 3.4.4.

Finally, additional information on the system itself would also be beneficial to validate some of the assumptions made in the analysis, including:

1. Whether the domestic hot water value provided is a part of the heat generation value or supplementary to it
2. The make and model of the meters to allow error calculations
3. Exact locations of meters in the system
4. Control system details e.g. weather compensation setting

4 Case Study #2 – The Heights

The following chapter investigates the long-term performance of another ground source heat pump installation, in this case a residential system with multiple heat pumps in individual flats and a shared ground loop. Similarly to the first case study, the objectives for this analysis are to:

- Evaluate the long-term performance of the ground source heat pump system at multiple system boundaries.
- Draw out any performance issues with associated causes and potential solutions.
- Provide insights into the performance and utilisation of the shared ground heat exchanger, as little to no reported data for such systems in the UK is available.

The chapter will be set out with an introduction to the system followed by an explanation of the methodology for the analysis, including the data cleaning required and KPIs used. The results of the analyses are then presented, firstly investigating the ground heat exchangers, and then comparing the individual flats. Finally, the performances of the flats will be compared to one another, and then to other similar systems found in the literature. Any conclusions of note are then reported, along with recommendations to improve the efficiencies of these systems.

4.1 System & Instrumentation

4.1.1 The building

An opportunity arose to instrument a number of new ground source heat pumps to be retrofitted within two blocks of social housing in Leeds. This was in collaboration with Leeds City Council, as well as Leeds Beckett University who have compared the electricity usage for heating before and after the heat pump installations.

The Heights East and the Heights West, Figure 65, are two very similar blocks of flats owned by Leeds City Council, opened in 1960. Each block is 10 storeys tall and contains a total of 60 residential flats which are a mixture of one and two bedrooms, originally heated via storage heaters. In late 2020 and early 2021, these storage heaters were replaced with individual ground source heat pumps for the space heating, assisted by a Sunamp heat battery utilising phase change technology to provide supplementary heating and hot water. This retrofit also required an entire new wet heating system to be installed, with radiators installed in all occupied rooms.

Figure 65 - Left: The Heights East, Right: The Heights West Photos © Betty Longbottom (cc-by-sa/2.0)

Table 28 and Table 29 give the main characteristics of the building and the GSHP system.

Table 28 - Summary of the building features

Location	Leeds, United Kingdom
Year of building construction	1960
Ground source system operation start date	2020
Building Type	Residential
Building floor area (net, gross)	Est 50m^2 per flat
Analysed monitoring start date	01/02/2021
Analysed monitoring period	16 months

Table 29 - Summary of the system configuration

Heat distribution	Radiators
Cooling distribution	N/A
Domestic hot water (DHW) production by system	Heat pump
Supplementary heat for DHW	Sunamp Heat Battery with Immersion
Supplementary cooling	N/A

Nominal capacity of supplementary heating for DHW	Heat Battery: 9.5kWh storage – 2.8kW Immersion
Heat pump type	Water-to-Water
Reversible	No
Compressor type	Single/Twin Reciprocal
Speeds	Single Speed
Heat pump system	De-centralised
Number of heat pumps	120: 60 per Block (9 Monitored)
Nominal total heat pump heating capacity	3 kW / 6kW per flat
Refrigerant	R134a

4.1.2 The ground source system

Each block of flats has its own ground source, made up of 30 vertical borehole heat exchangers. The total length of the borehole heat exchangers is 5030m for East and 5047m for West, distributed in 4 separate circuits per building as detailed in Table 30,Table 31, Figure 66 and Figure 67. The boreholes in each circuit are the same depth, but each circuit has a different depth depending on the estimated load as each circuit feeds a number of different floors. Each borehole consists of a single 40mm diameter polyethylene U-tube in which a 22% Glycol and water mixture is circulated.

Table 30 - Summary of the ground heat exchangers – Boreholes

Number of boreholes	East: 30 West: 30
Borehole length	151-183 m
Total borehole length	East: 5030 m West: 5047 m
Borehole diameter	150 mm
Borehole filling material	Thermally Enhanced Grout (Min Conductivity 1.78 W/mK)
Borehole heat exchanger type	Single U-tube
Source side pipe characteristics	BH to Building: PE100 SD11 (40/90mm) Building to HP Units: MCLP (32/60/90 mm)

Table 31 - Ground Loop Arrays

Array	Floors	Number of Flats	Number of BHs	Depth per BH (m)
East A1	-1 & G	8	4	151
East A2	1, 2, & 3	18	8	182
East A3	4, 5, & 6	18	9	169
East A4	7, 8, & 9	16	9	161
West A1	-1 & G	8	4	151
West A2	1, 2, & 3	18	8	183
West A3	4, 5, & 6	18	9	170
West A4	7, 8, & 9	16	9	161

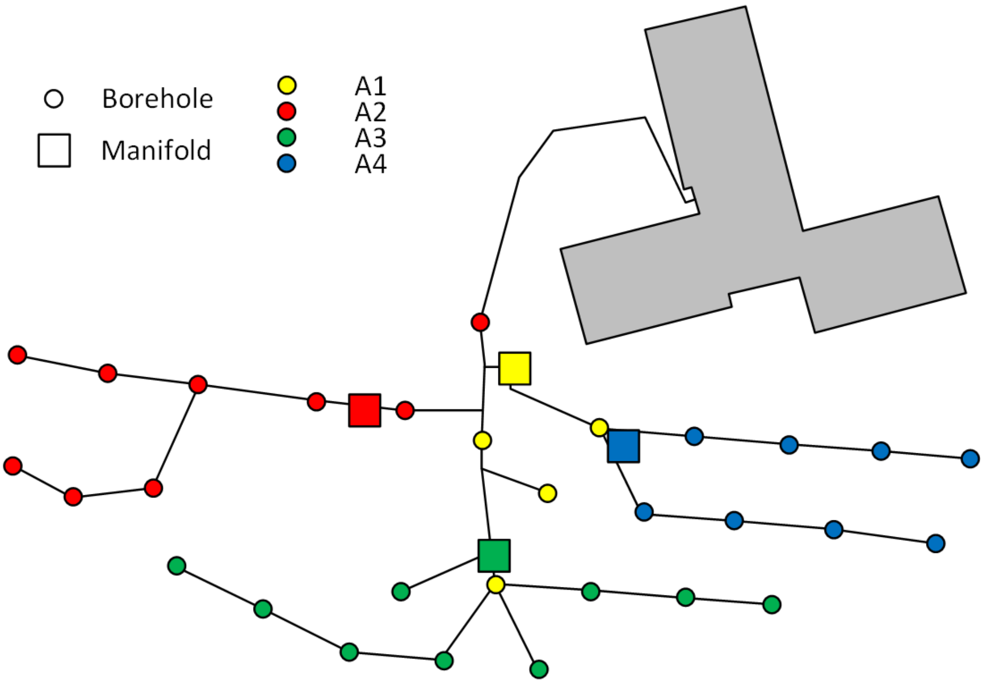


Figure 66 - The Heights East Boreholes Layout – Top View

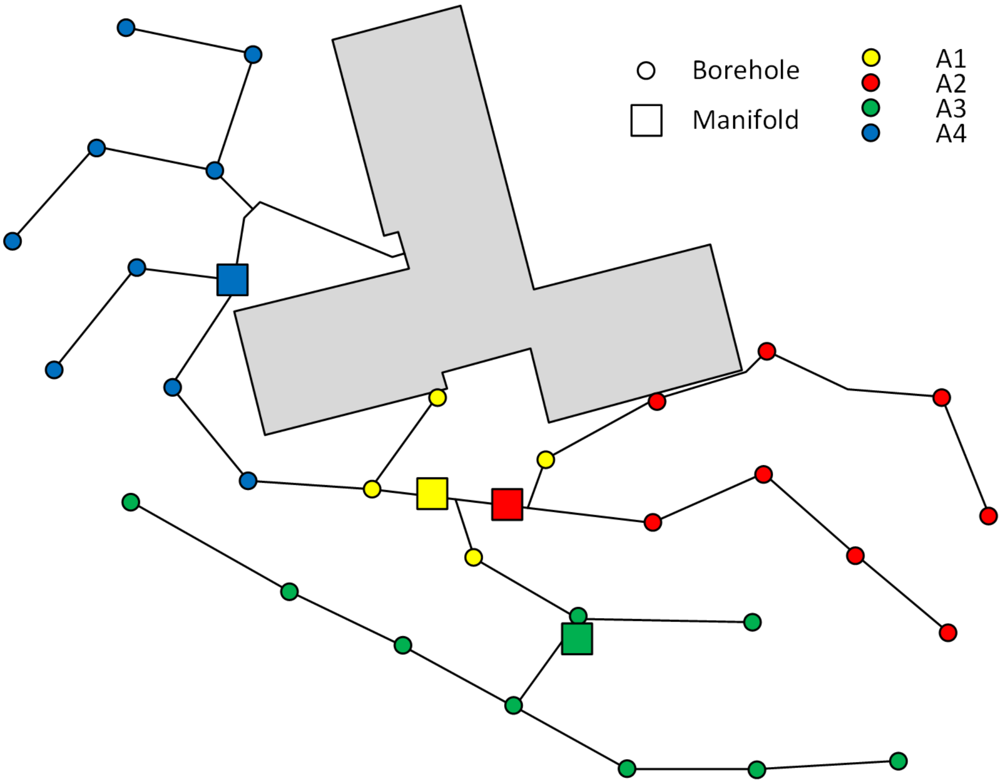


Figure 67 - The Heights West Boreholes Layout – Top View

For each block of flats, the boreholes feed 60 de-centralised Kensa Shoebox heat pumps, providing heating and domestic hot water for the individual flats. These heat pumps are either the single compressor, or the twin compressor variant depending on the predicted demand of the flats providing a heating capacity of either 3kW or 6kW. The heat pumps have been set to produce space heating at a flow temperature of 50°C. Each flat, regardless of the heat pump size, is also fitted with a Sunamp Heat Battery UniQ HW 9+i. These heat batteries utilize phase change technology to store heat from the heat pump and release as domestic hot water when required. The Sunamp Heat battery has a 2.8kW immersion heating capacity, a storage capacity of 9.5kWh when used with a high temperature heat pump, a minimum heat source temperature of 65°C, and a heat supply temperature of 55°C.

The individual heat pumps control the circulation of the fluid from the ground loop, varying the flow rate of the water-glycol mixture in each to loop to meet the specific demand of those flats connected to it. As such there are no dedicated ground loop circulation pumps.

This system is shown diagrammatically in Figure 68 and is the same for both blocks.

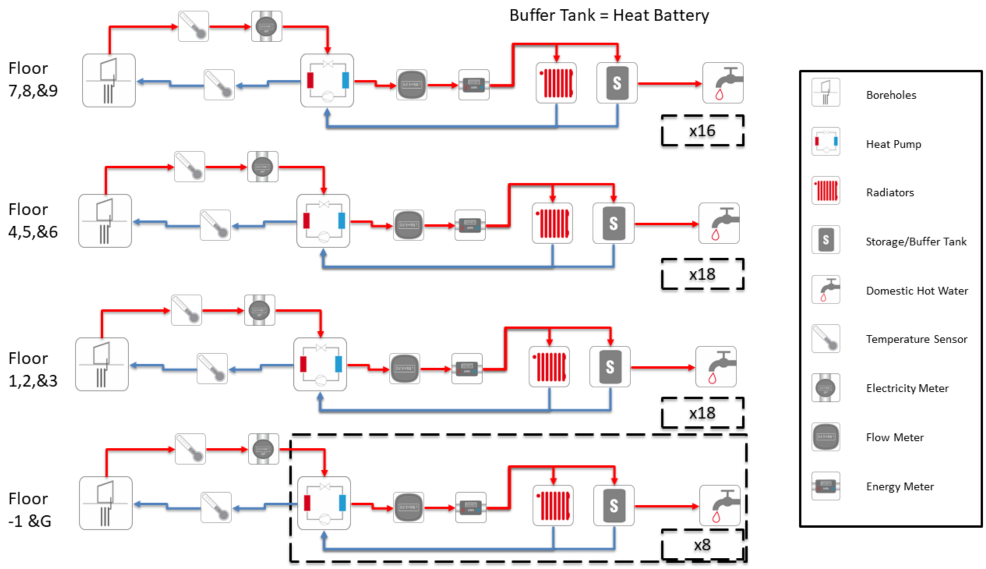


Figure 68 - The Heights Heat Pump System Schematic: Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52

Table 32 – Summary of the ground source and sink

Ground source	East: 30 Boreholes West: 30 Boreholes
Loop type	Closed loop
Ground composition	See table 33
Maximum Groundwater level [m]	4 m
Annual mean air temperature (measured)	11.1°C (06/01/2021 – 06/01/2022)
Undisturbed ground temperature	Measured: 13.2°C Used in design: 9.4°C
Measured ground thermal conductivity	2.81 W/m,K
Assumed Volumetric ground heat capacity	2.0232 MJ/m^3,K (Calculated from Diffusivity)
Minimum ground heat exchanger exiting fluid temperature ($ExFT_{min}$)	0°C (Design Condition) 1.34°C (Measured)
Maximum ground heat exchanger exiting fluid temperature ($ExFT_{max}$)	16.73°C (Measured)

The values given for the ground thermal conductivity, the thermal diffusivity, and the undisturbed ground temperature, have all been provided by Genius Energy Lab after conducting an on-site thermal response test (TRT). By dividing the thermal conductivity by the thermal diffusivity, the assumed ground volumetric heat capacity in Table 32 was calculated.

Finally, the table also includes the measured values for the minimum and maximum exiting fluid temperature of all the ground loops over the monitoring period, as well as the design condition.

From the initial desktop assessment of the anticipated geology conducted by Genius Energy Lab, a GSHP design consultancy, the geology in the region is expected to consist of Pennine lower coal measures formation to a depth of 182 m below ground level, beyond which is the milstone grit group up to the max depth of all of the boreholes, as shown in Figure 69. The sandstone layers found in the coal measures can be minor aquifers, which may explain the increased thermal conductivity. This is also true of the milstone grit layer. This same assessment also suggested that the groundwater level is around 4m below ground level as per local records.

Table 33 - Summary of the ground layers

Strata	Description	Depth
Made Ground	Fine to coarse brick and concrete gravel; soft to firm black sandy gravelly clay.	2m
Pennine Lower Coal Measures Formation	Mudstone, Siltstone & Sandstone	182m
Milstone Grit Group	Sandstone, Mudstone & Siltstone	>182m to max depth of BHs

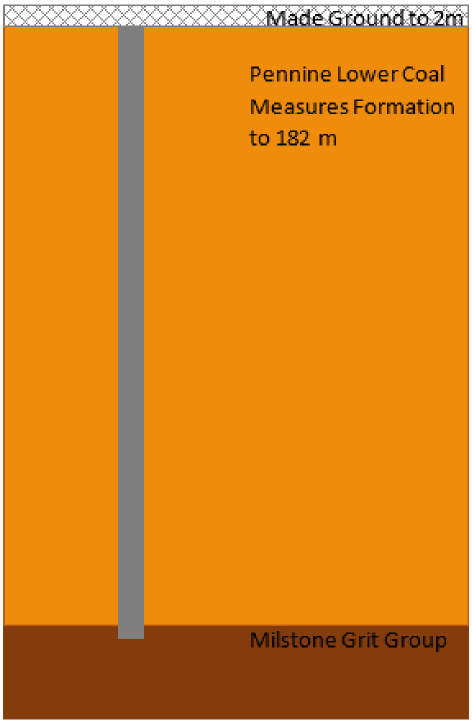


Figure 69 - Summary of the ground layers

4.1.3 Previous Reporting

The original report monitoring the retrofit of these heat pumps (Fletcher, Gorse and Miles-Shenton, 2021), sampled 20 flats and focussed on a number of different measures including electricity usage, running costs, internal temperatures, internal humidity, and qualitative information from the end users. The primary focus of the original research was to compare the new heat pumps with the previous storage heaters and determine whether this project was worth applying to additional social housing owned by the council.

Some of the key conclusions of this report included:

- The heat pumps led to a reduction in electrical consumption of 33% per flat on average, but not necessarily a running cost reduction due primarily to a tariff change.
- The heat pumps led to greater comfort levels and most residents preferred the new system to the storage heaters.
- The noise of the heat pumps and loss of storage space in the flats were common complaints.
- A number of consumption profiles were present with many end users not using the system in an optimal way.
- The operating guidance provided to the end users' needs to be improved.

The research in the following chapter builds on the original work with more of a focus on the performance of the heat pumps themselves as well as the ground heat exchangers. To achieve this, additional monitoring equipment was installed.

4.1.4 Instrumentation & Monitoring

The flow through each of the eight ground loops is being monitored via a non-invasive, ultrasonic flow meter installed on the risers in each building. Two PT100 temperature probes are also installed via a thermowell in each manifold, one measuring the flow and one the return temperature. From the combination of these measurements, the heat energy being extracted from the ground loops can be calculated. These sensors are connected to a Campbell Scientific datalogging set up which is configured to be accessed remotely.

As part of the initial study carried out by Leeds Beckett University, inline kWh meters were installed in 19 flats, across the two buildings, to monitor the power usage of the newly installed heat pumps. Eltek transmitters were then used to transmit this data to two centralised dataloggers per block of flats. Additionally, Eltek sensors transmitted temperature and humidity data from the flats to the two dataloggers. Of these original 19 flats, 12 residents agreed to share this data with us.

The original intention was to install heat meters in each of these 12 flats to monitor all heat delivered by the heat pump, however due to access issues during COVID, only 9 heat meters were installed successfully, 5 in the Heights East, and 4 in the Heights West. The heat meter used was a Sontex Superstatic 789 Heat Meter which communicated via wireless MBus to a Elvaco datalogging system also configured to be accessed remotely.

Finally, the outdoor air temperature for the monitoring period was taken from a local weather station in Leeds set up by the School of Earth and Environment at the University of Leeds (School of Earth and Environment UoL, 2022).

The ground loop sensors and dataloggers were installed during October and November 2020 and the heat meters were installed in early 2021. As such the monitoring period for this system is from January 2021 to June 2022.

Table 34 details the measurements available from these sensors, the typical data intervals, and the reported accuracy of the measurements.

Table 34 - Summary of the system monitoring

Measurement	Unit	Recording Interval	Instrumentation	Accuracy	Comments
Ground Loop Flow Temperature	°C	1/15/60 min	PT100	DIN 1/10 +/- 0.03°C	Installed for this work
Ground Loop Return Temperature	°C	1/15/60 min	PT100	DIN 1/10 +/- 0.03°C	Installed for this work
Ground Loop Flow	l/min	1/15/60 min	Micronics U1000 (Ultrasonic)	±1% – 3% of flow reading for >0.3m/s	Installed for this work
HP Electricity	Wh	10 min	Emlite ECA2 100A in-line kWh meter	Class B (1%), to EN 50470 1-3	Installed for LBU work
Heat Pump Heat	kWh	15 min	Sontex Superstatic 789 W-MBus	Class 2, To EN 1434	Installed for this work
Heat Pump Flow Rate	m^3/h	15 min	Sontex Superstatic 789 W-MBus		Installed for this work

Heat Pump Demand Side Flow Temperature	°C	15 min	PT1000		Installed for this work (Integrated with Heat Meter)
Heat Pump Demand Side Return Temperature	°C	15 min	PT1000		Installed for this work (Integrated with Heat Meter)
Indoor Temperature	°C	10 min	Eltek GC10	+/-0.4°C	Installed for LBU work
Indoor Relative Humidity	%	10 min	Eltek GC10	+/- 4%	Installed for LBU work
Outdoor Temperature	°C	5 min	Unknown		Taken from local Leeds weather station

4.2 Data Analysis & KPIs

4.2.1 Minutely PF & SEI

The instantaneous readings from the heat meters allow the performance factor at a small timescale to be calculated, an “Instantaneous Performance Factor“ (IPF). A Performance Factor (PF) at such a small timescale would often be referred to as the COP in literature, but this thesis adopts the proposed definitions in Gehlin *et al.* (2022) that COP refers to controlled lab conditions, and PFs are used for field measurements.

For accurate values at these small timescales, the raw data has been used rather than the backfilled values as these will not align with the electricity readings. The backfilled values will however be used when calculating performance factors over longer periods.

To calculate the IPF, the electricity data was divided into minutely intervals and the heat was calculated from the instantaneous flow rate and temperatures readings from the heat meter. The IPF is then calculated using Equation (22).

$$IPF = \frac{Instantaneous\ Heat\ as\ per\ reading}{Interpolated\ minutely\ electricity\ useage} \tag{22}$$

As seen in Equation (23) to Equation (25), the calculation of the Seasonal Efficiency Index (SEI) requires the leaving ground loop fluid temperature.

$$SEI = \frac{IPF}{\frac{T_{ref,h,1}}{T_{ref,h,1} - T_{ref,c,1}}} \tag{23}$$

$$T_{ref,h,1} = \frac{(T_{h,in,1} + T_{h,out,1})}{2} = \frac{(T_{HP\ Return} + T_{HP\ Flow})}{2} \tag{24}$$

$$T_{ref,c,1} = \frac{(T_{c,in,1} + T_{c,out,1})}{2} = \frac{(T_{GL\ Return} + T_{GL\ FLow})}{2} \tag{25}$$

The SEI provides the COP, in this case the IPF, as a percentage of the theoretical maximum COP, also known as the Carnot COP, at the given conditions and as such, it should never be over 100%. In fact, Gehlin *et al.* (2022) suggests that values greater than 40% represent a well performing heat pump. This is a useful measure not only to measure the performance of the heat pump, but to highlight and remove any erroneous IPF values that occur as a result of data issues.

4.2.2 Performance Factors over longer periods

To provide insight into the performance of the heat pumps in each flat, the performance factors were calculated from the heat and electricity data for each on, over varying timescales.

Given the sporadic nature of the heat and electricity data, calculating the performance factors is not as simple as aggregating all of the available data within a given timeframe. This is because if, for example, the electricity meter stops working halfway through a month, the heat value will be significantly higher than the electricity data providing an unreliably high performance factor. As such, it was important to determine where the meters experienced issues causing gaps in data. These erroneous values were then removed from the performance factor calculations, as discussed in Section 4.3.

Table 35 - Performance Factor Boundaries for the Heights

Boundary description	HPT Annex 52 Boundary levels	
	H1/C1	H1+/C1+
Ground Source (circulation pumps+ ground source)		
Heat pump unit including internal energy use, excluding internal circulation pump	✓	✓
Buffer tank (including circulation pumps between heat pump and buffer tank)		
Circulation pump on load-side (between buffer tank & building Heating/Cooling distribution system)		
Building Heating/Cooling distribution system		
Ground Source (circulation pumps+ ground source)		✓
Equivalent in the SEPEMO boundary schema	H1/C1	

Of the available IEA PT Annex 52 boundaries the only system boundary 1* and 1+* is available to be reported on. As with case study 1, the asterisk in this instance indicated the inclusion of the heat pump internal circulation pump power as this is not available as a separate reading in this instance.

The fluid is circulated around the ground loops using the circulation pumps internal to the heat pumps, there is no centralised ground loop circulation pump, and as such boundary zero is not applicable.

Similarly, boundary levels 3 and 4 are not applicable as there is no buffer tank in the system, and boundary level 5 cannot be reported on as whilst there is a circulation pump on the building distribution side, the electricity for this pump is not being monitored.

In the case of the auxiliary heat sources, the immersion heater in the heat battery is assumed to be 100% efficient at converting the electricity into heat to be stored.

These performance factors will be calculated for each flat according to Equations (26) and (27).

$$PF1^{*} = \frac{Heat_{GSHP}}{Elec_{GSHP}} \tag{26}$$

$$PF1+^{*} = \frac{Heat_{GSHP} + Elec_{Immersion}}{Elec_{GSHP} + Elec_{Immersion}} \tag{27}$$

4.2.3 Ground Loop Utilisation

From the study conducted by Leeds Beckett University (Fletcher, Gorse and Miles-Shenton, 2021), it is understood that all flats on the bottom floor, top floor and at the edges of the buildings contain the twin compressor 6kW heat pumps, to counter the additional heat losses. Table 36 and Table 37 are summaries of the different arrays, including the monitored heat pumps.

Table 36 - Equipment Distribution - Heights East

Array	Floors	# of Flats	# of 3kW HPs	# of 6kW HPs	Total kW	Monitored Flats	3/6 kW
1	-1, G	2, 6	2	6	39	A	6
2	1, 2, 3	6, 6, 6	9	9	81	E	6
3	4, 5, 6	6, 6, 6	9	9	81		
4	7, 8, 9	6, 6, 4	5	11	78	G,I,J	3,6,3
Total	11	60	27	33	279		

Table 37 - Equipment Distribution - Heights West

Array	Floors	# of Flats	# of 3kW HPs	# of 6kW HPs	Total kW	Monitored Flats	3/6 kW
1	-1, G	2, 6	2	6	39	K,L	6,3
2	1, 2, 3	6, 6, 6	9	9	81		
3	4, 5, 6	6, 6, 6	9	9	81	Q	3
4	7, 8, 9	6, 6, 4	5	11	78	R	6
Total	11	60	27	33	279		

Combining the above data with the design brine flow rates for the two heat pumps, as noted in the manufacturer's data, allows an estimation of how many heat pumps are running at once in the arrays. These flow rates are 9.2kg/min for the 3kW model and 18.4 kg/min for the 6kW variant.

Due to the combination of 3kw and 6kw heat pumps on each riser, it is impossible to determine exactly how many heat pumps are operating at any one time, only a minimum and maximum. For example, a flow rate of 18.4 kg/min could be a single 6kw heat pump or it could be two 3kw heat pumps. Instead, the percentage utilisation rate for each array has been calculated as per equations (28) to (31).

Given the varying number of heat pumps on each array, the maximum theoretical flow rate for each array was calculated based on the design flow rates of the individual heat pumps, as per the manufacturer's documentation. This is shown in Equation (28).

$$Max\ Array\ Mass\ Flow\ Rate = \frac{(\#of\ 3kW\ HPs \times 9.2)+(\#of\ 6kW\ HPs \times 18.4)}{60} \quad (28)$$

The values can be found in Table 38.

Table 38 - Max Ground Array Flow Rates – East & West

	Max mass flow rate (kg/s)
Array 1	2.15
Array 2	4.14
Array 3	4.14
Array 4	4.14

The density for the glycol mixture was extrapolated from known densities at 0°C (Engineering ToolBox, 2003), based on a 24% concentration.

This was then used to convert the measured flow rate per array to a mass flow rate as per Equation (29).

$$Array\ Mass\ Flow\ Rate\ \left(\frac{kg}{s}\right) = \left(Array\ Flow\ Rate\ \left(\frac{l}{min}\right) \div 60\right) \times \frac{1043.2}{1000} \quad (29)$$

The percentage utilisation for each array was calculated as a percentage of this maximum as per Equation (30).

$$\%\ Utilisation = \left(\frac{Current\ Riser\ Mass\ Flow\ Rate}{Max\ Riser\ Mass\ Flow\ Rate}\right) \times 100 \quad (30)$$

4.3 Data Cleaning

One of the big challenges with attempting to obtain such comprehensive data over long time periods is ensuring the quality of the data. With each of the sensors and meters reporting data with varying degrees of success and reliability, a large amount of data cleaning was required to ensure the analysis that follows allowed for sensible conclusions to be drawn.

This section contains a summary of this data cleaning for each of the datasets, with details of the methods used can be found in Appendix B.

4.3.1 Time standardisation

It was noted that the timestamps for the ground loop datalogger in the Heights West was aligned with BST year-round, whilst all other meters were recording on GMT. As such all readings were standardised to GMT, by subtracting an hour from the timestamps of any aligned to BST, and BST was not accounted for in any of the analysis.

4.3.2 Temperature probe calibration

From the initial ground loop TRT the undisturbed ground temperature was found to be 13.2°C, which provides a baseline figure for temperatures to expect from the borehole flow temperatures.

Calibration of the temperature probes was attempted once installed in the ground and connected to the datalogging equipment. This was done by comparing their readings to that of a reference thermometer, one manifold at a time, with repeat measurements to improve reliability.

From the multiple readings, a correction factor was derived to be applied to the recorded readings to provide the true temperatures.

This calibration process was repeated for two of the arrays feeding the West building, West A1 and West A2, as the temperature readings being recorded were significantly different than expected.

Figure 70 and Figure 71 show the comparison of the raw data to the data once the correction factor has been applied for two example arrays. The dashed red line is the point at which the calibration was attempted. The remaining arrays can be found in Appendix B1.

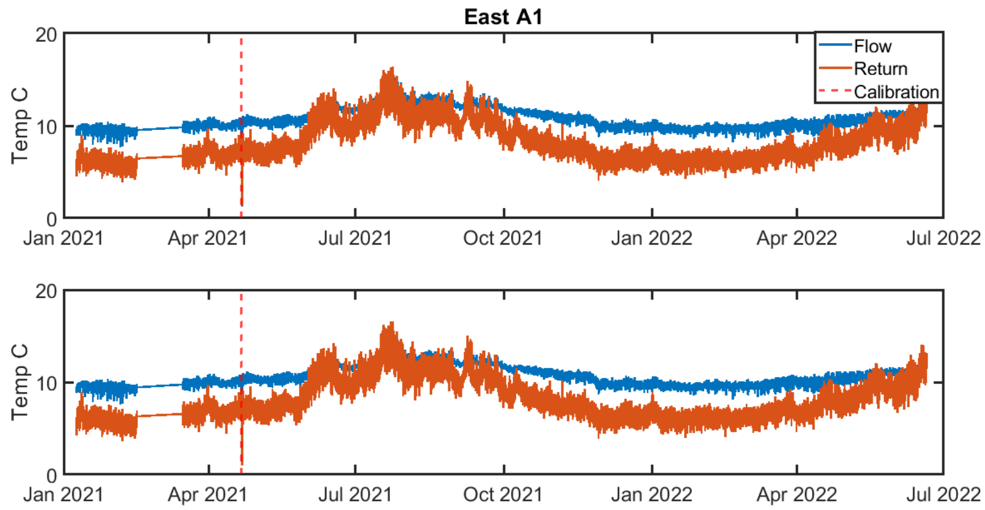


Figure 70 - East A1 Uncalibrated Temperatures (Top) and Calibrated Temperatures (Bottom)

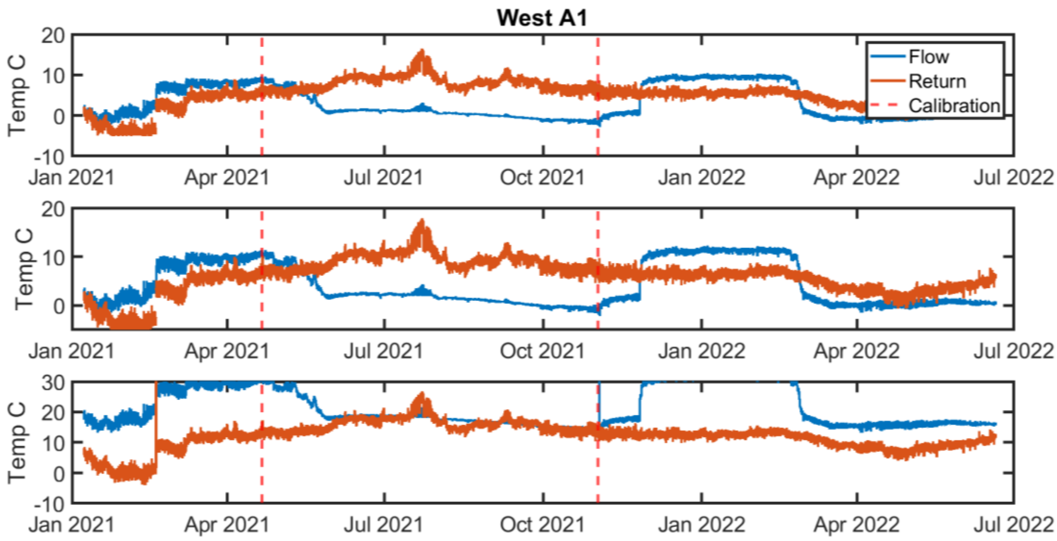


Figure 71 - West A1 Uncalibrated Temperatures (Top), Calibration Attempt 1 (Middle) and Calibration Attempt 2 (Bottom)

With East A1 the correction factors appear to make minor adjustments to the uncalibrated temperatures. With West A1 however, the correction factors are clearly not suitable across the whole range of data, producing some unrealistic values. It is also clear that at several points, the temperature probe records a sudden and unrealistic change in temperature, suggesting that either it has been knocked or damaged in a way such that the resistance being recorded changes significantly. As such, change point analysis has been applied to the temperature data to determine when these events have occurred and what this may mean for the temperature data and calibration corrections.

Change point analysis is a statistical method in which a signal is interrogated to find the points where a statistical measure changes significantly. This can be the mean, the root mean squared value, the standard deviation, or the mean & slope. It was decided that change point analysis would be used to provide some statistical rigour to the engineering judgement being used in cleaning the temperature data.

A more detailed explanation and the results from this analysis can be found in Appendix B1 but for context, change point analysis is an iterative process that will continue to split the signal until either the maximum number of splits is reached or, the residual error does not decrease by ‘Minimum Threshold’ when split again. The value used for this minimum threshold parameter was set based on analysis of a data set without any large, unexpected changes in recorded temperature.

This value was then applied in the change point analysis for the remaining data sets to identify where any of these ‘events’ occurred along with the natural change points expected due to usage and weather patterns.

This analysis determined which data sets to use for the temperature readings based on the calibration dates and event dates and provided clear points from which the data should be removed from the analysis.

For most arrays this meant the omission of a few months data, however in some cases this only left a few months of usable data. This is shown, array by array, in Section 4.4.1.

4.3.3 Ground Loop Flow Rate Data

The flow sensors installed often struggled to pick up flow through the pipes, and initially reported zero values despite the heat pumps drawing flow through them. Therefore, some of the meters had to be moved from the flow to the return pipes to enable satisfactory data collection.

The flow rates are transmitted from the flow rate sensors to the dataloggers as frequency signals. This means that any reverse flow in the pipes which is picked up by the sensors will simply be transmitted as a zero value to the datalogger. Similarly, any values of flow greater than the maximum set on the sensor, will be transmitted as the maximum frequency, in this case 200Hz. This means that all logged values will fall within the allowable flow rates, but a zero value could either indicate no flow or reversed flow, and a value of 200Hz could indicate a max flow rate or slightly higher than maximum flow rate. As such, within the flow data there are periods of unexpected 'zero flow' as well as other unusual data patterns. The resulting flow readings are presented and discussed in Section 4.4.1.

4.3.4 Backfilling heat meter data

In an attempt to minimise the disruption to the residents, heat meters that transmit the data via wireless MBus were chosen, allowing for the data to be collected by centralised dataloggers, and reducing the need for any additional transmitters or dataloggers in the flats.

Unfortunately, it became clear that the signals from the heat meters were not always being received by the dataloggers at the desired time intervals, with the meters furthest from the dataloggers struggling with data transmission the most. As such, wireless MBus repeaters were installed in an attempt to alleviate this issue, passing the messages from the meters via a series of repeaters to the central datalogger. Despite this, the ability of the datalogger to receive the heat meter readings proved fairly inconsistent.

With infrequent and irregular readings being received for the heat meters, it was necessary to interpolate the data that was logged to gain a clearer understanding of the heat demands of each flat and make the most out of the available data.

The readings from the heat meters provide a number of instantaneous values, such as flow rate and flow and return temperatures as well as a cumulative flow volume value. This indicates whether the heat pump has been operational since the last reading and this value alongside the electricity data for the heat pump can indicate when the heat pump was operational, allowing the heat meter records to be interpolated, filling the gap in readings. The method for this can be found in Appendix 0.

The backfilled data available for each of the heat pumps is presented and analysed in Section 4.5.

4.3.5 Backfilling electricity data

As previously discussed, the metering for the electricity data of both the heat pumps and thermal battery was carried over from the research conducted by Leeds Beckett University. The electricity data is received in ten minute increments and records the Wh used since the last reading. This means that if the datalogger doesn't receive a reading, the next reading will contain the Wh used over the previous two timesteps i.e. 20 minutes.

As each data set is transmitted to two data loggers located at opposite ends of the building, the chances of receiving the readings are significantly higher than with the heat meters. If one data logger does not receive the reading for a given timestep, the other datalogger may do. This means that through combining the data from the two dataloggers, a more complete dataset can be obtained to provide more detailed insight into the heat pump usage patterns.

Where the combination of the two datasets does not fill any gaps due to missing readings, the next available reading was averaged back over the period of missing data. This is possible as the dataloggers record accumulatively.

More details of these processes can be found in Appendix 0 and, similarly to the heat meter data, electricity data available for each of the heat pumps is presented and analysed in Section 4.5

4.4 Results: Ground Heat Exchangers

Due to the gaps in the data that has been collected, the overall load characteristics would not provide much useful information and as such have been omitted from this case study.

4.4.1 GHE Flow and Return Data

This cleaning of the data and removal of many erroneous temperature readings limits the ground loop data available for interrogation and interpretation. Figure 72 to Figure 79 show the flow and return temperatures as well as the flow rate data available for each of the arrays after this process. They also show the heat extracted from these arrays where the combination of these readings is available.

As can be seen in Figure 72 to Figure 75, East arrays 1,2, 3, and 4 have good periods of temperature and flow data, though each array had periods without reliable data.

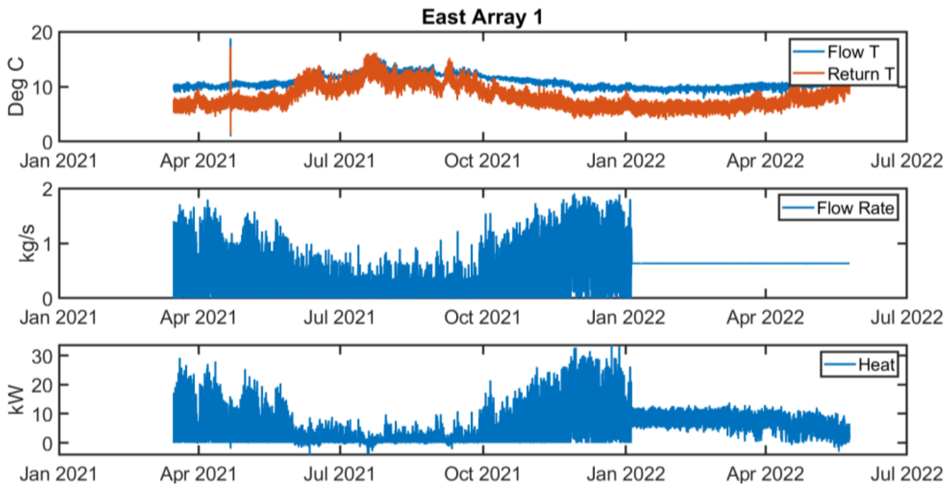


Figure 72 - East Array 1 Data Sets

East array 1 has reasonable data for temperature and flow rate up until January 2022. At this point the flow rate becomes a constant value, with no variation as has been seen to this point. The cause of this is not known but as the value lies within the plausible range, as per the readings up until 2022, it has been left in.

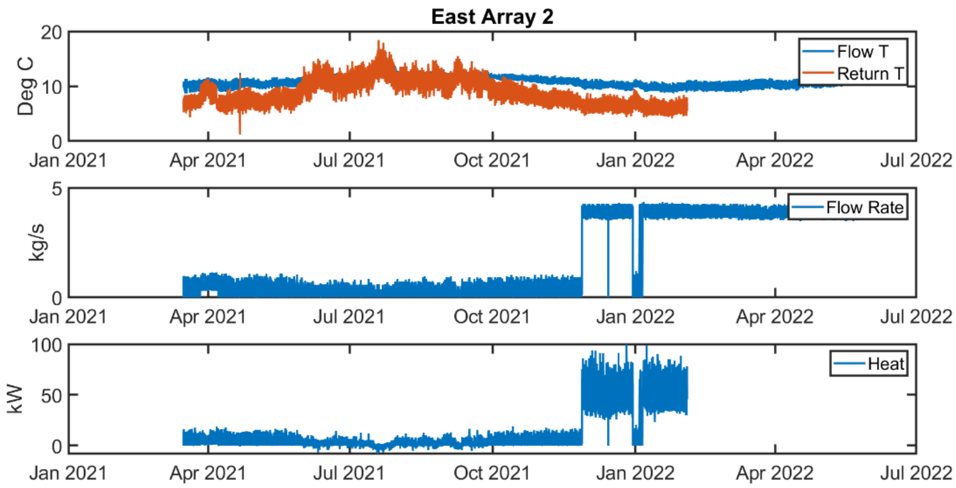


Figure 73 - East Array 2 Data Sets

East array two shows a large jump in flow rate around December 2021. This again lies within the maximum theoretical flow rate and so has not been discounted at this initial stage. Following this increase there is a small period of reduced flow rate again in January, and this coincides with an increase in the return temperature, supporting the idea of reduced usage at this point allowing the ground loop temperature to recover as less heat is being extracted.

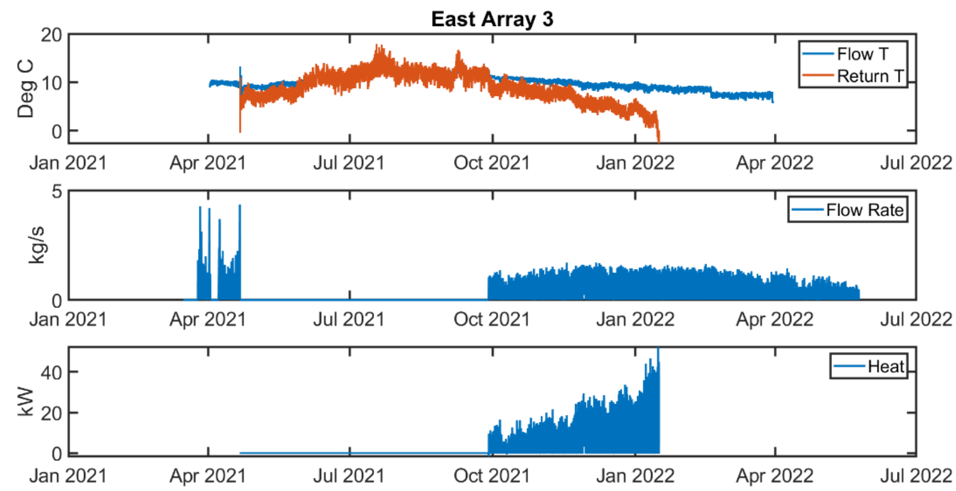


Figure 74 - East Array 3 Data Sets

Despite the sensors initially working in East array 3, either there was zero flow and thus zero heat requirement from this array from mid-April to October 2021, or more likely, the sensor was not functioning correctly. In early October the flow sensor was moved from the flow pipe to the return pipe, and the data became much more consistent, supporting the conclusion that it was a sensor issue rather than no flow and therefore the readings of zero flow are neglected in the subsequent analysis.

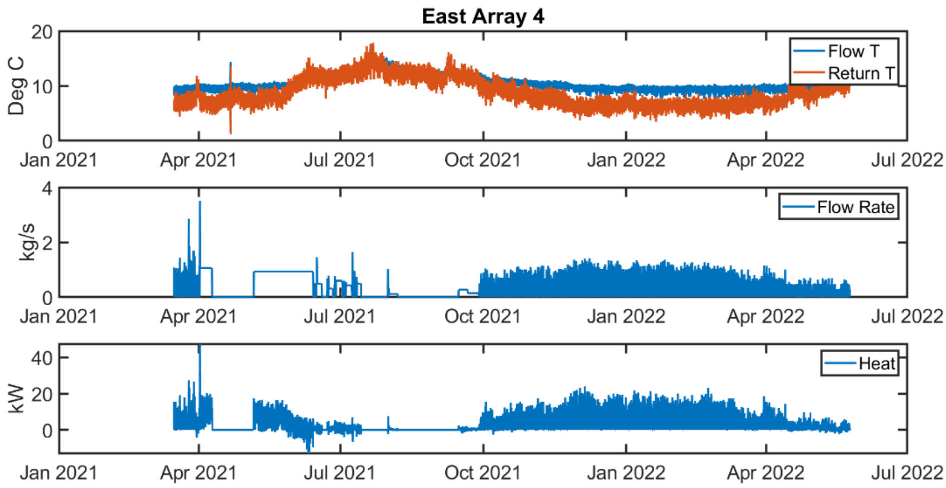


Figure 75 - East Array 4 Data Sets

Similarly, the flow rate sensor for East array four provided intermittent data from mid-April 2021 and was also moved from the flow to the return pipe in early October. This allowed for reliable readings for the heating period over 2021/2022.

Whilst the majority of the data issues with East ground loop are due to the flow rate data, the issues is the West ground loops are primarily due to the temperature sensors, as demonstrated in Figure 76 to Figure 79.

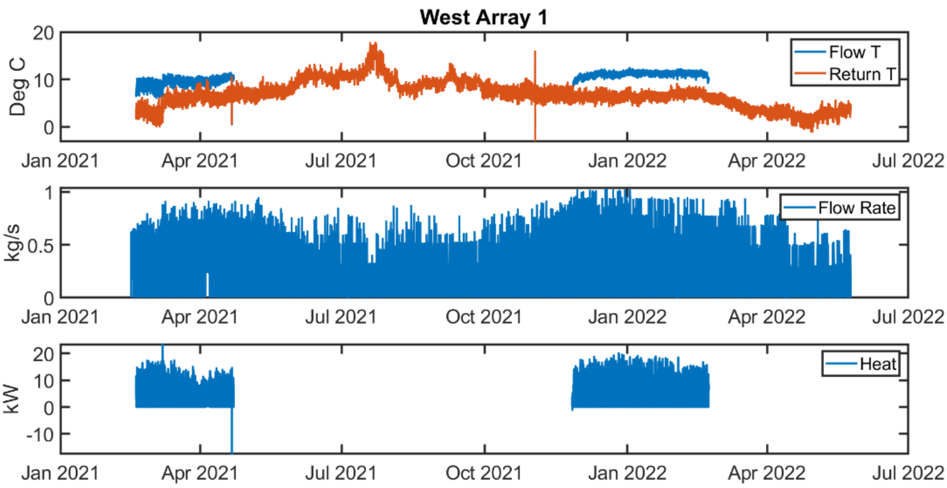


Figure 76 - West Array 1 Data Sets

West array 1 had reported multiple periods of unreasonable data from the flow temperature probe, meaning the heat from the ground loop could be only calculated over two periods of a few months each. Fortunately, both periods are during the heating season rather than during the summer months, which are typically the points of interest in a heating only system. It is worth noting that the flow rate for this array does not drop as dramatically in the summer months as some of the other arrays, though it is at a lower value to begin with.

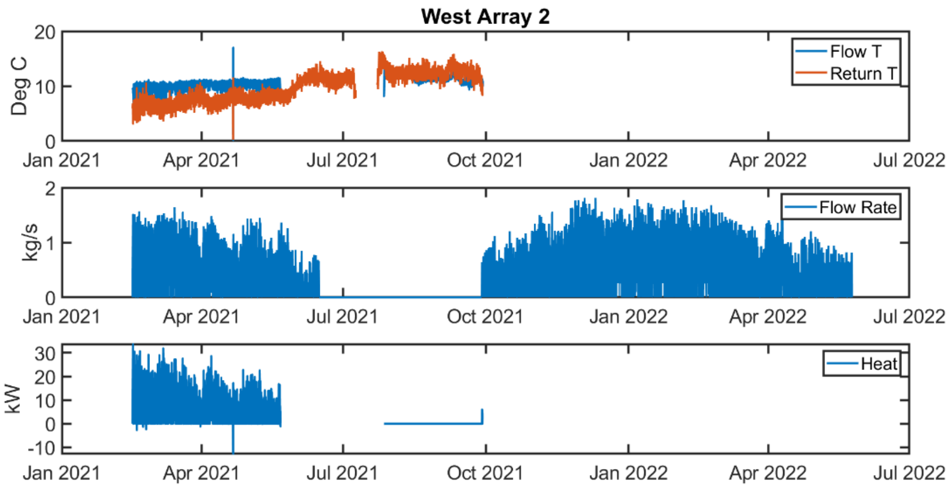


Figure 77 - West Array 2 Data Sets

West array 2 shows the flow rate drop to zero during the summer of 2021, suggesting that no heat pumps are active on this array during that time, The temperature data is full of gaps for this array due to a number of unreliable readings, but those readings that remain show the flow and return temperatures closely aligned over this period, suggesting that there is little to no heat being taken from this array at that time. Unfortunately, none of the monitored flats are connected to this array to validate this.

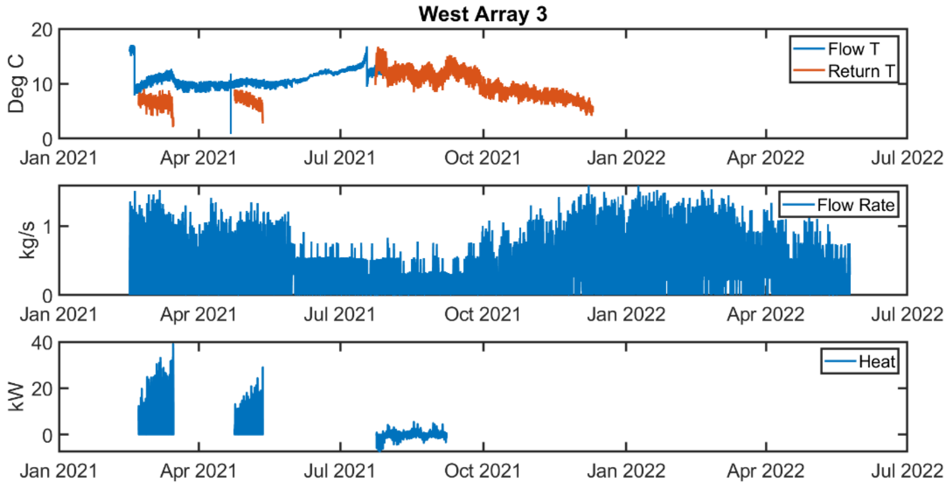


Figure 78 - West Array 3 Data Sets

West array 3 has very few time periods with reliable flow *and* return temperature values and thus very little information on the heat from this ground loop. The flow rate data however shows the expected drop in use over the summer months of 2021 and towards the summer of 2022.

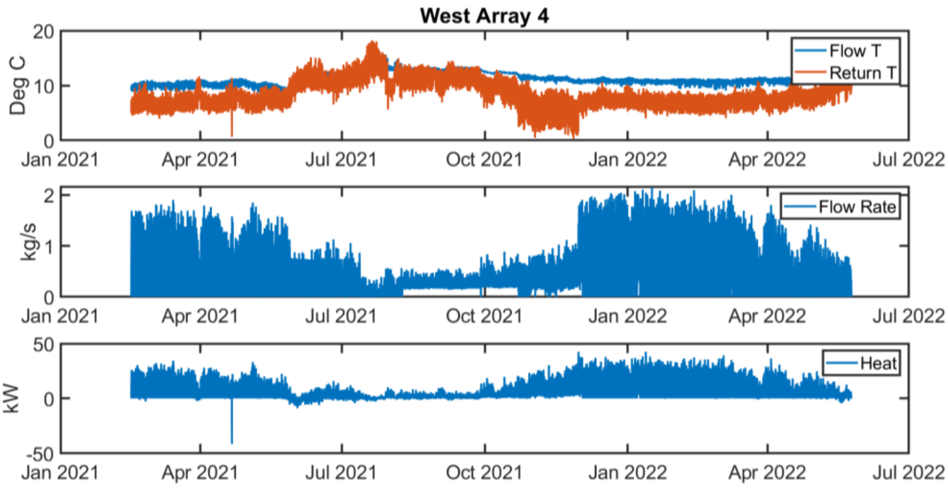


Figure 79 - West Array 4 Data Sets

West array 4 is one of the only arrays with good data for both temperatures and flow rate for the duration of the monitoring period. This shows a large difference in usage over the year.

4.4.2 Monthly Heat Demand

The ground heat exchange per month has also been calculated, as shown in Figure 80, using the cleaned temperature data and flow rates from the installed sensors. The ground heat exchange figures are for the arrays supplying all of the flats, not just those that have been monitored with heat meters. It is worth restating that due to the intermittency of the data, these values do not represent the total heat extracted from the ground in each month but should be used to give an indication as to the pattern of usage.

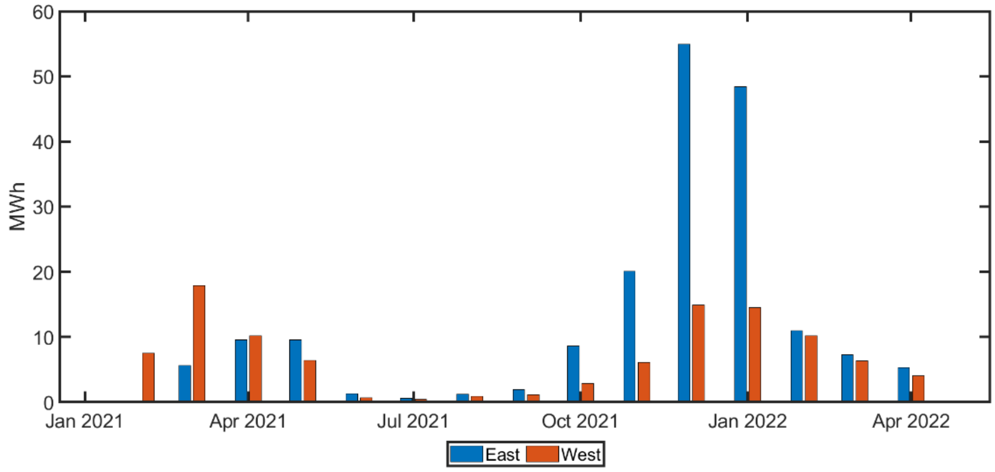


Figure 80 – Monthly Heat Extracted from the Ground Loops at Each Building

Comparing the two buildings, the seasonal patterns look quite similar, up until November 2021, at which point the heat extracted in the East building increases significantly. This coincides with the increased flow rates seen in East array 2.

The temperature plots in Figure 72 to Figure 79 also indicate some passive recharging of the ground during the summer months. This is not captured in Figure 80 as it is assumed to be generally passive, and as such there would be no flow rate to calculate the magnitude of the heat accurately.

Figure 81 and Figure 82 show the heats for each array separately, again highlighting the differences between arrays as well as the seasonal variations.

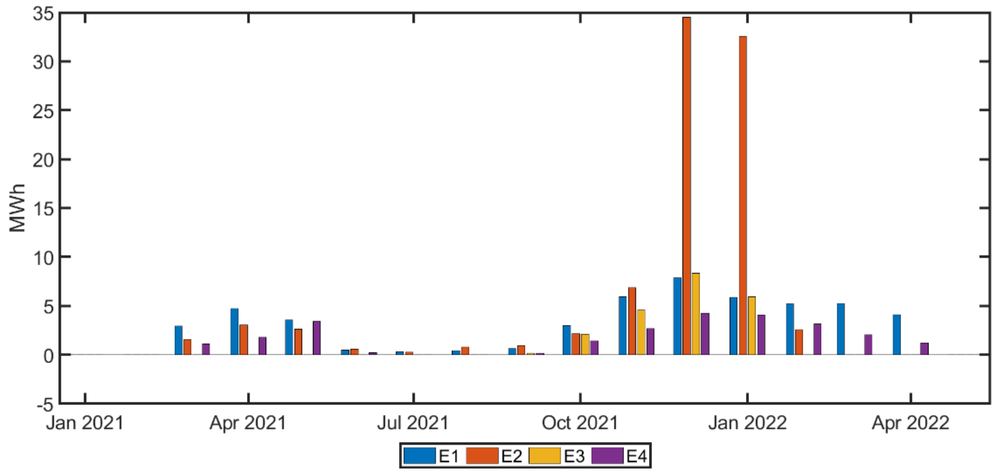


Figure 81 - Monthly Heat Extracted for Each Ground Array at Heights East

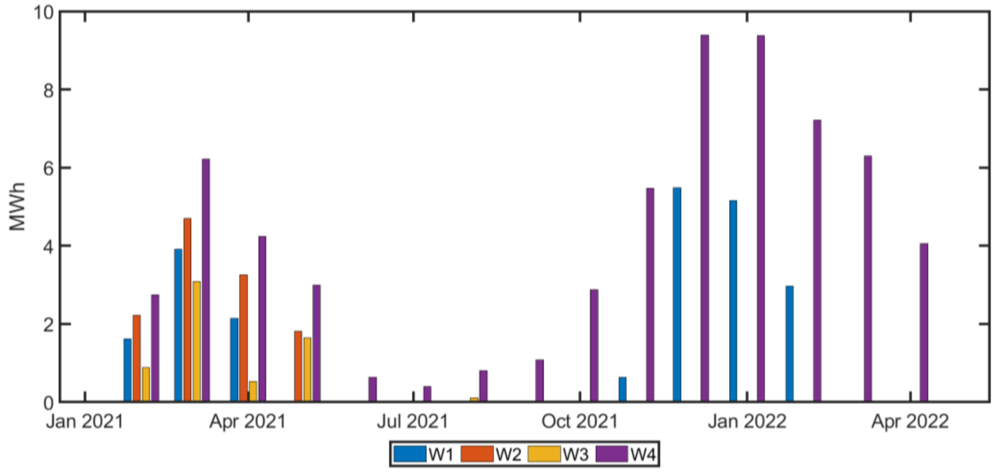


Figure 82 - Monthly Heat Extracted for Each Ground Array at Heights West

To understand the behaviour of the ground loops and in attempt to mitigate the intermittency of the data, the average hourly ground heat exchange for each array has been plotted against the outdoor air temperature. This is shown in Figure 83 and Figure 84.

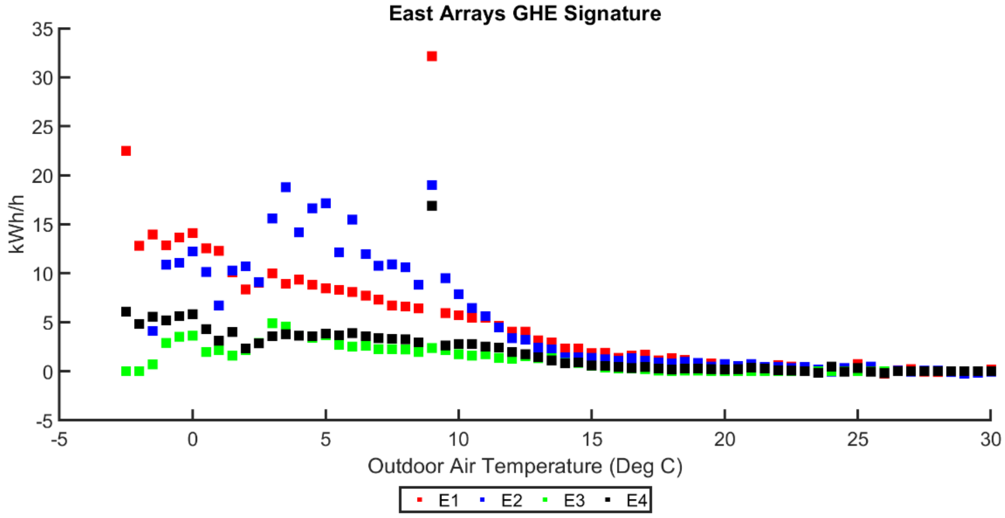


Figure 83 - Heat Extracted vs Outdoor Air Temperature - Heights East Arrays

Figure 83 shows a similar pattern across the arrays, with the amount of heat being extracted falling away as the outdoor air temperature increases. This does however raise some questions, as it could be expected that given the greatly reduced number of heat pumps, array 1 should be extracting less heat than the remaining three arrays. This is clearly not the case, with array 3 actually recording the lower heat demands, though this must be taken in the context of the data limitations, as increased data issues will result in less sample points for each temperature bin.

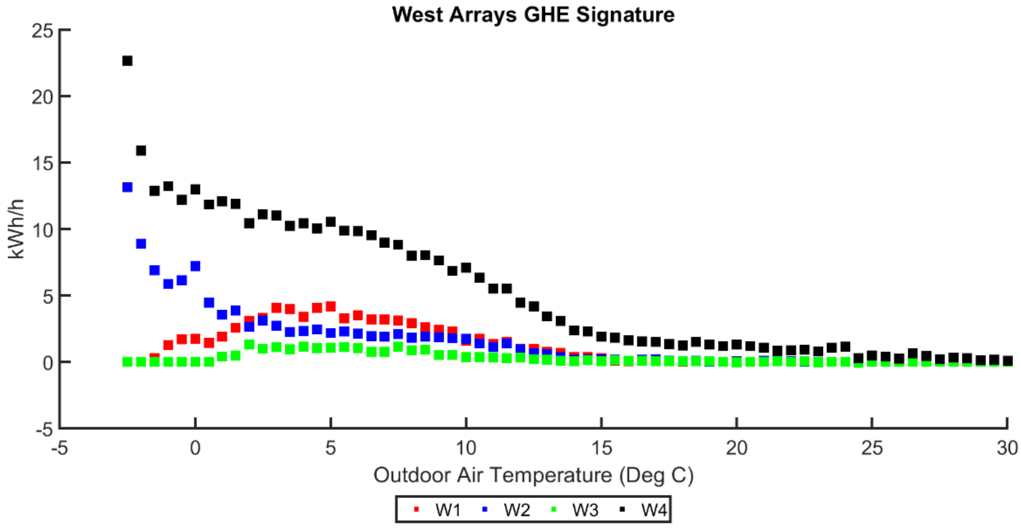


Figure 84 - Heat Extracted vs Outdoor Air Temperature - Heights West Arrays

This is evident with the West arrays (Figure 84), in particular with array 3 where very little heat data was available. Unusually, arrays 1 and 3 seem to initially increase the heat demand along with the increase in air temperature up to around 5°C. This again could be due to limited data points at these temperatures.

Combining the heat from the individual arrays, as in Figure 85, provides an insight into how the different buildings are utilising the ground arrays, with the East building seemingly extracting more heat than the West.

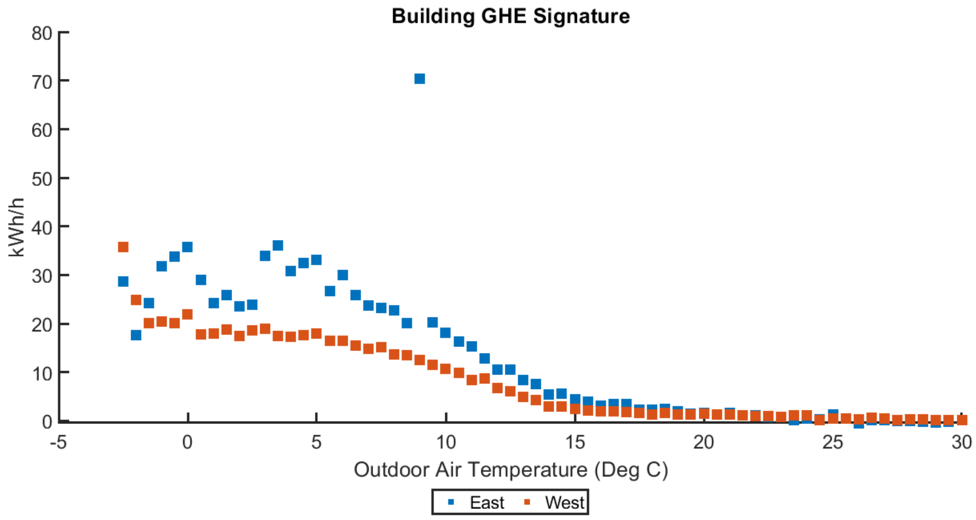


Figure 85 - Heat Extracted vs Outdoor Air Temperature - Heights East & Heights West

All three of these figures suggest that heat demand curtails at an outdoor air temperature of around 15°C. It would be expected that some residual heat demand would remain on these arrays at the higher temperatures, due to the DHW demand. This size of this strain on the ground arrays could provide an indication as to the general usage patter for DHW and whether residents are generally using the Sunamp immersion or heat pumps. However, as shown in Section 4.4.1, the issues in the data for the ground arrays generally occurs over the summer months, impacting the analysis at these elevated outdoor air temperatures.

4.4.3 Ground Array Utilisation

Figure 86 to Figure 93 shows the utilisation of each of the arrays as a percentage of the calculated maximum flow rate.

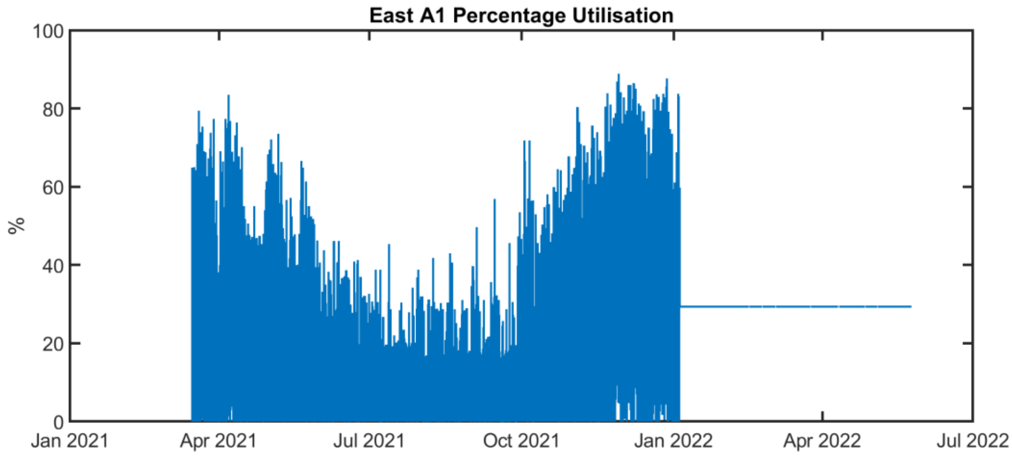


Figure 86 - Percentage Utilisation - East Array 1

East array 1 appears to be fairly well sized, with utilisation rates at around the 80% mark in the heating periods and dropping away to as little as 20% in the summer months.

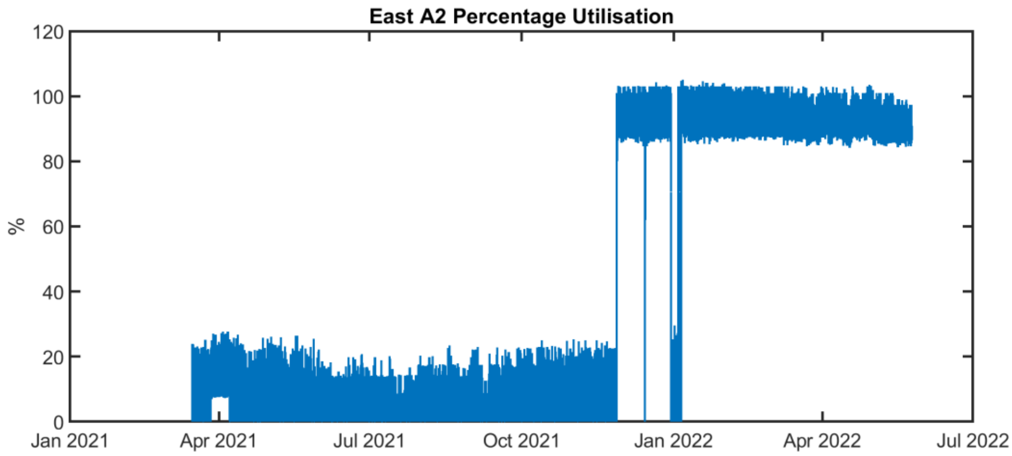


Figure 87 - Percentage Utilisation - East Array 2

East array 2 has an interesting utilisation profile. Similarly to array 1, during the summer months the utilisation stands at around the 20% mark, however there is little deviation from this in the months before or after, until a rapid increase to approximately 80 to 100% in December 2021. If this is not a sensor issue, this would potentially be explained by the majority, if not all, of the users on this array using the heat pumps simultaneously. This is extremely unlikely however, and it is much more likely that either the initial readings are incorrect, and the usage over the April to December 2021 period is actually higher than recorded, or the readings from December 2021 are incorrect, and the increase is actually much smaller than shown.

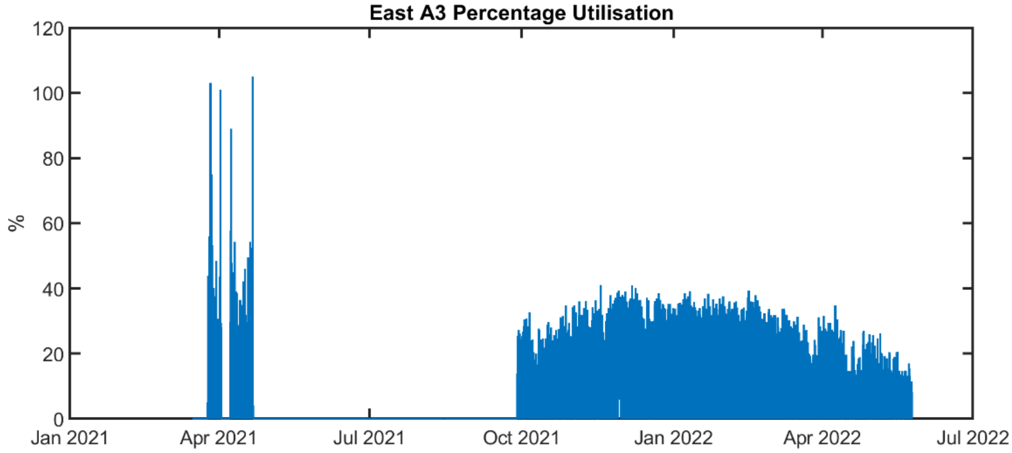


Figure 88 - Percentage Utilisation - East Array 3

This is supported by the utilisation of East array 3 (Figure 88) and East array 4 (Figure 89). These readings show high utilisation rates in the early periods before the sensors were relocated onto the return pipes. Following this relocation, the utilisation of these arrays typically lies between 30 and 50%. Given the number of heat pumps is the same between array 2 and 3 it would be expected that these have roughly similar utilisation unless the residents were operating the heat pumps in vastly different ways.

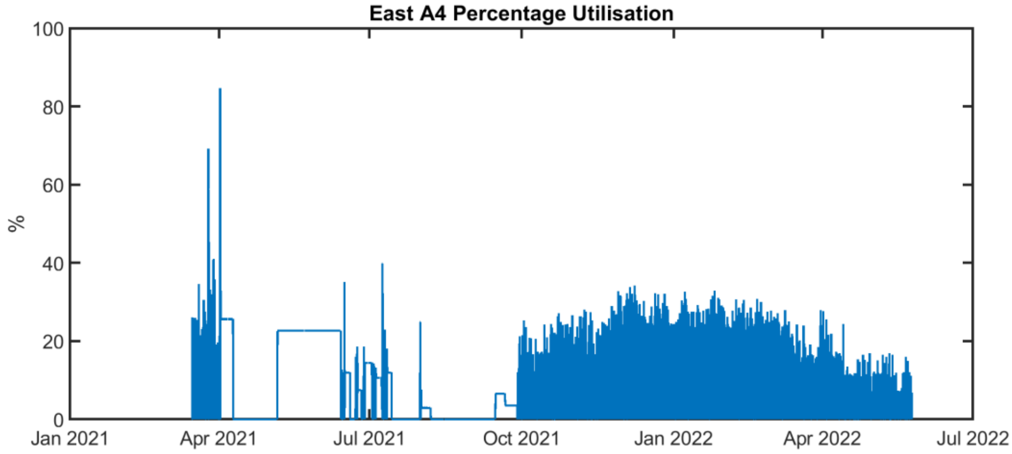


Figure 89 - Percentage Utilisation - East Array 4

The following figures, Figure 90 to Figure 93, show the utilisation of the ground arrays for the West building.

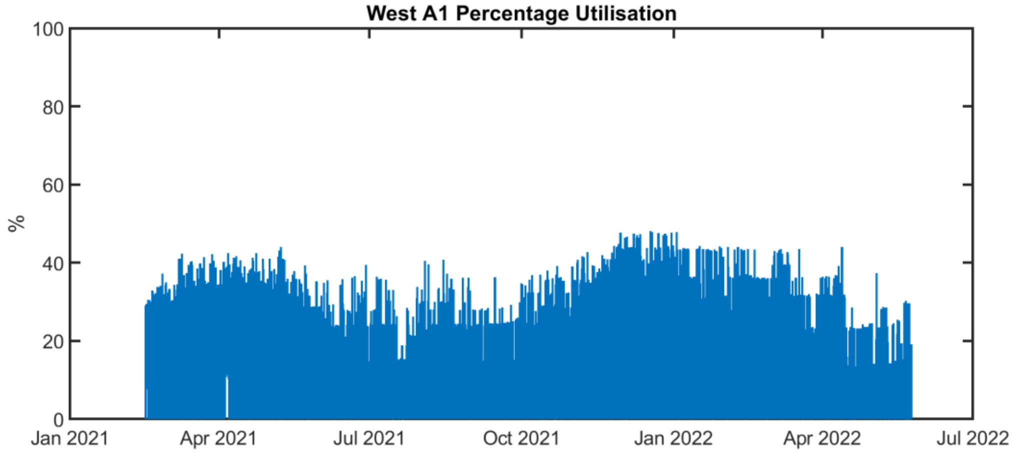


Figure 90 - Percentage Utilisation - West Array 1

Contrasting array 1 in the West building with array 1 in the East building, it is clear that that the utilisation rate is much lower in the West building. The maximum utilisation rate recorded in this instance is around 40-50%, compared to the 60-80% in the East building.

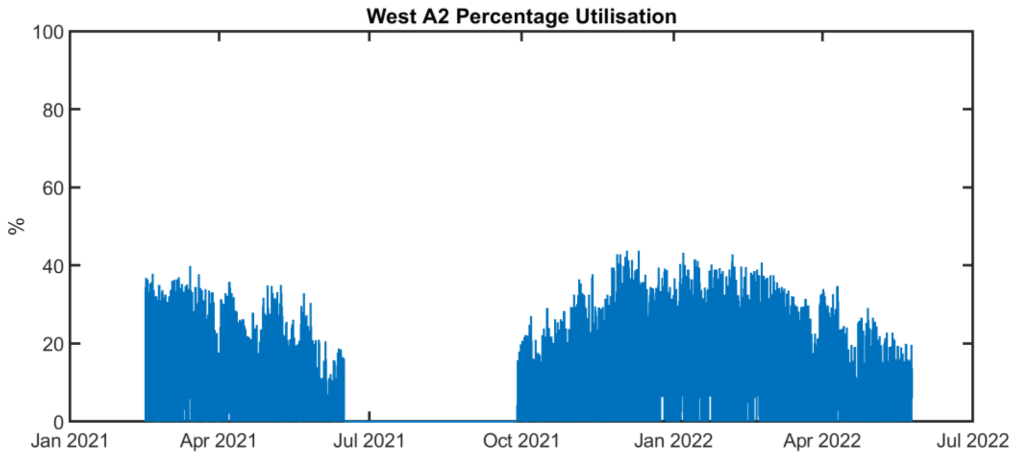


Figure 91 - Percentage Utilisation - West Array 2

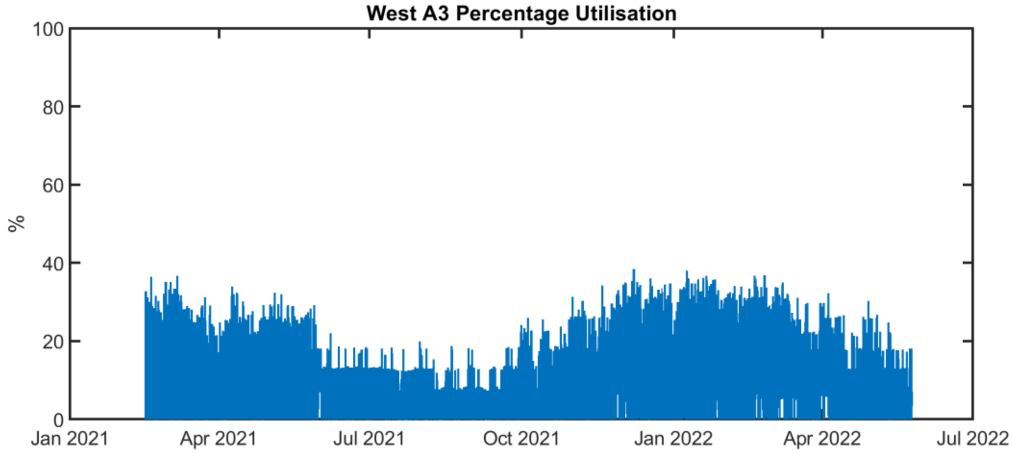


Figure 92 - Percentage Utilisation - West Array 3

West arrays 2 and 3 both show peak utilisation rates close to 40% with array three showing a low of between 5 and 10% in the summer. But, unlike in the East building, both of these arrays seem to follow very similar patterns to one another, as might be expected.

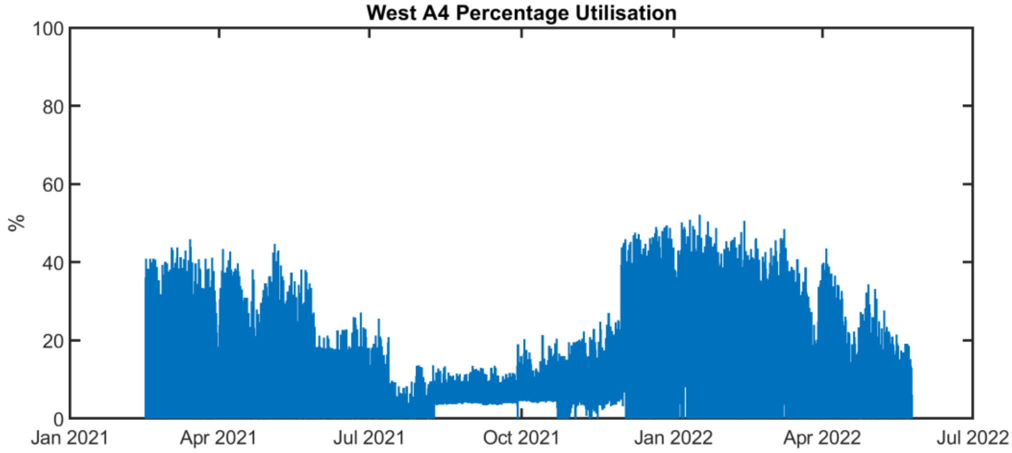


Figure 93 - Percentage Utilisation - West Array 4

West array 4 also follows a similar utilisation pattern to arrays 2 and 3, again peaking at around 50%. From August to December however, this array experiences a period of reduced variation and appears have at least a minimal flow rate for most of this period.

4.4.4 Ground Heat Exchange Rate

The heat exchange rate per meter depth of boreholes has been calculated for each ground loop. This is demonstrated for the East and West buildings in

Figure 94 and Figure 95 respectively, and, for clarity, they show the moving mean of each borehole with a period of 1 day.

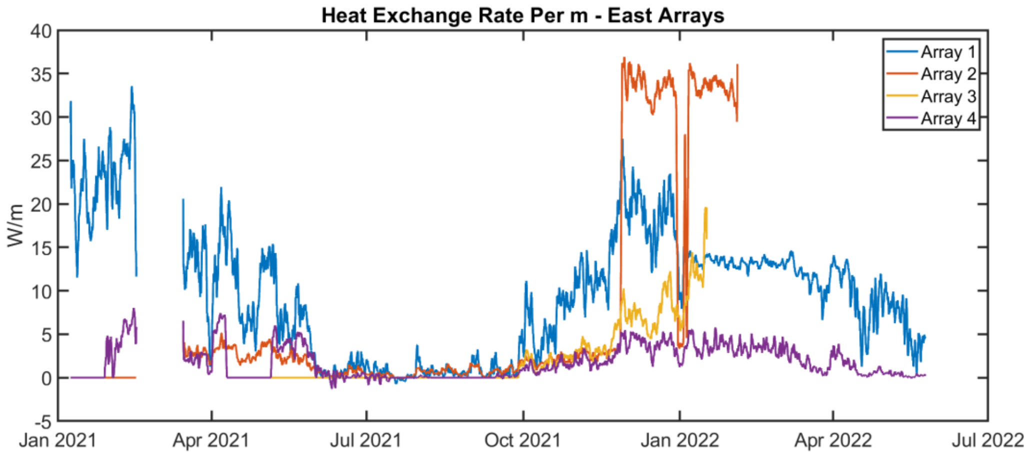


Figure 94 - Heat Exchange Rate per m - Heights East Arrays

Despite the various data issues the seasonal variations in the heat exchange rate are clearly visible. This is a very clear way of visualising the under-utilisation of the various arrays, with East array 1 showing values close to and at points within the estimated range of 20-55 W/m detailed in the literature (The Chartered Institution of Building Services Engineers, 2013) and therefore in keeping with utilisation data. If the dramatic increase in utilisation of array 2 is correct, then this array also reaches a heat exchange rate per depth borehole within that range for that period.

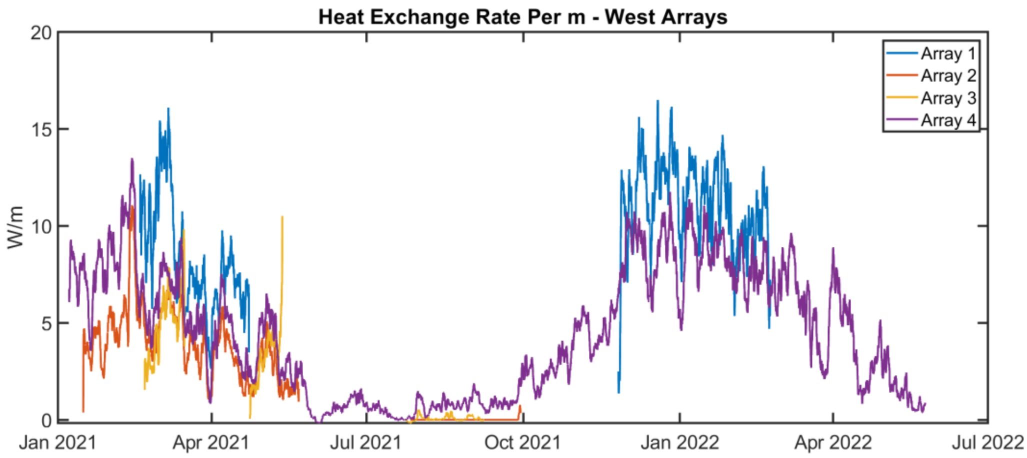


Figure 95 - Heat Exchange Rate per m - Heights West Arrays

The West arrays generally have a more comparable heat exchange rate to one another, though it does peak at around 15 W/m, a much lower rate than seen in the East building, and below the expected range of 20-55 W/m.

4.4.5 Minimum Ground Temperatures

Another important characteristic of the ground loop design to monitor is the minimum temperatures to and from the ground. This informs the length of the heat exchangers required as if it drops too low, the heat pumps will not work effectively. Figure 96 and Figure 97 shows the weekly minimum flow temperatures for each array in the East and West buildings respectively.

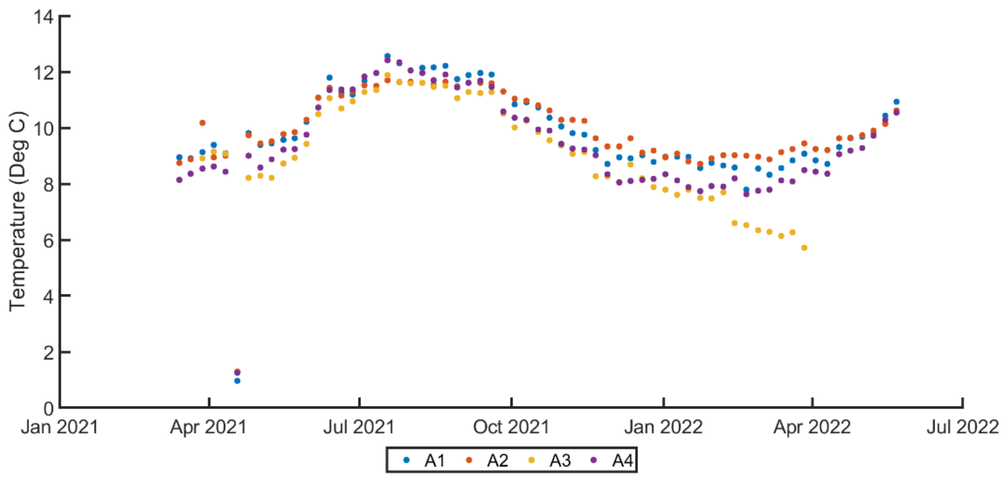


Figure 96 - East Arrays - Weekly Minimum Flow Temperature

Figure 96, with the exception of one or two anomalies, shows a clear picture of the seasonal fluctuations in flow temperature. East array 4 appears to fluctuate to a greater extent than the other arrays, with lower temperatures in the winter, and higher temperatures in the summer, potentially indicating a larger swing in usage. East array 2 on the other hand maintains a higher minimum flow temperature, with less seasonal fluctuation.

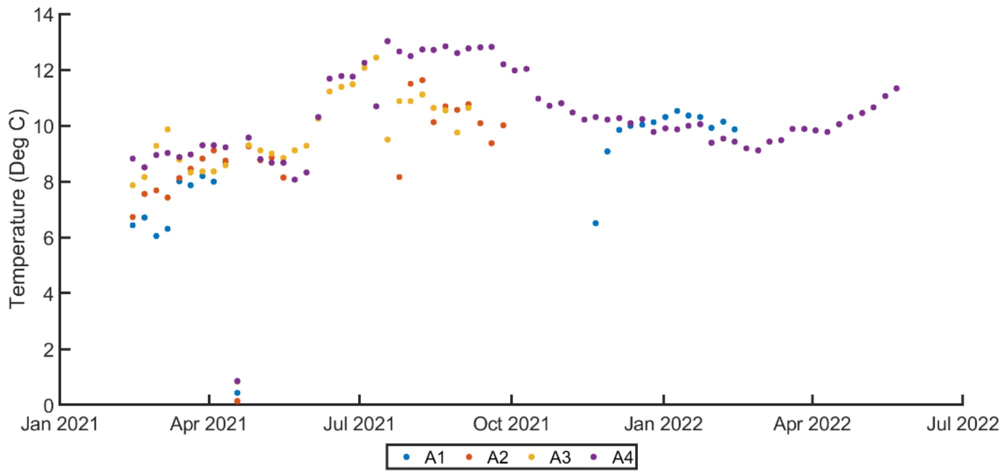


Figure 97 - West Arrays - Weekly minimum Flow Temperature

Figure 97 again highlights the data issues experienced with the temperature sensors, with intermittent data points for each for the arrays with the exception of West array 4. However, the general trend is once again showing a temperature tending to around 8°C during the winter periods, with a few readings on array 1 and 2 dropping below this at the start of the monitoring period.

The development of these fluid temperatures in the years to come will allow an additional measure of evaluating the ground loop, though after the first year there doesn't appear to be any noticeable drop off in temperatures.

4.4.6 Ground Loop Summary

The ground array data shows that the arrays are typically only achieving a maximum of around 50% utilisation, with the exception being East array 1, which reaches much closer to full utilisation in the winter months. This array is one of the two arrays instrumented that are smaller both in terms of number of boreholes, and number of heat pumps connected. It is possible that this is the cause of the increased utilisation, and corresponding borehole heat exchange rate, as there is less potential for diversity on the array.

This could show that with the increased number of heat pumps connected to the arrays, the greater the diversity within the array, and thus the smaller the overall depth of ground heat exchanger required.

The other smaller array however, West array 1, appears to experience similar diversity of flow to the remaining, larger arrays, with a maximum utilisation rate of around 50%. Further research into how the number of heat pumps affects the diversity in the ground loop will be required to inform the designs of future systems.

4.5 Results: Monitored Flats

A summary for each of the monitored flats has been provided in the following section however as previously discussed, the quantity and quality of each data set varies significantly from one flat to another. Flat A for example has relatively frequent heat meter data, but no electricity data due to a meter or transmitter error. Flats E and Q on the other hand, have no data from the installed heat meters but do have some data from the electricity meters.

In the following sections individual data sets for the flats are investigated, with usage patterns drawn out alongside other KPIs.

The systems' performance are then compared in more detail, looking at how the use of the immersion heaters for DHW and the cycling of the heat pumps affect their performance. This is summarised in Table 40 at the end of this section.

Table 39 provides a summary of the data available for each of the flats.

Table 39 - Equipment in Monitored Flats

Building	**East**					**West**			
Flats	A	E	G	I	J	K	L	Q	R
Elec Data		✓	✓	✓	✓	✓	✓	✓	✓
Heat Data	✓		✓	✓	✓	✓	✓		✓
Temperature & Humidity Data		✓	✓	✓	✓	✓	✓	✓	✓

4.5.1 Flat A

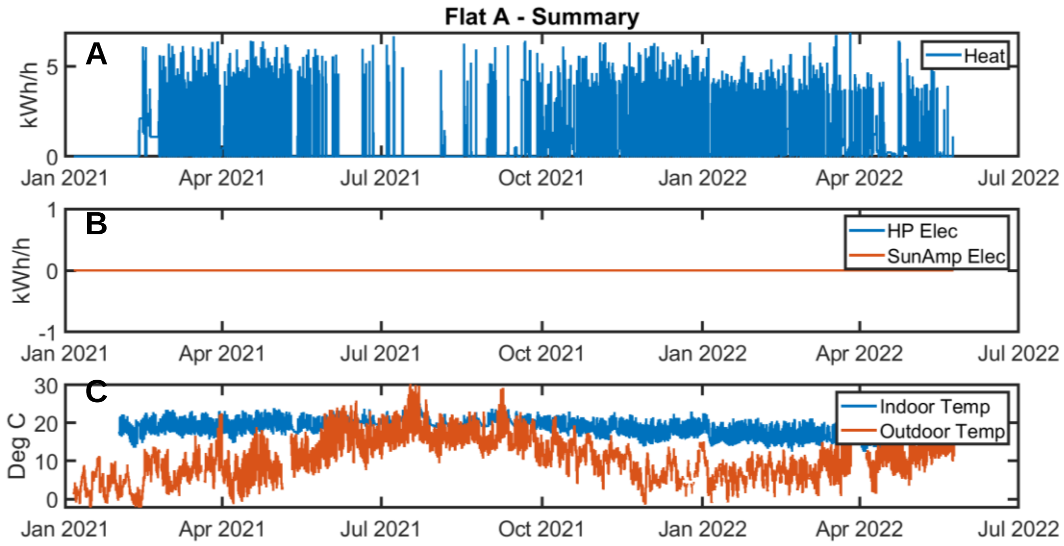


Figure 98 - Flat A Summary – A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

The first plot in the flat summary figures, such as Figure 98, shows the heat obtained from the heat meter readings, in kWh/h. The second plot shows the electricity used by both the heat pump and the Sunamp heat battery immersion heater, again in kWh/h. Finally, the third plot shows the outdoor air temperature and the internal air temperature within the flat.

The internal temperature of Flat A suggests the resident has a preferred comfort level that is to be maintained year-round. This is supported by the heat meter readings suggesting the heat pump has been in use at high levels apart from the summer period.

To further understand the usage patterns withing the flats, one or two one-week periods have also been investigated in closer detail. These periods have been chosen where good data has been available for a week in the required illustrative period, for example in the heating season. Figure 99 shows a one-week period in the heating season for Flat A, December 6th to December 13th 2021.

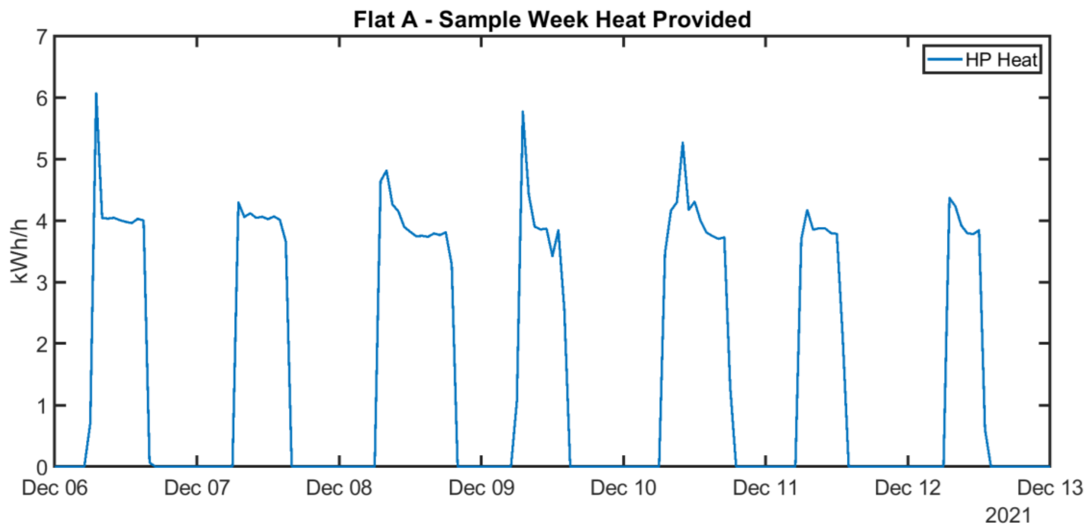


Figure 99 - Flat A Sample Week - Heat

It can be seen that during this period the heat pump typically only operates for one cycle per day for varying durations, most often producing 4kWh/h, with the occasional spike to the 6kWh/h that the heat pump is rated at.

Despite not having the electricity data to determine the contributions of the heat pump and heat battery to the heat provided, the flow temperature from the heat meters installed on the heat pump give an indication of the Sunamp's usage.

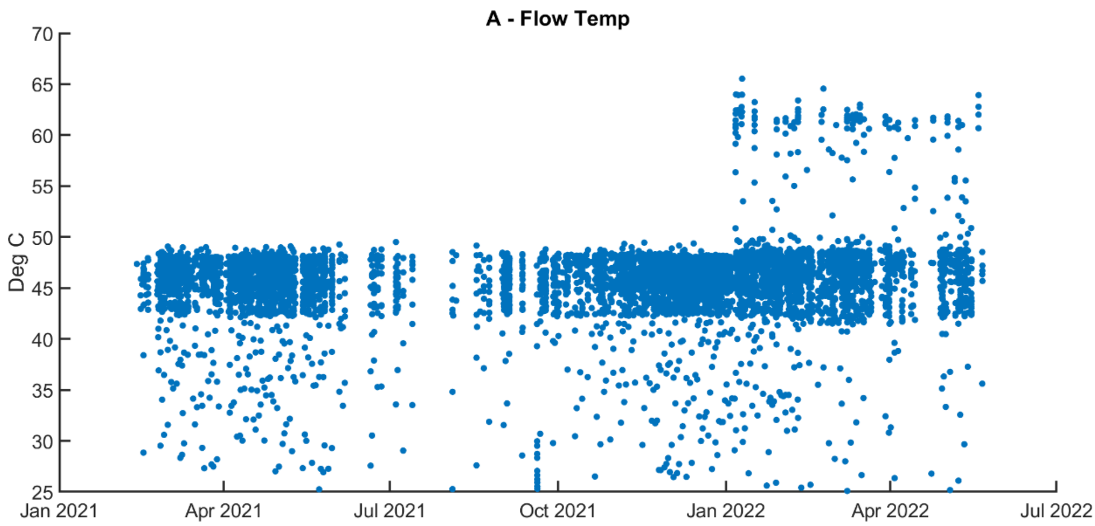


Figure 100 - Flat A Heat Pump Flow Temperature

As Figure 100 shows, up until January 2022, the flow temperature remains steady at around 50°C, which is the design set point for space heating for each flat. The readings with lower values than this are likely taken whilst the heat pump is ramping up/down. From January 2022 however, the maximum temperature climbs to above 60°C, indicating the use of the heat pump to charge the heat battery. The other explanation could be a change in operating strategy requiring a higher flow temperature for the space heating, or simply a fault within the heat pump but given the melting temperature for the phase change material in the Sunamp is 65°C, the former is more likely. This also suggests that until this point, either the heat battery was being charged by the immersion heater in the Sunamp rather than the heat pump, or the heat battery was not being used. The latter is unlikely however, as this would mean the user was not using any hot water.

4.5.2 Flat E

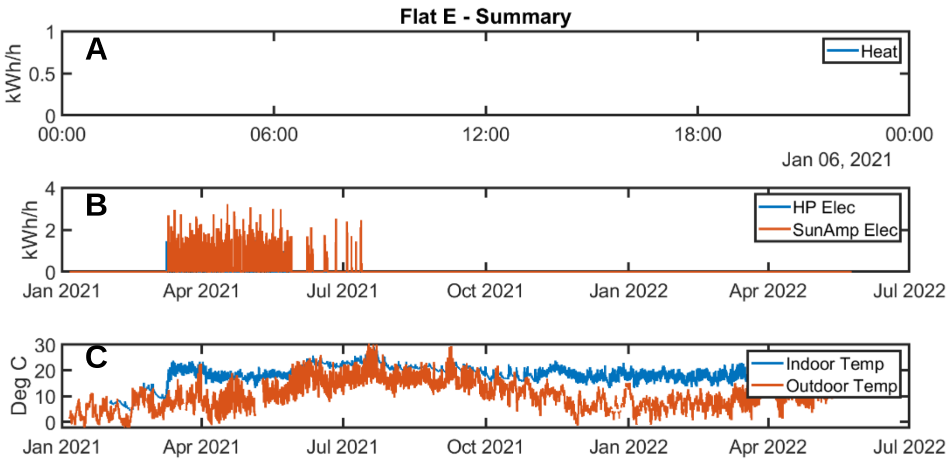


Figure 101 - Flat E Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

Flat E shows a much higher than expected electricity reading for the thermal battery during the period of electricity data that is available. The electrical usage for a single week during that period has been shown in isolation in Figure 102 for clarity.

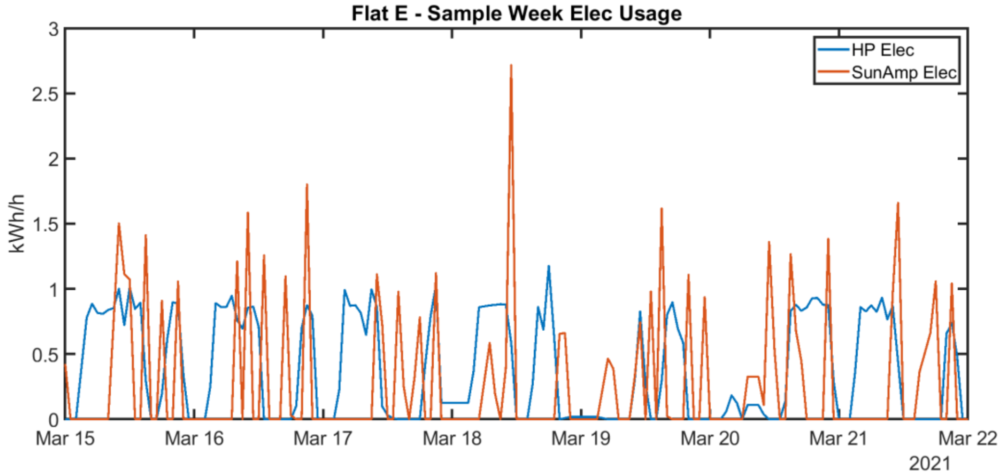


Figure 102 - Flat E Sample Week - Electricity

This sample week of data shows the Sunamp peak load is higher than that of the heat pump, with multiple cycles per day. The heat pump is also being used multiple times per day and the high usage of the immersion heater suggests that the heat pump is likely not meeting the space heating and hot water needs of this resident, possibly due to an increased hot water demand in this flat. This is likely a less efficient method of providing the required heat as the immersion is limited to 100% efficiency, however without any heat meter data, this is difficult to confirm.

4.5.3 Flat G

Flat G is the first of the flats to have both heat and electricity data available. Similarly, to Flat E, Flat G shows frequent use of the immersion back up in the heat battery, so much so that it is hard to see the heat pump electricity usage from Figure 103. As such the two have been separated for clarity in Figure 104.

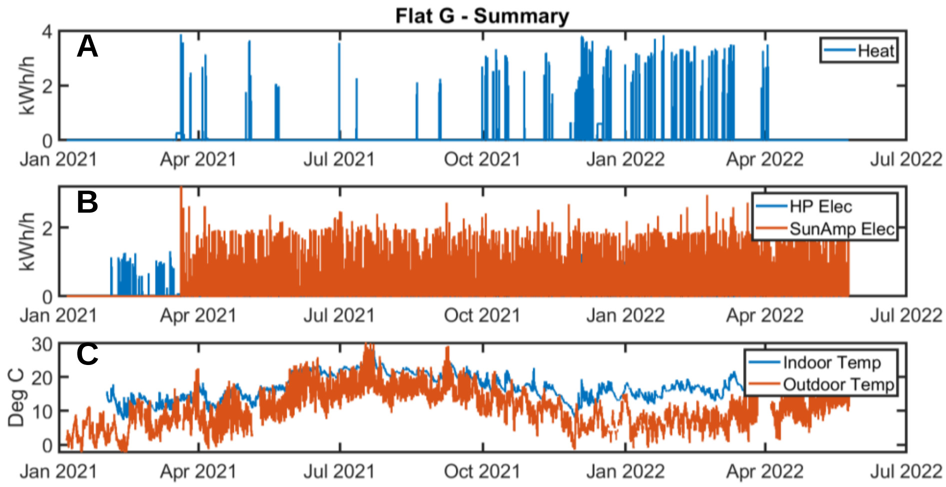


Figure 103 - Flat G Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

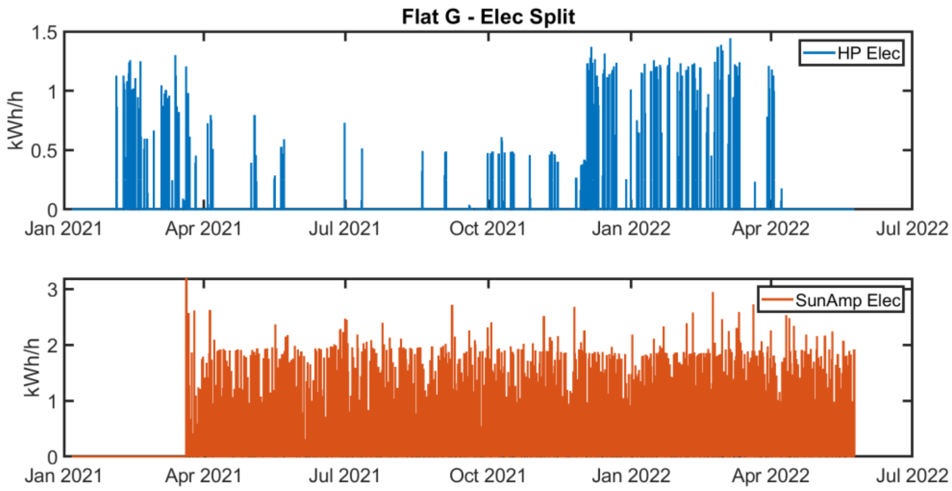


Figure 104 - Flat G Heat Pump and Sunamp Electricity

The electricity data for the heat pump suggests that it appears to be operating much less frequently than with Flat A, particularly from April to around December at which point the heat pump usage increases. This is supported by the indoor temperature data which suggests that this resident is comfortable at lower temperatures than in Flats A and E. The indoor temperature variation appears to closely match that of the outdoor air temperature until around December which perhaps suggests that the resident is using other means to heat the flat or stay warm and using the system predominantly for hot water during this period. The immersion for the heat battery is used almost constantly throughout the monitoring period, which will provide an interesting comparison against the intended usage pattern in which the heat pump is used to charge the battery instead.

For this flat two sample weeks of the electricity use have been shown in Figure 105, one in the summer where the heat pump is not being utilised, and one in the winter where both the heat pump and immersion are in operation.

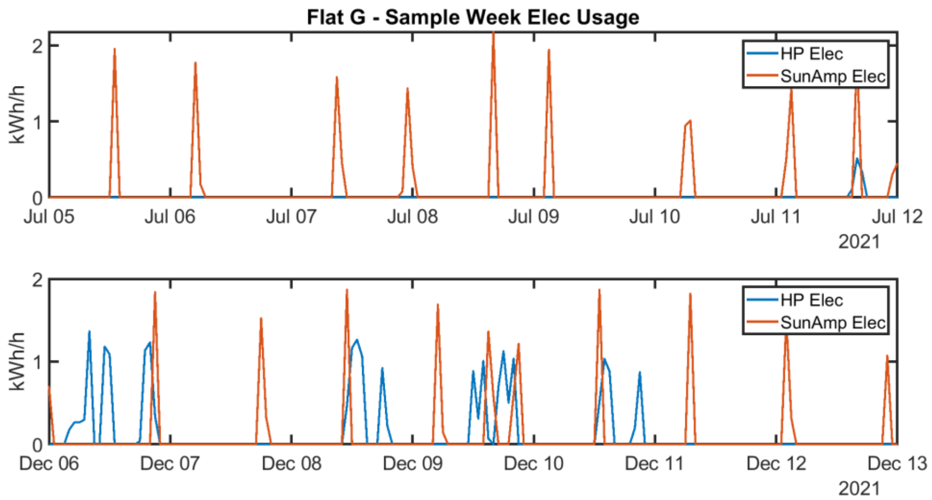


Figure 105 - Flat G Sample Weeks - Electricity

Figure 105 shows that even when the heat pump was being used, it wasn't used daily, and the cycles were generally shorter than with Flat A for example. The immersion for the heat battery shows very similar usage between the two weeks, however.

The heat pump flow temperatures for Flat G, Figure 106, are more difficult to interpret than Flat A due to the limited number of readings. However, it does appear that the flow temperature set point has once again been increased in December from under 50°C to around 55°C in this case. This isn't high enough to charge the heat battery but may indicate a change in operation as a reaction to the lower outdoor air temperatures and requirement for more space heating.

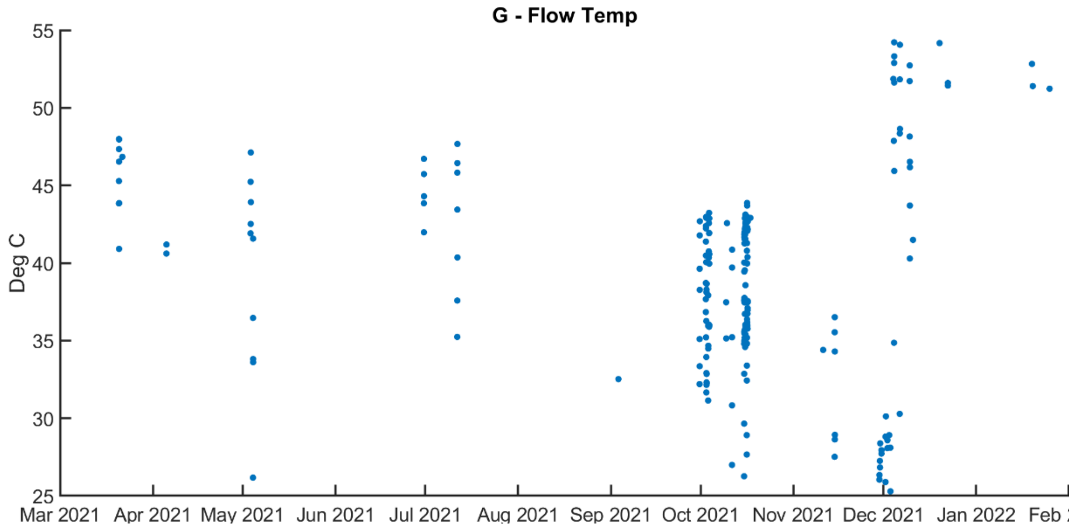


Figure 106 - Flat G Heat Pump Flow Temperature

It is likely that this resident is using the heat battery for the hot water provision, as seen by the year-round use of this system and only activating the heat pump when personal comfort levels are low rather than allowing the controller to determine when it should be active or not. This may be in an attempt to reduce the cost of electricity required to run the system.

Figure 107 shows the instantaneous PFs and SEIs for Flat G calculated from the individual heat meter readings and the interpolated electricity meter readings.

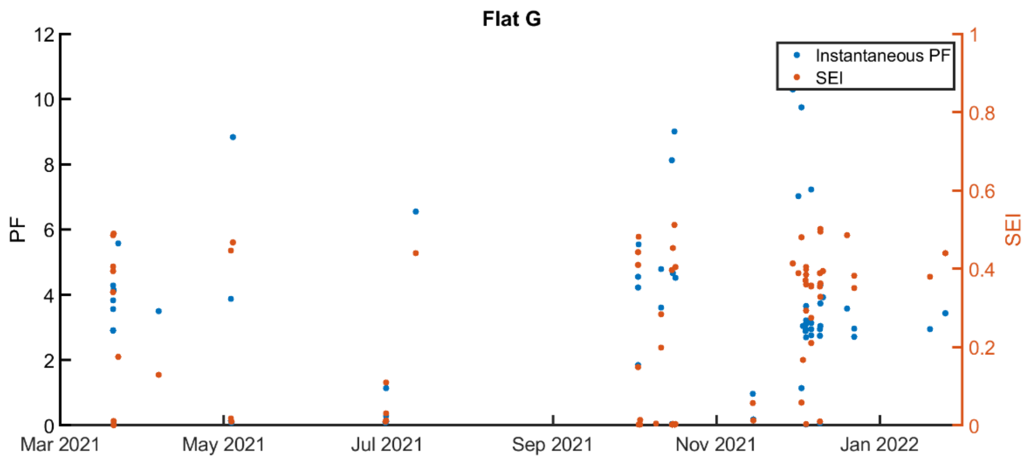


Figure 107 - Flat G IPF and SEI

As discussed, the interpolation naturally introduces some error into these values, and the larger values of IPF are likely due to the remaining heat circulating once the compressor has shut down and the heat pump has stopped actively providing heat. This can be seen with Flat G as the two periods of high IPFs, around 8, between September and November correspond to the dropping flow temperatures as seen in Figure 106.

This limits the value of interrogating the IPFs in isolation, with the hourly performance factors providing a much more useful insight into the system performance over time as these values should reduce these errors and inaccuracies. However, comparing the IPFs to the SEIs provides an insight as to how the heat pump is performing in the current conditions and Figure 108 shows the same KPIs but filtered to only include readings that have a flow temperature greater than 40°C, and heat output greater than 1kW, and so are likely still actively providing heat. In this figure the IPF and SEI are plotted against the temperature lift.

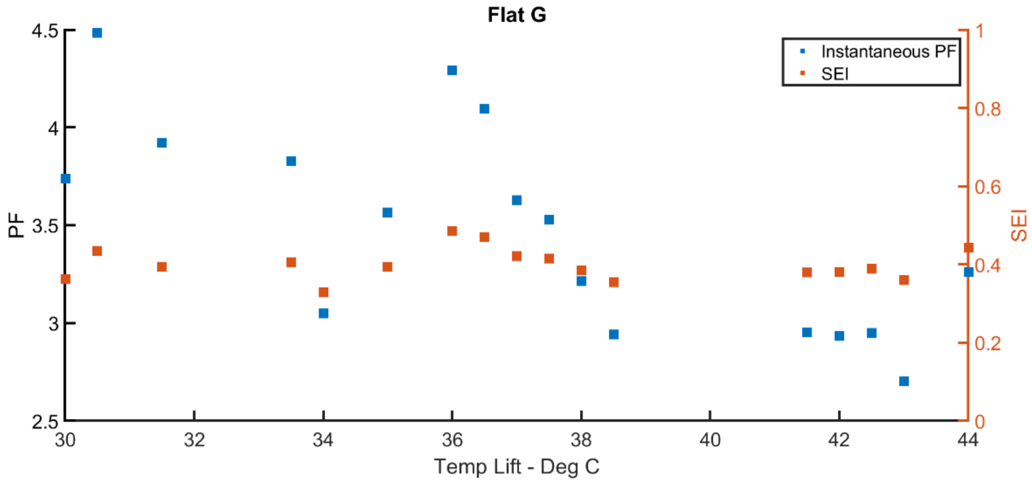


Figure 108 - Flat G IPF and SEI vs Temperature Lift

This figure shows the expected decline in IPF with increase of temperature lift, though it is not very clear, and an SEI that appears relatively stable as the temperature lift increases.

4.5.4 Flat I

Flat I on the other hand appears to utilise the heat pump year-round rather than intermittently as seen in Flat G. Again, the flats internal temperature suggests a specific comfort level temperature of 19-20°C, as with Flat E, which is likely responsible for this additional use of the heat pump. In the summer months with a higher outdoor temperature, the heat pump is initially continuing to run, albeit less frequently, likely to charge the heat battery.

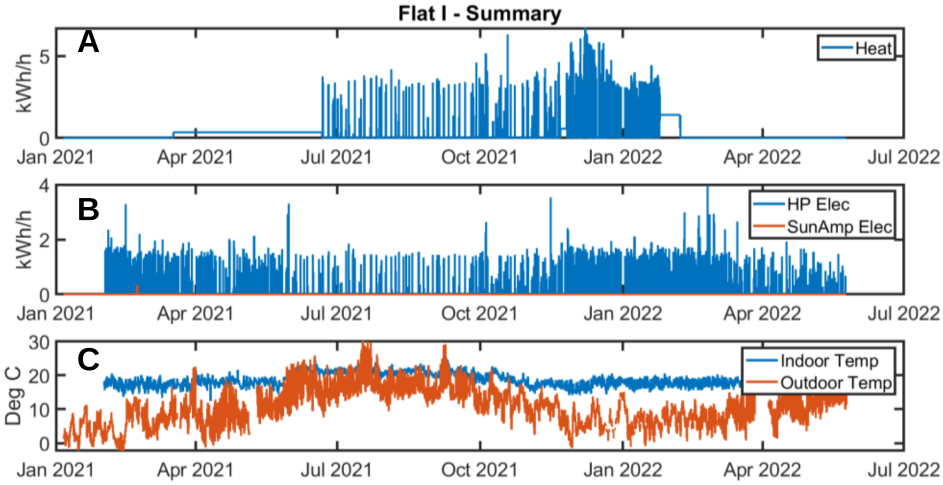


Figure 109 - Flat I Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

This is supported by the high flow temperatures shown in Figure 111. However, around September this usage pattern appears to change with the heat pump usage increasing with the reducing outdoor air temperature. Interestingly this flat does not appear to be using the immersion on the heat battery at all, suggesting the heat pump is capable at providing all of the required space heating and hot water for this resident.

Two one-week periods have been isolated in Figure 110 to show the difference between the electricity profile in the summer and the winter.

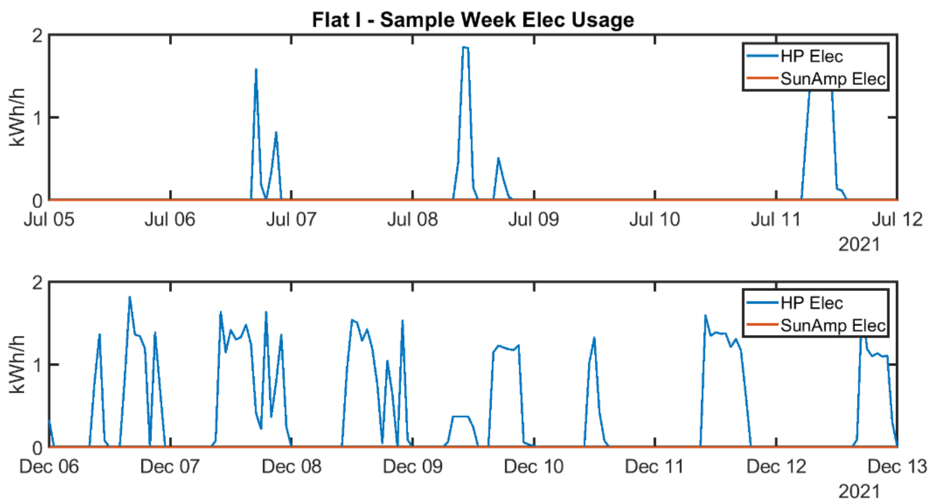


Figure 110 - Flat I Sample Weeks - Electricity

It can be seen that the heat pump is often cycling multiple times a day during the winter and is in operation every day, whereas in the summer week, the heat pump is only active on three of the days.

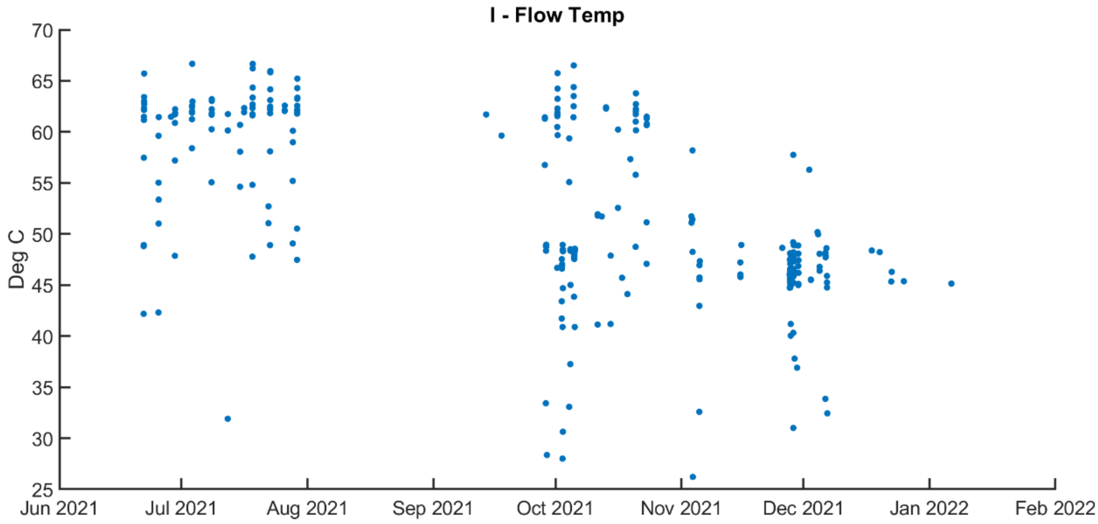


Figure 111 - Flat I Heat Pump Flow Temperatures

As with Flat G, the reduced number of heat meter readings for Flat I make the flow temperature trends more difficult to interpret, however it is clear that this flat has a significantly higher set point earlier in the year, with readings showing over 65°C in June 2021. At this point it is likely that hot water demands will dominate the load over space heating, perhaps explaining the higher temperatures as this is the minimum temperature required for the heat battery.

Figure 112 shows the IPFs and SEIs for Flat I, again plotted against the temperature lift. As with Flat G, this only includes readings with a flow temperature greater than 40°C and a heat output greater than 1kW.

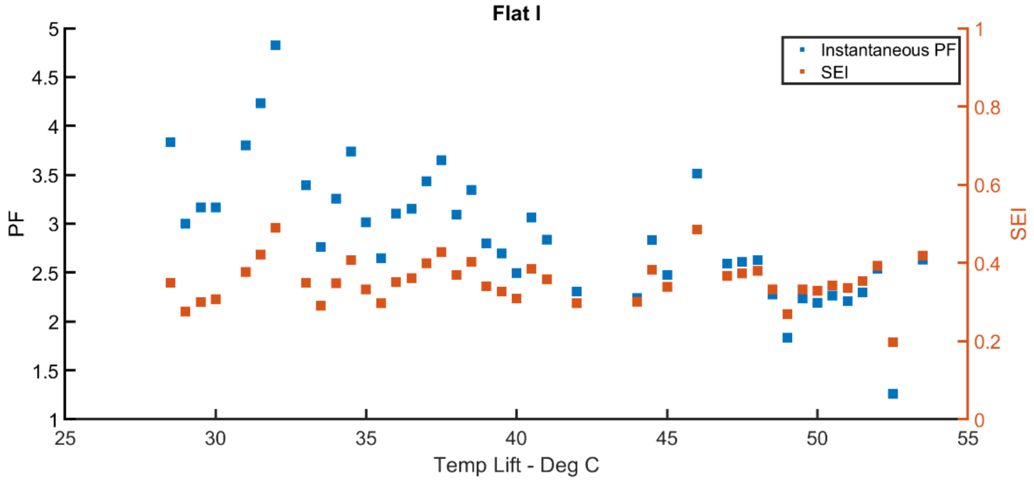


Figure 112 - Flat I IPF and SEI

The IPFs shown here show similar values to Flat G for the same temperature lifts, however due to the increased data available, Figure 112 presents the performance for a wider range of temperature lifts than for Flat G. This shows a clearer trend than Flat G, with the IPF decreasing with temperature lift. The SEI, however, appears relatively stable once again.

4.5.5 Flat J

It is clear from the heat and electricity data that is available, that similarly to Flat I, the heat pump in Flat J is being used for both the space heating and domestic hot water, as was originally intended in the system design. The electricity usage data shows that the immersion for the heat battery has not been used at all in the monitoring period.

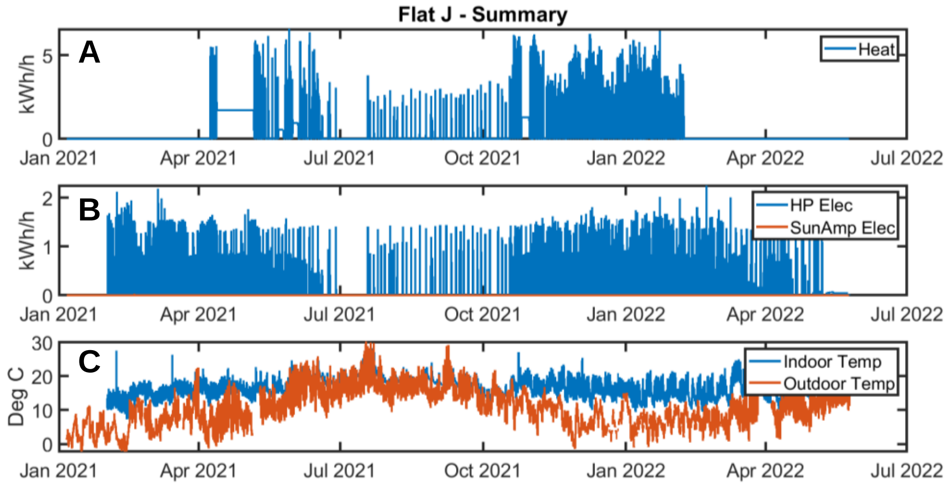


Figure 113 - Flat J Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

Figure 114 provides a comparison of the electricity used in two sample weeks, one during the summer months where the majority of the heat is likely being used for hot water, and one in the heating season.

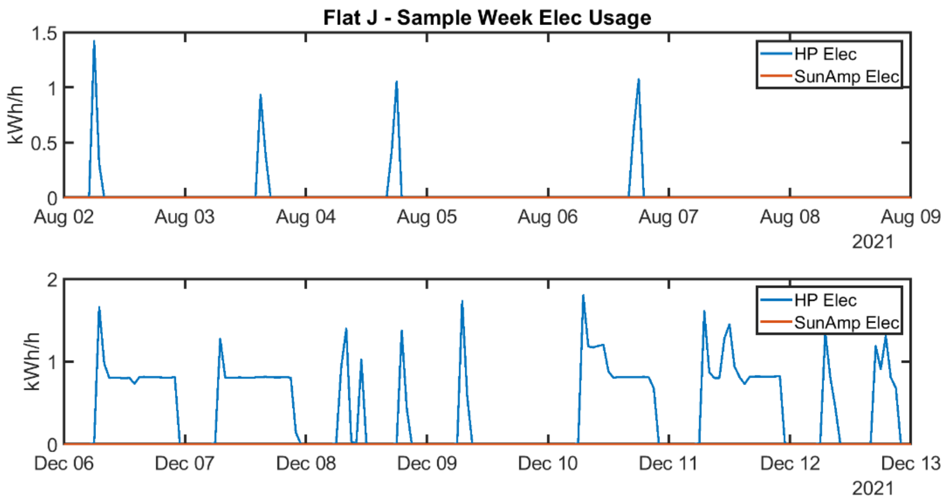


Figure 114 - Flat J Sample Weeks - Electricity

As has been seen with other flats, in the summer months, the heat pump is not operating every day and cycling just once for a short period of time when it is active. In contrast, during the winter months the heat pump is in operation every day. In some cases, the heat pump is active for a longer period of time, almost all day, and in other cases for multiple quicker cycles.

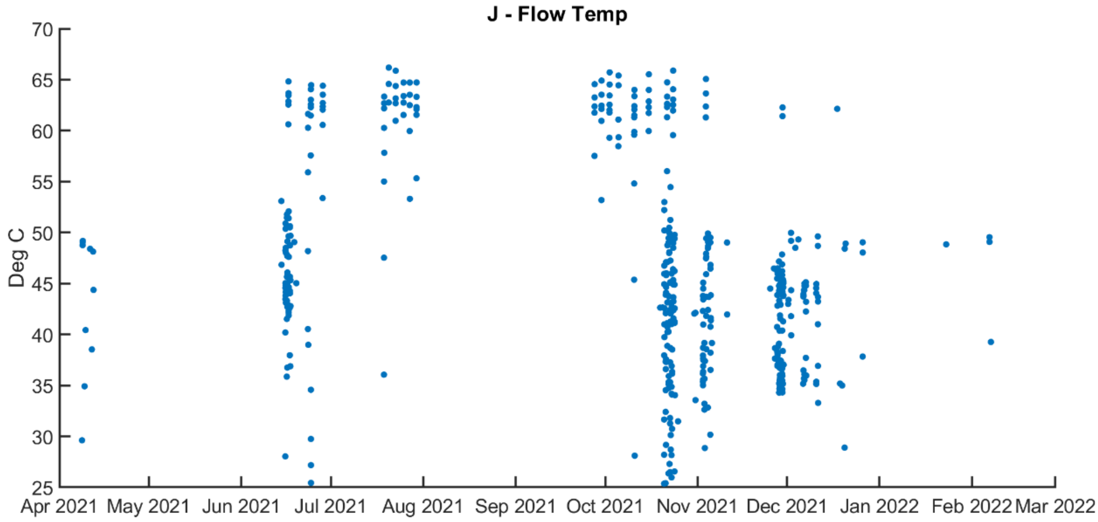


Figure 115 - Flat J Heat Pump Flow Temperatures

The heat pump flow temperatures for this flat, as shown in Figure 115, seem to peak at around the 65-degree mark supporting the notion that the heat pump is being used to charge the heat battery. There also appears to be more instances of lower flow temperatures during the winter months, potentially suggesting the increased use of the heat pump for space heating, and the less frequent charging of the Sunamp, however this may also be attributed to the general increase in number of readings for this period.

Figure 116 shows the IPF and SEI for this flat, again only including the data points with a flow temperature above 40°C and a heat output of at least 1kW. This is to remove the anomalous data points associated with the reading whilst the heat pumps are ramping on or off.

Flat J experiences a sharp drop off in IPF when the temperature lift increases beyond 40°C, and then remains relatively constant with increasing temperature lift beyond this point. The SEI appears to follow a similar profile, albeit less pronounced, and varies between around 0.3 and 0.5 across the range of temperature lifts.

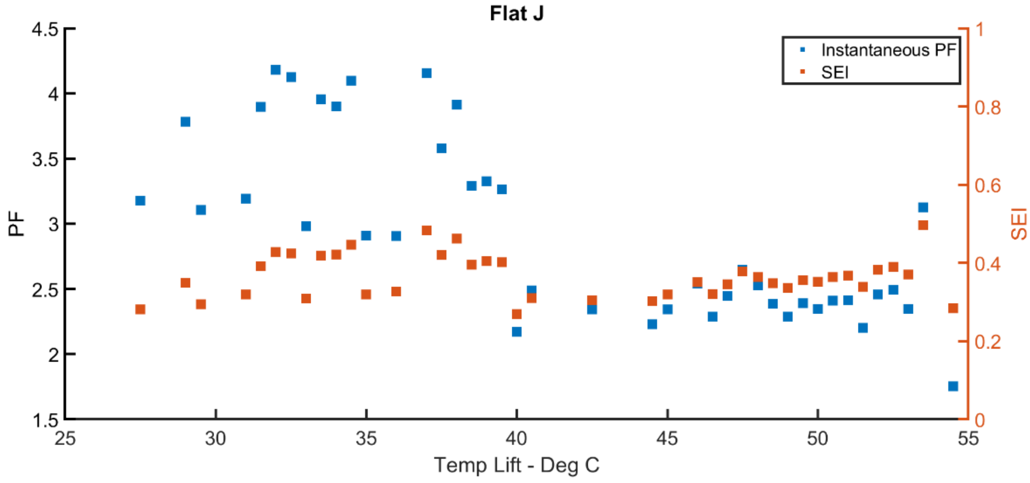


Figure 116 - Flat J IPF and SEI

4.5.6 Flat K

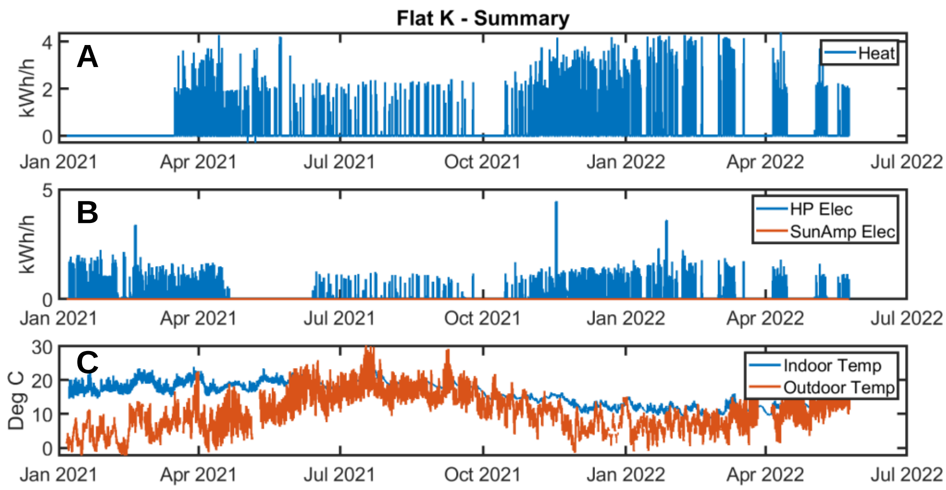


Figure 117 - Flat K Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

As seen repeatedly in other flats, Flat K in the summer months sees a reduction in heat pump operation as expected, with the system likely being used for hot water only.

Initially, this system appeared to be following the design intention in terms of usage patterns, with no use of the Sunamp immersion.

Again, Figure 118 shows a comparison between the summer months and the heating season in terms of electricity use for the heat pumps.

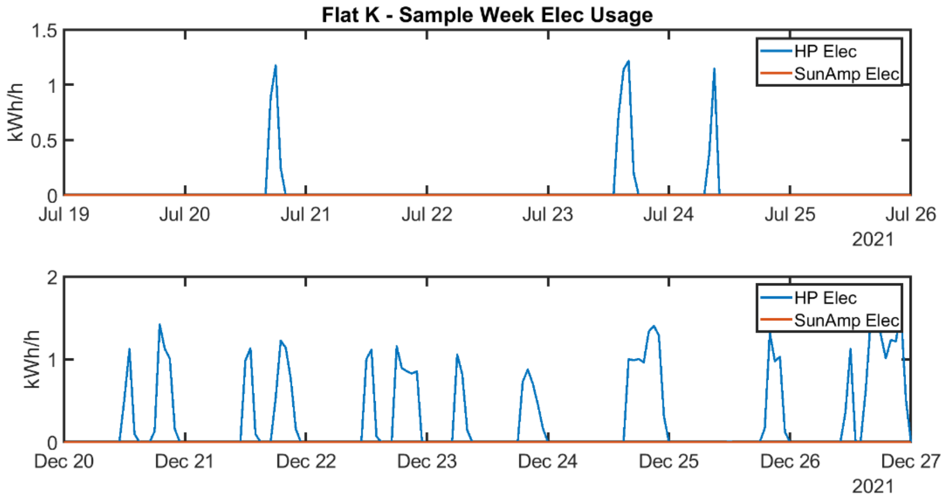


Figure 118 - Flat K Sample Weeks - Electricity

The heat pump goes from 3 cycles per week to one or two cycles per day. When contrasted with Flat J, the heat pump is operating for much shorter periods in the winter, with multiple cycles instead of the longer periods of operation. This is likely less efficient.

The abundance of heat meter readings for this flat allow for a detailed look at the flow temperatures, as in Figure 119.

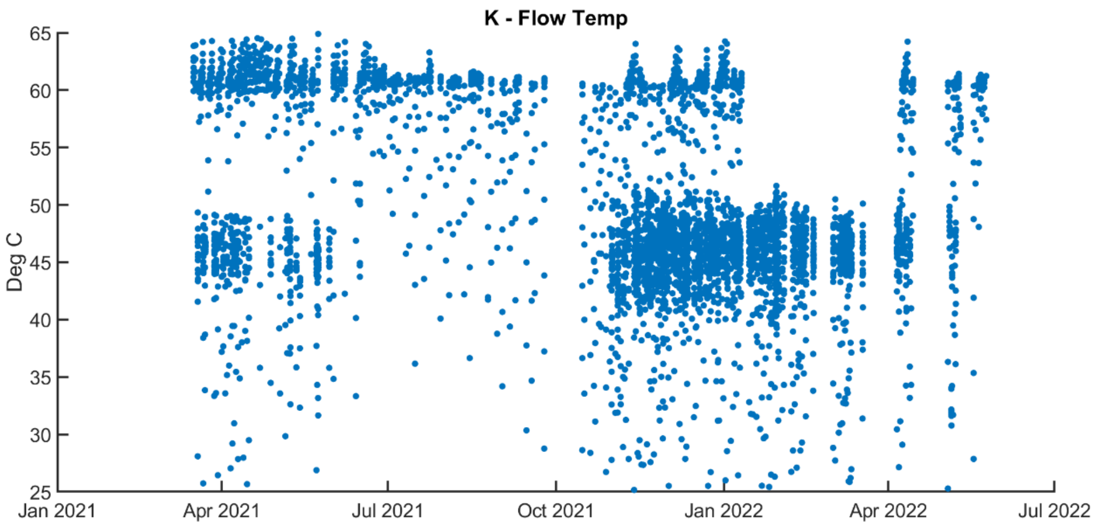


Figure 119 - Flat K Heat Pump Flow Temperatures

There are clearly two set points for this set up, a higher set point between 60 and 65°C, and a lower set point close to the 50°C mark. This pattern has been noticed in some of the previous flats' readings, and the clear absence of the lower set point during the summer months supports the hypothesis that the this is used for the space heating mode of the heat pump. It is also interesting to note that when operating predominantly or solely in hot water mode, the heat pump appears to manage a lower set point temperature of around 60-61 rather than 64-65°C. This raises a question as to whether the system can provide the hot water directly rather than charging the heat battery, which required 65°C to activate the phase change material, or whether the readings just did not capture the peak cycle temperature during this time period.

Figure 120 shows the SEI and IPFs for this heat pump, with the same filters applied as the previous flats.

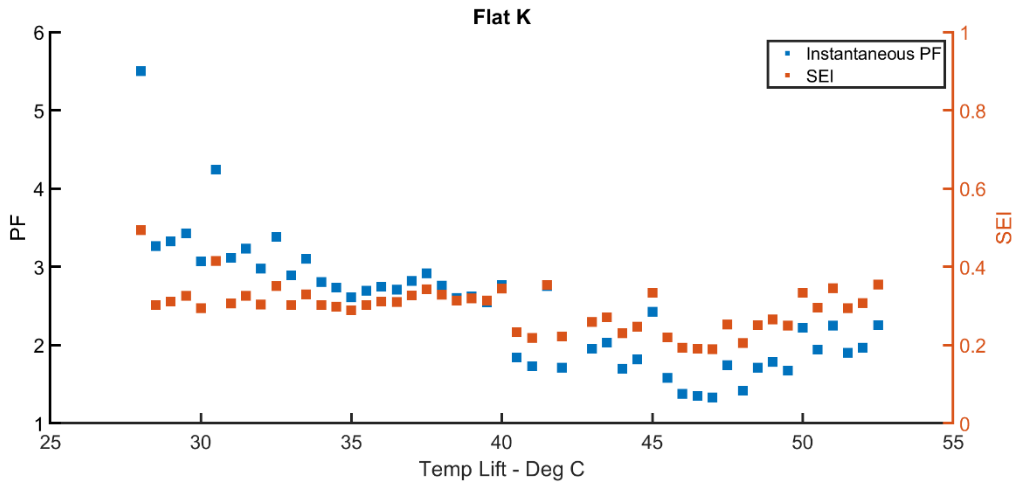


Figure 120 - Flat K IPF and SEI

The IPF for the included readings in Flat K drop significantly beyond the 40 degree temperature lift. This is a similar profile to Flat J, however at lower absolute values reaching down to just above 1.

4.5.7 Flat L

Flat L unfortunately has a limited period of data from the heat meter, demonstrated in Figure 121 A. Fortunately, it is good frequency data and overlaps with one of the periods of electricity data for this system, Figure 121 B, so some performance values will be available.

The electricity data shows a high usage of the immersion system on the thermal battery alongside a high usage of the heat pump, similar to Flat G. Figure 122 shows these two data sets separately for clarity.

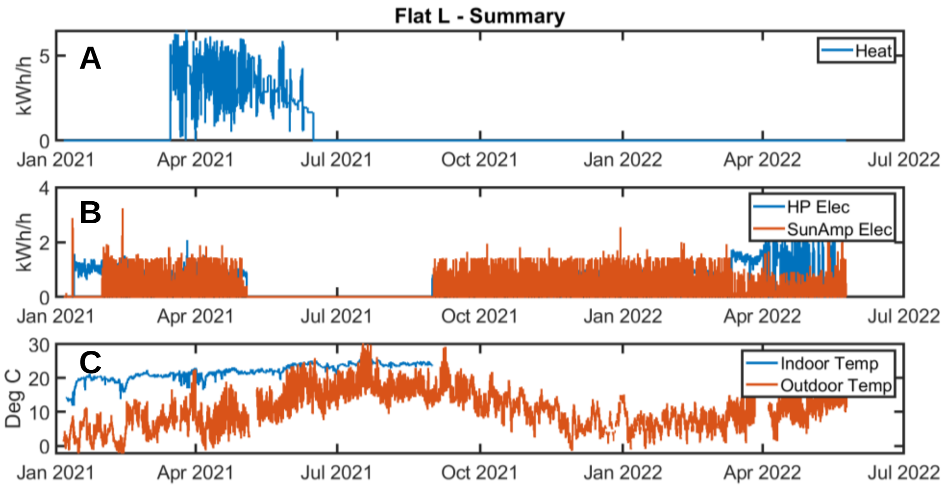


Figure 121 - Flat L Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

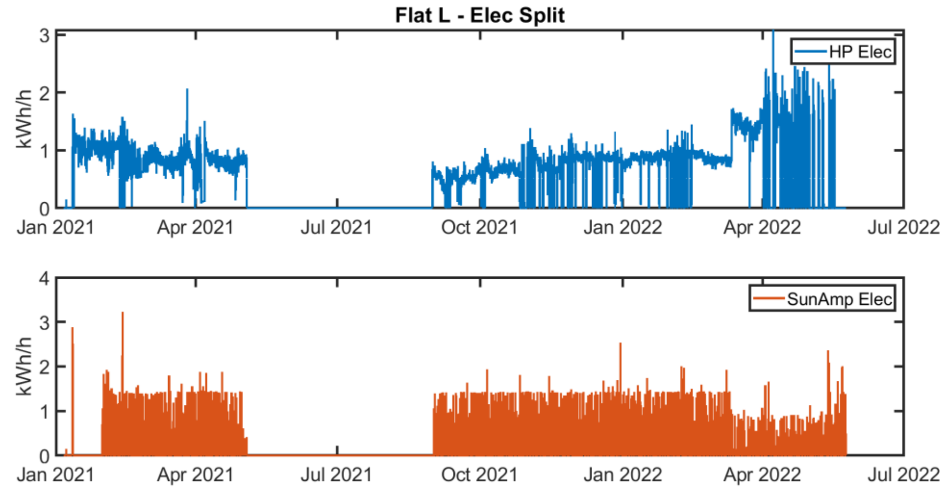


Figure 122 - Flat L Heat Pump and Sunamp Electricity

It is striking that the heat pump is in use almost constantly during the heating seasons in this flat, rather than cycling as needed as seen in the other flats. This, and the sustained use for the immersion heater alongside the heat pump either suggests that the heat pump alone is not capable of meeting this user's needs, or that this flat is following a different control strategy, not utilising the heat pump to charge the heat battery at all. This strategy may be using the heat pump for space heating, and the Sunamp for meeting the domestic hot water needs.

The electricity data for both the heat pump and the heat battery drops to zero from May through to September, though this is likely a meter or transmitter error as it is highly unlikely that there would be no hot water demand during this period. As there is no electricity data in the summer months, Figure 123 compares a week in February with a week in November where the usage pattern appears to change slightly.

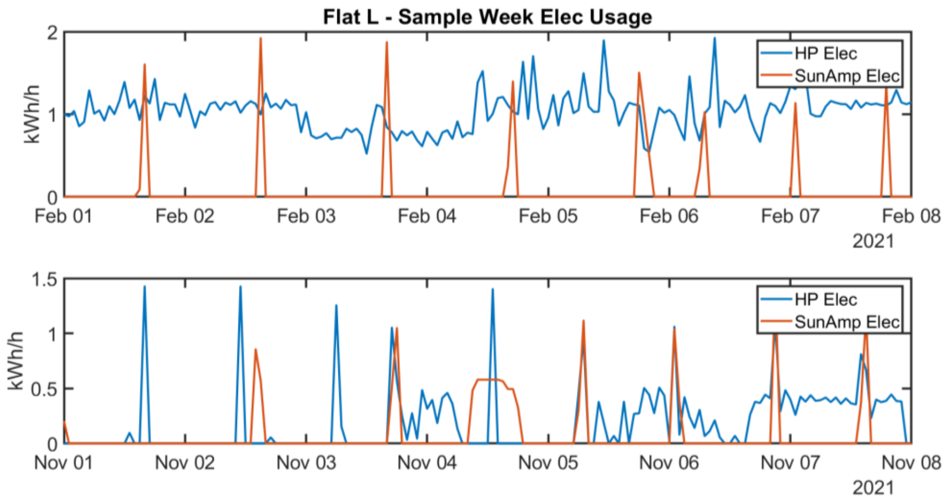


Figure 123 - Flat L Sample Weeks - Electricity

For this flat, the first plot depicting a week in February is much more typical, with the heat pump being active constantly throughout the week, with frequent additional use of the immersion for the Sunamp. As can be seen in Figure 122, this is the case for a large part of the monitoring period, however the second plot shows the heat pump initially operating in a more cyclical fashion before reverting back to a near constant use towards the end of the week. The heat pump appears to alternate between these usage patterns multiple times across the monitoring period, and it is not entirely clear what is causing this. A constant use of the heat pump might suggest that the heat pump is struggling to maintain the desired comfort level of the resident, possibly due to a high heat loss for this flat or a high temperature comfort level requirement. The internal temperature data that is available supports this, showing an internal temperature higher than the other monitored flats, reaching over 26°C at its peak.

The flow temperatures for this heat pump come from the period of heat meter readings at the end of the heating season to the middle of summer, and are shown in Figure 124.

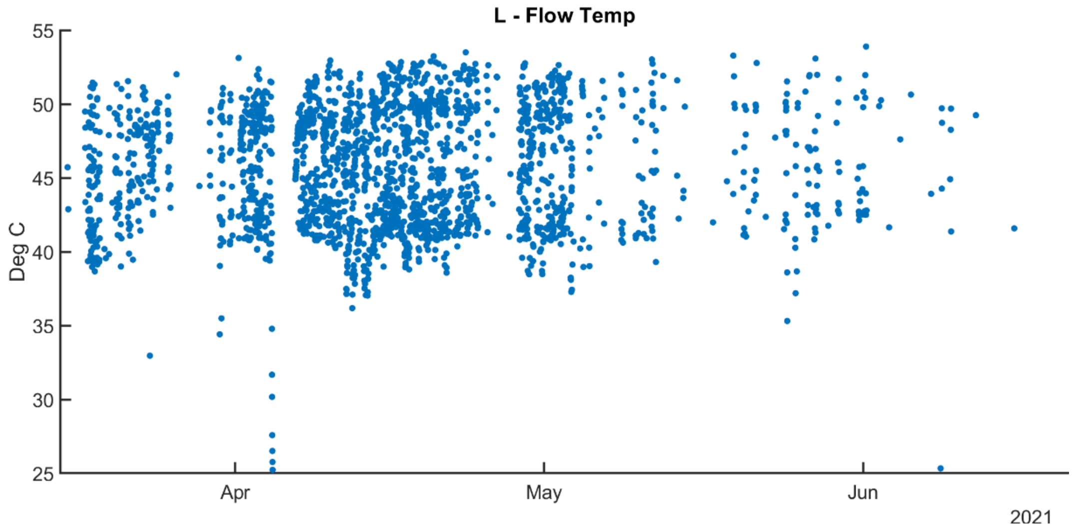


Figure 124 - Flat L Heat Pump Flow Temperatures

These show a relatively low set point compared to the previous flats of around 52-53°C rather than 65°C. This supports the idea that this flat is using the immersion in the heat battery as the primary source of hot water and the heat pump is predominantly providing space heating. This is also seen in the reduced number of measurement points towards the summer months.

Figure 125 presents the limited IPF and SEI data points for Flat L that met the filtering criteria.

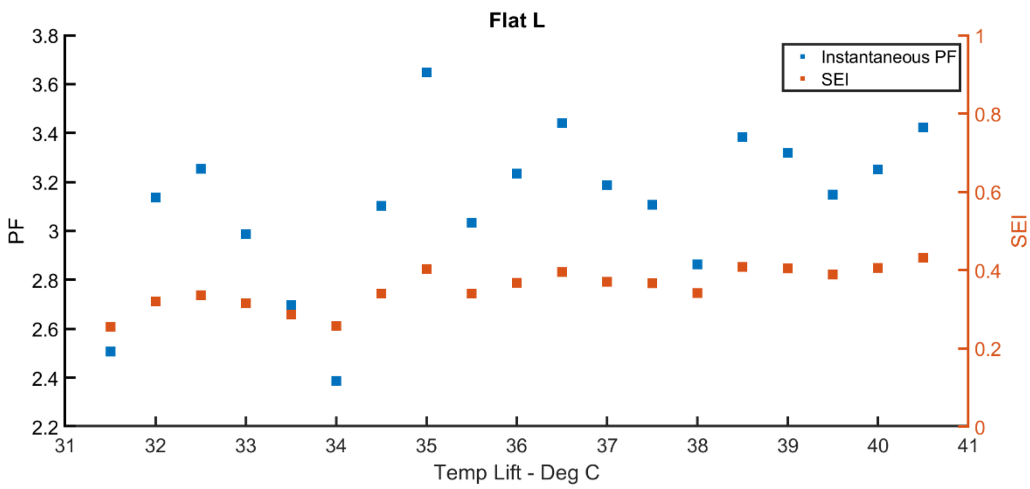


Figure 125 - Flat L IPF and SEI

Interestingly, Flat L is the only flat with slightly increasing IPF and SEI with increasing temperature lift. This is likely due to limited data points from which to calculate these KPIs and thus not an accurate picture of the systems performance in general. It is also worth noting that due to the limited data, the range of temperature lifts available to analyse spans from 31°C to 41°C, with most other heat pumps showing data from around 25°C to 55°C.

4.5.8 Flat Q

Flat Q has no heat meter installed but does have very high frequency electricity data to infer the heat pumps usage.

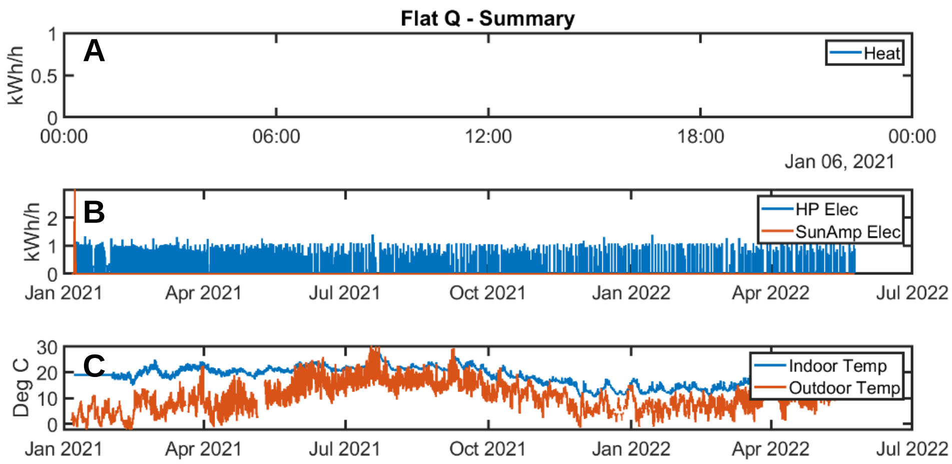


Figure 126 - Flat Q Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

Figure 126 shows the heat pump being used without the need for the immersion on the Sunamp unit to provide the space heating and hot water, as was the original design intention. It can be seen, purely from the density of the electricity plot, that this resident has reduced the usage of the heat pump as the monitoring period has progressed. The summer months do not see as much of a reduction as has been seen in other flats, however the second heating period shows a less frequent use of the system compared to the first.

The internal temperature data suggests that this is due to a change in behaviour from the resident, settling for a lower, more variable, internal temperature for the second heating period rather than maintaining the temperature at around 20°C as in to the first.

Figure 127 demonstrates the reduced operation during the summer months, however as discussed, the five cycles in the sample week is still higher utilisation of the system than seen in other flats.

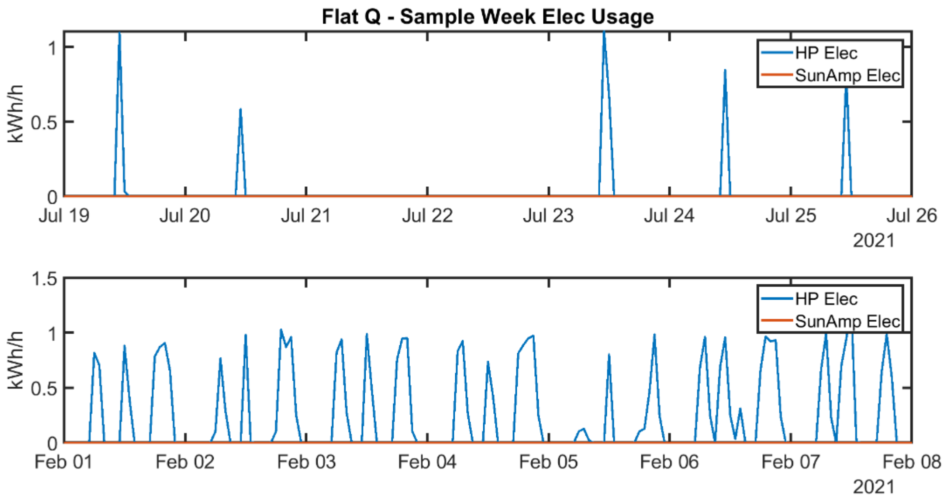


Figure 127 - Flat Q Sample Weeks - Electricity

4.5.9 Flat R

Flat R experienced problems with both the heat meter and electricity transmitters, each providing only a month or so of data at differing times to one another, as shown in Figure 128. This means that little can be gained from this data regarding usage patterns or performance factors, however the internal temperature profile of this flat is similar to that of Flat G in that rather than maintaining a temperature year-round it much more closely follows the pattern of the outdoor air temperature. This suggests the heat pump is being used mostly for hot water rather than space heating.

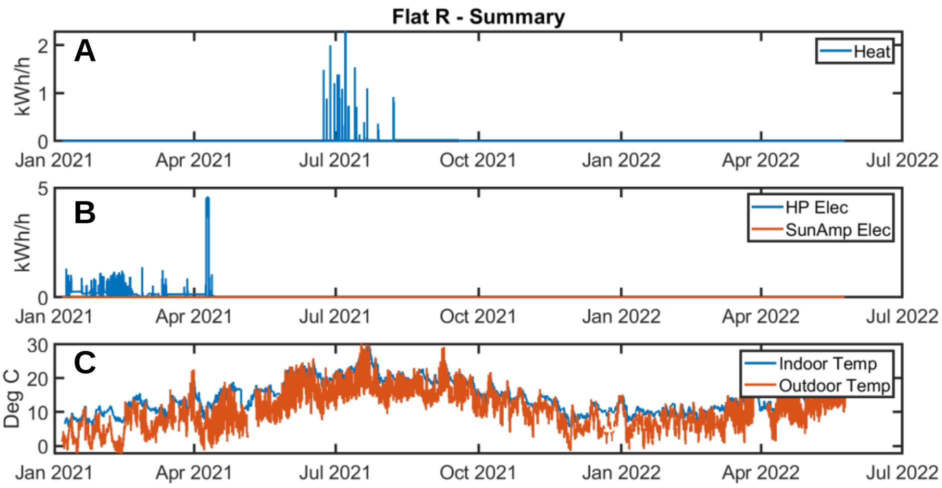


Figure 128 - Flat R Summary– A Heat from Heat Pump, B Electricity to Heat Pump and Sunamp, C Indoor and Outdoor Temperature

The very limited heat meter readings during the summer of 2021 for this flat means that it is difficult to extract any patterns in the flow temperatures shown in Figure 129, however none of these readings provided a flow temperature high enough to charge the heat battery.

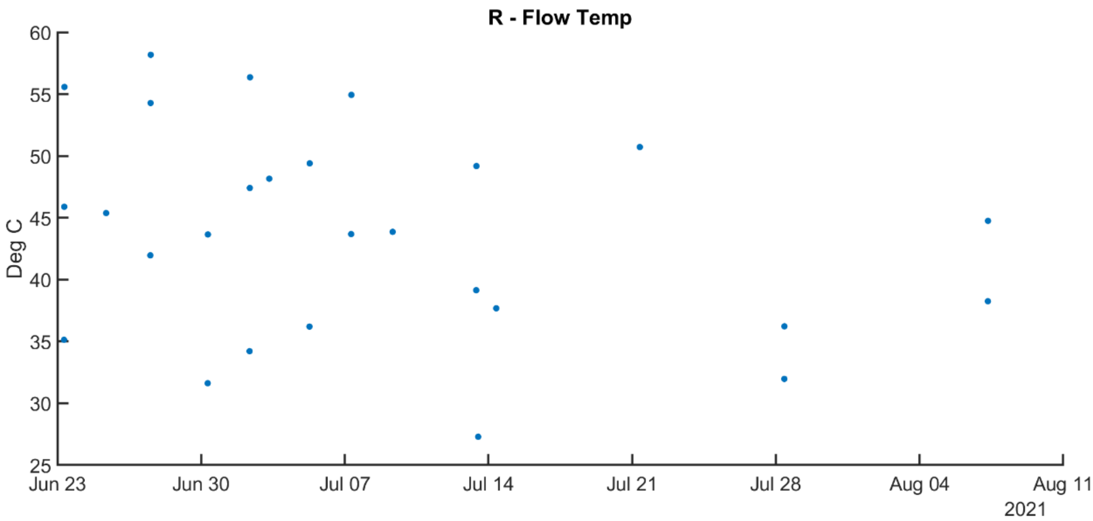


Figure 129 - Flat R Heat Pump Flow Temperatures

4.6 Flat Comparisons

4.6.1 Performance Factors

Figure 130 and Figure 131 detail the monthly performance factors for system boundary 1* and 1+* for the monitored flats in the East and West buildings respectively. A number of the performance factors are the same across both boundaries, for example with flats I and J. This is because there has been no use of the Sunamp immersion over the given period in these systems.

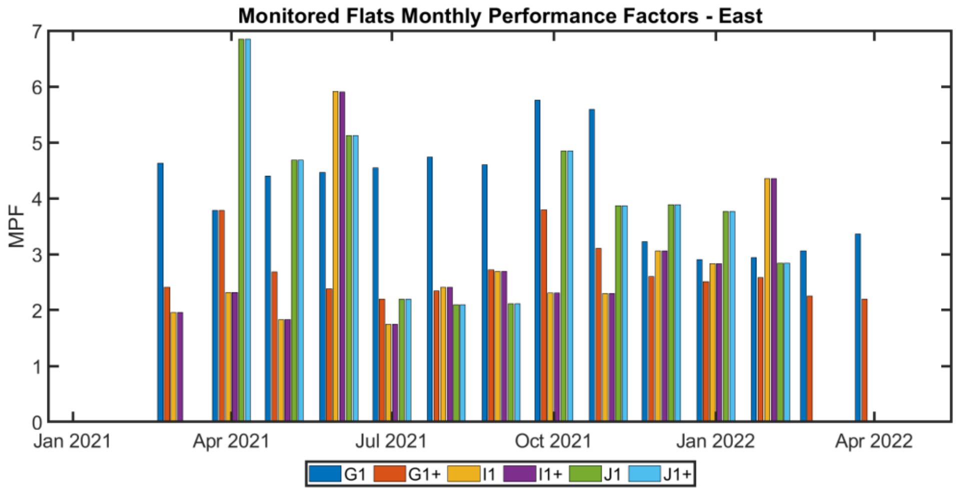


Figure 130 - MPF for Monitored Flats - Heights East

For the East building, the performance factors typically range from 2 to 5 when the heat data is present, with systems achieving a peak performance closer to 6 or 7 albeit only temporarily. It is interesting to note the drop in performance factor associated with the use of the immersion in Flat G, frequently reducing a competitive boundary level 1* performance factor to much a lower overall value, thus minimising any potential cost and emissions savings. Flat I on the other hand has a much more stable performance factor, typically between 2 and 3, with one or two exceptions such as the peak value of around 6 in June. The performance of Flat J appears initially quite high, beginning with a value of close to 7 in April before dropping away in the summer months to a low of just over 2. These peaks may be due in part to the interpolated heat values as shown in Figure 113. The performance does however appear to recover slightly into the heating season as the usage of the heat pump increases again.

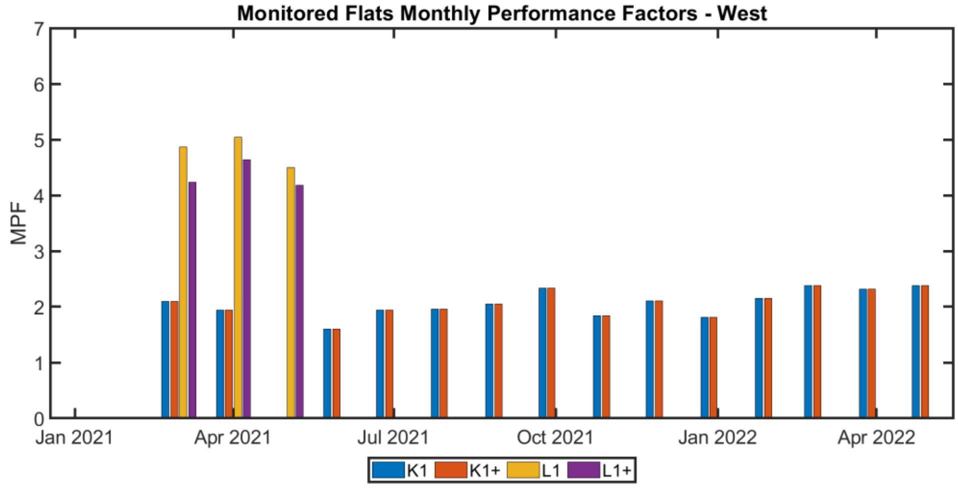


Figure 131 - MPF for Monitored Flats - Heights West

In the West building, the performance factors for Flat K are fairly consistent, ranging from 1.6 to a peak of around 2.4 in October and the limited data from Flat L show it to be performing well, consistently at performance factors between 4 and 5.

Figure 132 and Figure 133 show the hourly performance factors for these flats as a function of the outdoor air temperature.

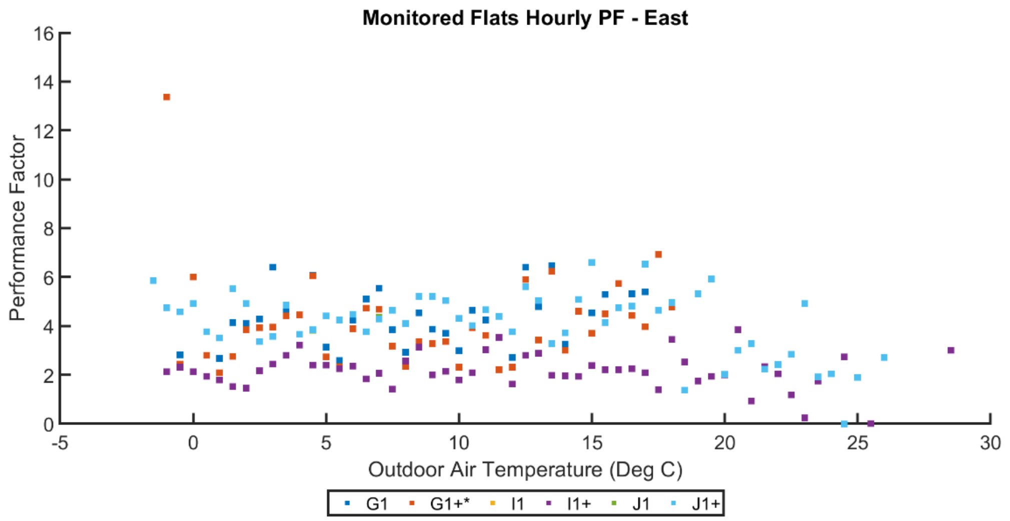


Figure 132 - HPF vs Outdoor Air Temperature - Monitored Flats Heights East

For the flats in the East building the performance factors are relatively independent of the outdoor air temperature, particularly from 5°C to 20°C, which would encompass a large part of the year. There is a slight trend towards reduced performance factors with increasing temperature beyond 20°C, likely as the system will be in use less frequently with hot water making up a larger proportion of the load, thus requiring a higher flow temperature.

Similarly, the performance factors in the West, Figure 133, also appear to be relatively independent of the outdoor air temperature. The very limited data for Flat L is likely to be a large factor in this, as data will not be available for a wide range of temperatures. Flat K on the other hand has significantly more data yet still shows a wide range of performance factors.

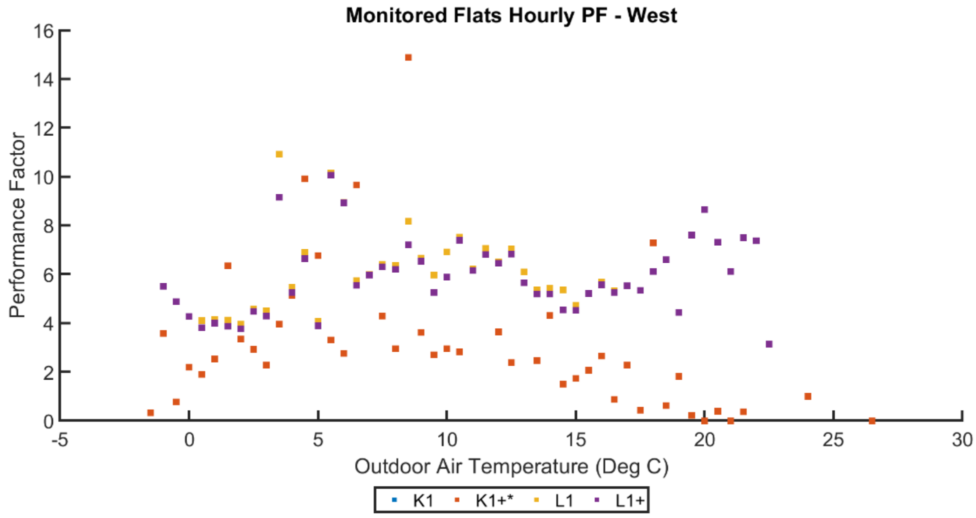


Figure 133 - HPF vs Outdoor Air Temperature - Monitored Flats Heights West

Figure 134 and Figure 135 show the average daily, weekly, and monthly performance factors at the PF1 and PF1+* boundaries respectively, for the flats with data available to calculate these values. The differences between these measures across the different timeframes will be due to the number of sample data points able to average across. Naturally Flats I, J and K have negligible differences between the two system boundaries due to the extremely low power usage of the Sunamp immersion.

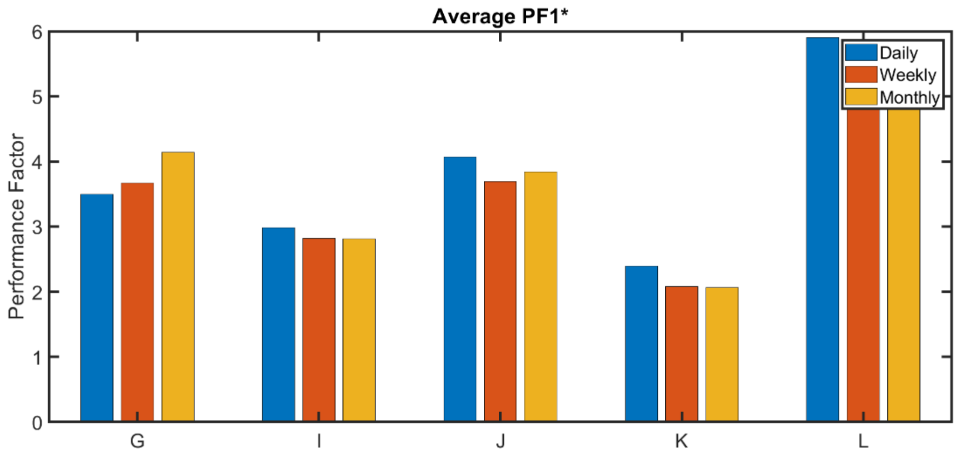


Figure 134 - Average PF1 for Monitored Flats at Varying Timescales

The boundary level 1* performance factors show average heat pump performance around the level expected, typically between 2 and 4. Flat L, which frequently ran the heat pump consistently for days at a time has achieved much higher performance factors from the heat pump.

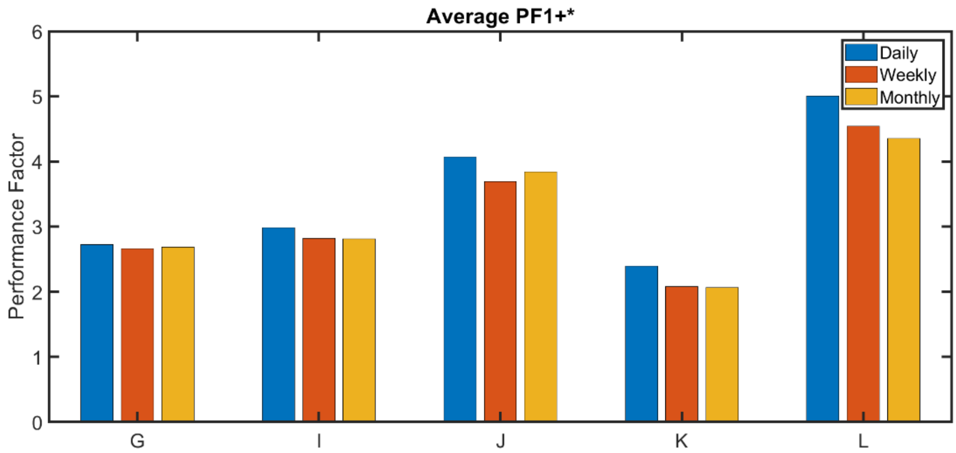


Figure 135 - Average PF1+ for Monitored Flats at Varying Timescales

Whereas Flats G and J had similar performance factors at boundary level 1, the use frequent use of the immersion heater in flat G means that at boundary 1+, the performance factor has dropped significantly whereas Flat J remains at the high level. Flat L, whilst experiencing a drop due to the use of the immersion heater, still shows the standout performance factors at this boundary, ranging between 4 and 5.

4.6.2 Summer and Winter Energy Usage

Figure 136 shows a comparison of the energy usage and heat production for the nine monitored flats during a week in the summer period, the 21st to the 28th of June 2021. Unfortunately, no data was available for Flat L during this week.

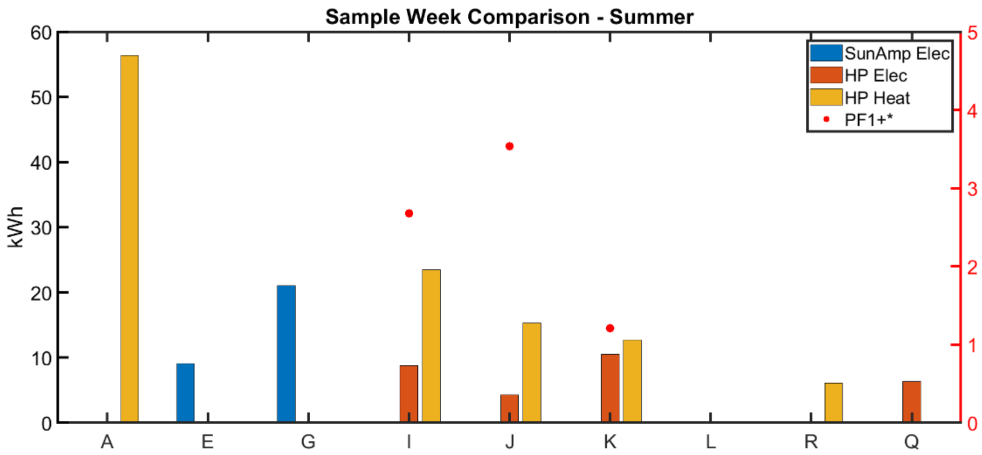


Figure 136 - Summer Sample Week - Flats Comparison

Not only does this highlight the difference in heat demand throughout the different flats it also shows the difference in energy usage and control strategies. Flats E and G only use the Sunamp immersion, providing the required domestic hot water, Flats I, J, K and Q used the heat pumps only during this period. Flats A and R do not have electricity data available for this period, so it is not clear whether the immersion is used or not, but both heat meters report usage of the heat pumps. Flats I, J, and K show that by using the heat pumps the electricity used to provide similar if not greater amount of hot water is significantly less than Flats E and G. Of the flats, Flat A shows the highest heat demand, greater than 50kWh.

Similarly, Figure 137 shows a comparison of the energy usage and heat production during a week in the winter period: the 3rd to the 10th of January 2022. Flats E and R have no data available in this week.

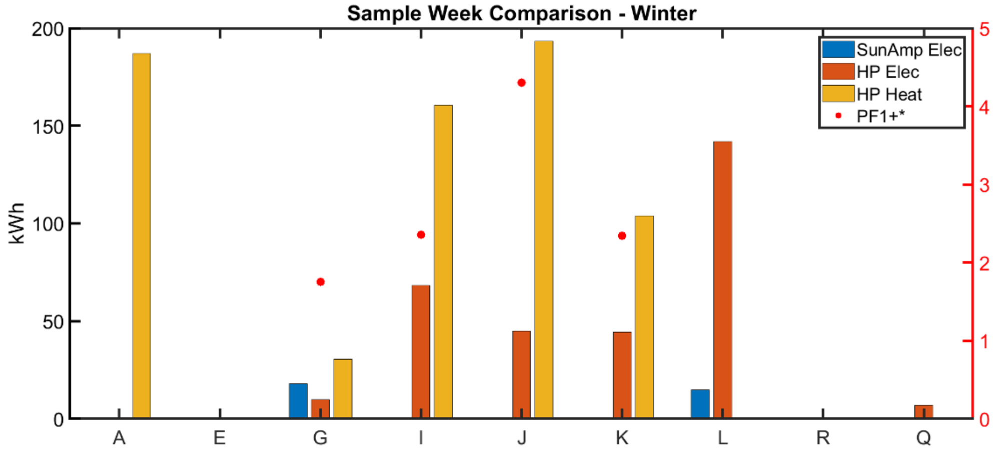


Figure 137 - Winter Sample Week - Flats Comparison

In this instance both Flat G and Flat L are using a combination of the heat pump and the thermal battery, albeit to meet vastly different demands. Of the heat data available, Flats J and A have the highest recorded heat demand at close to 200 kWh, around four times larger than the peak seen in the summer, however the electricity used suggests a much larger heat demand than this in Flat L. This also clearly shows how Flat G is trying to use the system sparingly, producing very little heat with the heat pump and very similar usage of the immersion, using 21kWh in the summer week and 18kWh in the winter.

4.6.3 Sunamp vs HP – Domestic Hot Water Provision

Figure 138 shows a comparison of four of the flats during a week in the height of summer, 19th July 2021 to 26th July 2021. This is to highlight the different energy usage required to meet the domestic hot water demands of the flat either through the Sunamp immersion as in Flat G, or with the heat pump, as with Flats I, J, and K. This week has been chosen as it was one of the hottest in the year, meaning it is likely that any heat from the heat pump will be used for hot water rather than space heating. This also assumes a 100% efficiency for the Sunamp immersion, so the electricity used as shown in the figure, also doubles as the heat provided by the immersion.

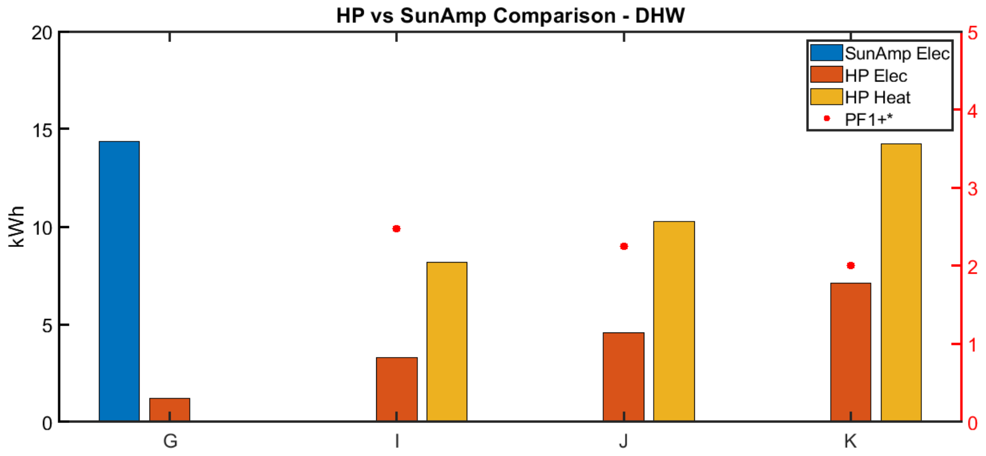


Figure 138 - Assumed Domestic Hot Water Production - Flats Comparison

This clearly shows the advantage of using the heat pump to charge the thermal battery and produce hot water in the summer rather than using the immersion, with performance factors between 2 and 3 for the three heat pump systems in Flats I, J, and K. Flat G does not have any heat meter readings for this period, and thus the PF cannot be accurately calculated. However, comparing the heat from the heat pump in Flat K to the heat from the immersion in Flat G, highlights similar hot water demands. Comparing the energy used by the heat pump in Flat K with the energy used by the immersion in Flat G, it is clear that using the heat pump is the more efficient method of meeting this demand.

4.6.4 HP Constantly On Vs HP Cycling - Flat L vs Flat K

Figure 139 compares Flat K and Flat L over the available monitoring period to demonstrate how the different control strategies affect the overall energy use. For reference, Flat K is operating the heat pump in a much more cyclical manner, with no use of the Sunamp immersion, but using the heat pump to charge the thermal battery. Flat L on the other hand is operating the heat pump much more consistently at a lower flow temperature and using the Sunamp immersion to charge the thermal store instead of the heat pump.

Flat L requires significantly more heat over this period, thus using significantly more electricity overall, however the performance factor indicates that the heat pump in Flat L is operating at a higher efficiency of 4.64 compared to the 2.00 for Flat K. This is likely due to a combination of the lower flow temperature achievable is not using the heat pump for DHW, and the reduced cycling minimising the low efficiency periods of running the heat pump.

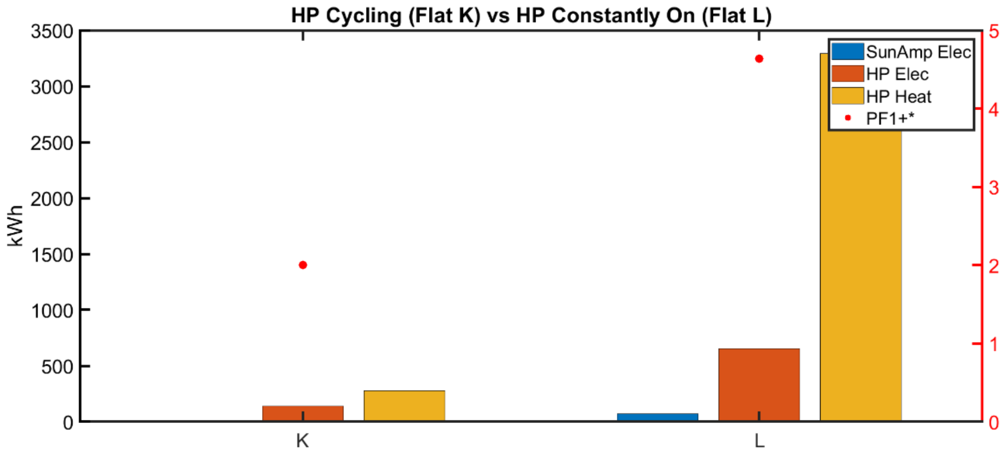


Figure 139 - Usage Patterns - Flats Comparison

The fact that the heat pump in Flat K is a 6kW Shoebox, and Flat L is a 3kW heat pump would also account for some of the reduction in performance. The manufacturer's data suggests the difference in performance for a 3kW Shoebox at 55°C compared to a 6kW Shoebox at 65°C would be between 0.53 and 0.61 depending on the source temperature (Kensa Heat Pumps, 2023). This suggests the remaining difference, ~2, would likely be attributable to the different usage patterns.

Table 40 groups the monitored heat pumps with available performance factors by usage pattern.

Table 40 - Summary of Usage Patterns and Associated PFs

Heat Pump Usage Patterns		**Flat/s**	**Average MPF1* (Individual Flats)**	**Average MPF1*+ (Individual Flats)**
Cycling HP Use	HP & Sunamp Immersion	G	4.14	2.68
	Heat Pump Only	I, J, K	2.91 (2.81, 3.84, 2.06)	2.91 (2.81, 3.84, 2.06)
Long periods of HP Use	HP & Sunamp Immersion	L	4.80	4.35

This highlights the higher heat pump PFs achievable with a lower flow temperature, with both systems using the immersions having an average MPF above 4 at boundary 1. However, under the expected cycling conditions of the heat pump, once the immersion has been accounted for the performance factor is worse than the average for using the heat pump only, and worse than 2 of the 3 individual systems. This means that the user would end up using more electricity and paying more for the same amount of heat. Flat L is an unusual usage pattern with extended run times of the heat pump allowing for higher efficiencies. Whilst this will mean better value for money, it will also lead to high bills due to the continued use of the heat pumps. The smaller drop off from PF1 to PF1+ in Flat L compared to Flat G is likely due in part to the smaller dataset available. Using the immersion over the summer months, when the heat pump provides less space heating, will result in lower efficiencies and reduce the average. Figure 122 shows a continued high usage of the Sunamp for this flat after the heat meter readings are no longer available which may have further reduced the MPF1+, though the required data is not available to validate this.

4.6.5 Building Energy Signature

Given only a sample of the flats in each building have been monitored, it is not possible to build up a complete building energy signature as in the other case studies. However, Figure 140 helps provide an indication of this by averaging the heat recorded from the monitored flats to show an indication of the average flat energy signature per building. As highlighted previously, the data from the heat meters is inconsistent and as such the raw data will have to be used rather than the data that has been backfilled. This will provide a more accurate picture of how the flats respond to the outdoor temperature. This also means that the units to be used will be kWh per 15-minute period, as the data is not regular enough to average over a whole hour for this purpose.

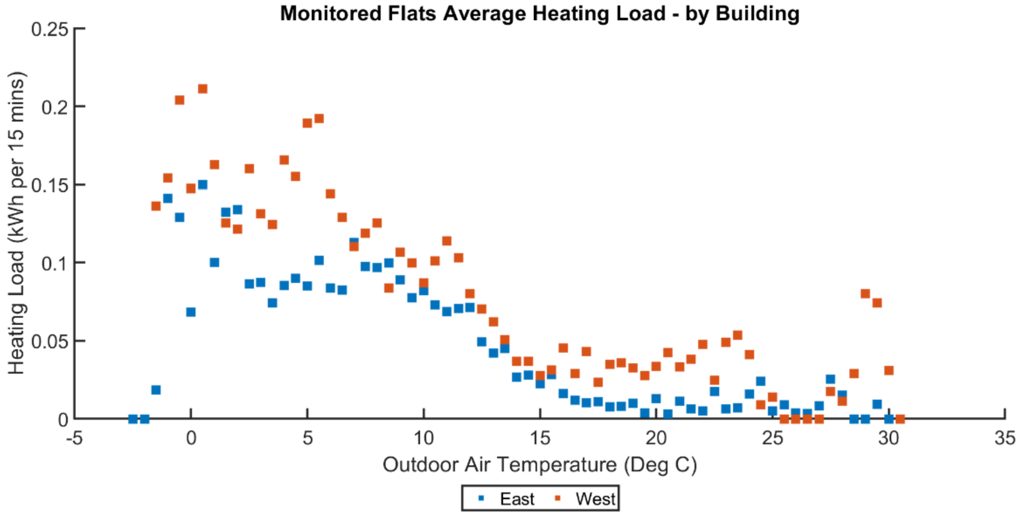


Figure 140 - Average Flat Energy Signature

As can be seen, this produces some unexpected patterns, with an initial increase in heat usage as the outdoor air temperature increases up to around 0°C in both buildings, and another increase above around 27°C. It is assumed that the reason for this is due to lack of a suitable sample size of data points for these temperatures, due in part to the heat meter issues previously noted. This is supported in Figure 141 which shows the same building energy signature along with the number of data points for each temperature.

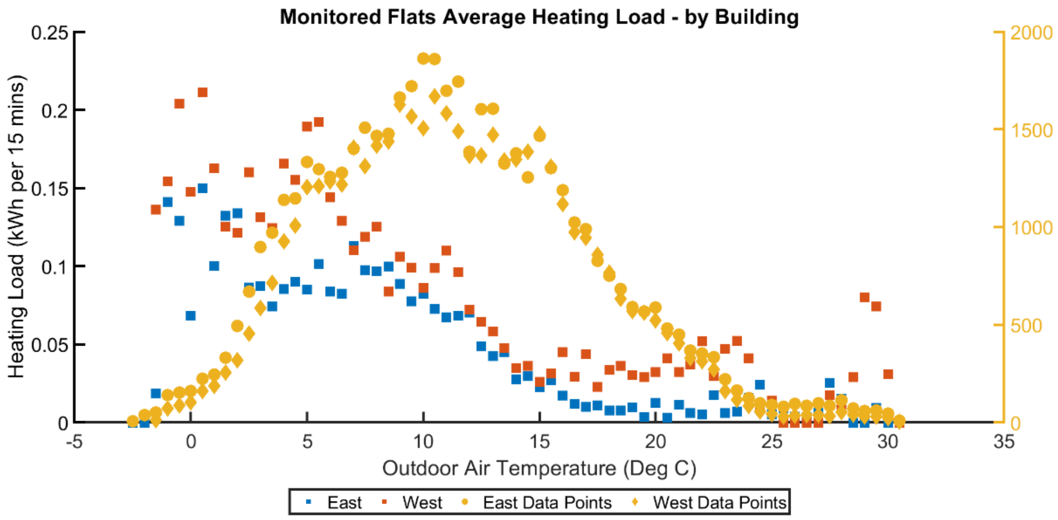


Figure 141 - Average Flat Energy Signature with Sample Size

Figure 142 and Figure 143 show the heat load of the individual flats against outdoor air temperature.

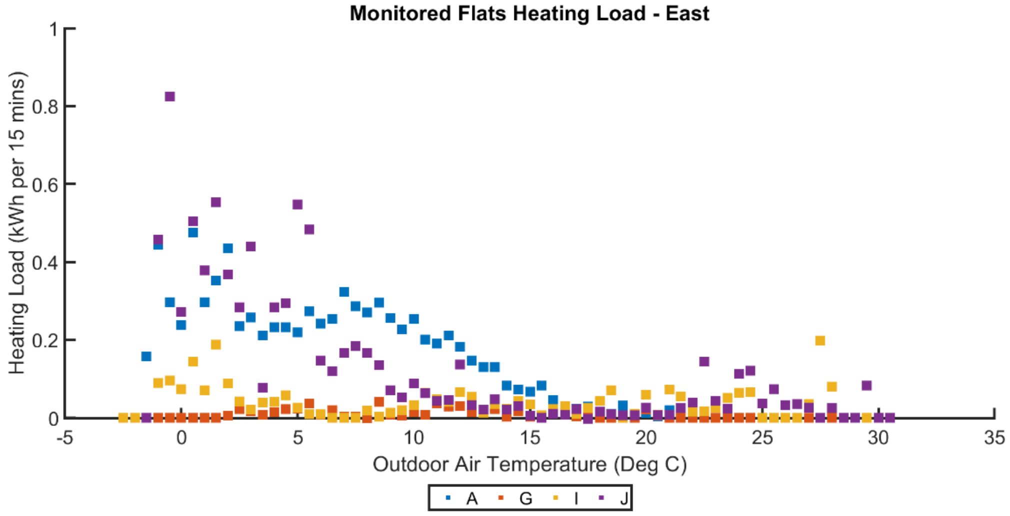


Figure 142 - Individual Flats Energy Signature - Heights East

Flat G in the East building appear to show very little heat demand no matter the outdoor air temperature, which is consistent with the analysis in the previous section indicating minimal usage of the heat pump system. Flat I also shows quite a flat heat profile, whilst Flat A and J show the expected trend of decreasing load with increasing air temperature.

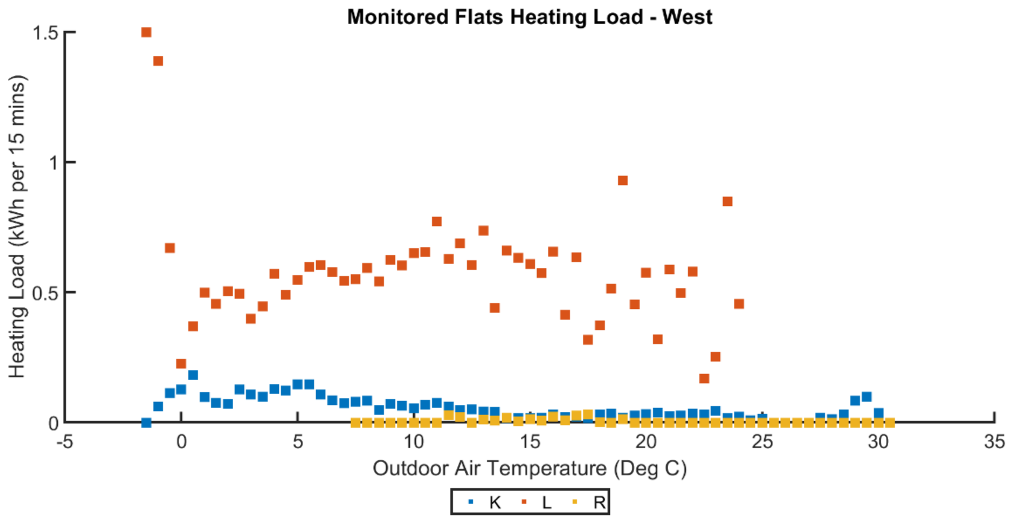


Figure 143 - Individual Flats Energy Signature - Heights West

With even fewer readings available, Figure 143 is not very informative for Flat R, however it does highlight the significantly increased demand from Flat L over Flat K. The magnitude of Flat K's load is much more similar to those in the East building. As with the ground heat exchangers, the demand in the majority of the monitored flats also appears to be curbed at around 15°C outdoor air temperature, with Flat L being the notable exception again.

Unlike the raw heat data used for the binned heat vs outdoor air temperature, Figure 140 to Figure 143, the interpolated heat data has been used to show the monthly recorded heat for the monitored flats. This has been grouped by building in Figure 144, showing the total heat recorded rather than the average per flat, and the split into the individual flats in Figure 145.

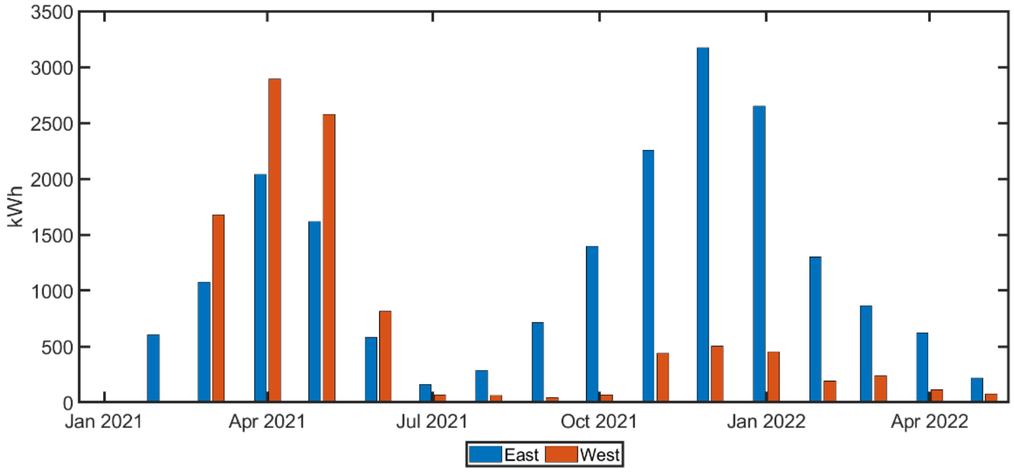


Figure 144 - Monitored Flats Total Monthly Heat per Building - Based on Meter Reading Interpolation

The lack of consistent heat data is clearly an issue here, particularly at the start of the monitoring period, where the heat demand increases from January to April in both buildings. It can be seen that this does not align with the change in outdoor air temperature during this period but is due at least in part to the increase in number of meters receiving readings, as shown in Figure 145.

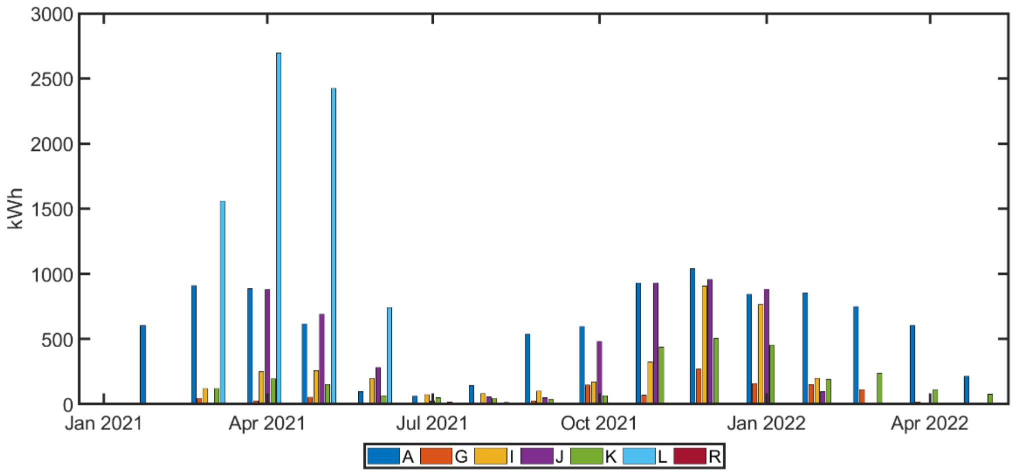


Figure 145 – Monitored Flats Total Monthly Heat per Flat - Based on Meter Reading Interpolation

4.7 Discussion

4.7.1 Logistical Challenges

The key to any good data driven decision is the data, which has to be high quality, representative, clean, and detailed enough to provide valuable insight, but first it has to be collected. This is, in theory, the easy bit, and as such is often overlooked in terms of effective planning. When it is considered, the focus is often on the technical side of data collection: the equipment specification, the data resolution, the handling of the data. The reality is, however, there are a number of potential pitfalls and unspoken challenges in this step that can hinder progress or even prevent data collection. This case study highlighted a number of these logistical challenges that are worth noting to provide learning for future monitoring projects.

There are many important parameters to consider when specifying appropriate equipment. The meters may differ for example in their accuracy, how they measure the required variables, how they transmit these variables, whether they are mains or battery powered, and whether they have any internal storage, among many other factors. Detailed planning ahead of time considering these factors and speaking to experts and instrumentation specialists can help guide the selection of the right equipment. Guides such as the data and instrumentation guideline from the IEA HPT Annex 52 (Davis *et al.*, 2021), can also help point the user in the right direction and hopefully minimise the amount of upfront research required.

Going beyond the technical advice of these guidelines, good communication with the principal contractor is key, whether the equipment is to be installed by the researcher or a third party. Either way, a clear understanding of project timelines is essential to minimise disruption and ensure the equipment is installed and commissioned in a timely manner. Due to this study continuing the work of a previous study with the agreement of the client, Leeds City Council, the principal contractor agreed to carry out the installation of the heat meters in the flats at the same time as the heat pumps. This theoretically meant no additional disruption to the residents. Unfortunately, as the contractor was carrying out this extra work on good will rather than a contract or official agreement being put in place, the paying client naturally took priority, and any additional work or communication will be of less importance. This meant that the timelines and progress of the project was not always apparent and this, along with long lead times for some of the components, COVID 19, and customs delays, meant that the heat meters arrived after the heat pump installations had started. This meant the contractors had to valve off and retrofit a couple of the heat meters, causing additional disruption as well as delaying the start of data collection.

Additionally, issues such as misplaced connectors needing replacing and installing the heat meters in the wrong locations highlight the need to have constant clear communication with the contractor, to ensure the directions provided are being cascaded to those doing the actual installations. The extra work as a result of these miscommunications, such as revisiting properties to obtain the ID of the heat meters, without which the heat data could not be tied with the electricity data, will not only delay the start of the data collection for the end user, but also mean additional work and delay for the contractors. As such should it is in the interest of all parties to avoid this. Whilst attempts to do this were made in this instance, with every heat meter clearly labelled with the installation location, the instructions were clearly not communicated at all levels, and progress was not continuously checked resulting in delays.

Similarly to the heat meters, due to the long lead times and the delayed communication of timelines, the ground loop temperature probes arrived close to the required installation date. This was dictated by the need to route the cables from the sensors to the datalogger before the trenches were backfilled. This meant that there wasn't time to conduct any laboratory calibration measures before installing them into the manifolds and the calibration had to be attempted in a separate visit after installation in a less controllable environment.

A number of these issues were unfortunately due to the retrofit project being significantly underway at the time of the monitoring project being agreed, which provided additional time constraints that could be avoided for most projects, but it is worth highlighting to emphasise the need for upfront planning.

These experiences reinforce the need to consider the project management implications alongside the technical requirements of the data collection noted in the guidelines provided for such monitoring projects. This will allow for data collection to start as early as possible, providing maximum value from the project.

Beyond planning and installation issues, commissioning the equipment can also throw up many additional hurdles and logistical challenges. In this project, a significant amount of time was spent troubleshooting the equipment installed by the research team only to eventually find that the issue was with the pre-wired components from a supplier. This highlights the need to check all components as they arrive, before installation, even if they are setup by competent and experienced suppliers.

Finally, upon completion of commissioning, it is incredibly important to continually monitor the data, ensuring its accuracy and quality as it is being recorded. This will allow faults and sensor issues to be found as early as possible, enabling troubleshooting and adjustments to be made and ensuring the maximum amount of quality, usable data. This isn't always possible, and the location, availability, and ease of access to some meters and sensors will cause issues with fixing any problems found. In this project, the monitoring of the ground loop flow rates allowed the repositioning of the flow meters for two of the arrays from the flow pipe to the return pipe, generating usable data where it had previously dropped out.

It is worth noting that despite the issues encountered in the data collection for this system, there are still relatively few long-term case studies for ground source heat pump systems in the UK, particularly shared ground loop systems such as these. Thus, the data collected and analysed in this instance is invaluable, even if it is not perfect, and can be used to further understand the multi-seasonal behaviour of these systems.

4.7.2 Ground Loop vs Original Design

The investigation into the ground loops, Figure 86 to Figure 93, shows the utilisation rarely rose above 50% in any of the four arrays for the system in the West building. The East ground loop utilisation however tells a slightly different story in that the smallest array, array 1 appears to be well sized for the winter loads, achieving close around 90% utilisation during these periods. The low utilisation during the summer months of around 20% may be useful in the sense that it allows the ground to recharge. East array 2 will need to be investigated further as either there is an issue with the flow meter, and it appears likely by comparison with the other arrays that this is the case, or the array is sitting at close to 100% utilisation even as the summer months approach, which would indicate a larger problem with the system. East arrays 3 and 4 generally show low utilisation rates, however both arrays also show a spike in the early months of monitoring showing a utilisation between 90 and 100%.

The difference in utilisation of the equivalent arrays in the East and West buildings is of interest as each array is supplying the same number of flats with the same heat loss profiles in each building and has very similar overall depths of heat exchangers. Any difference therefore directly reflects changes in the usage of the heat pumps. Therefore, the fact that East array 1 achieves a high utilisation rate suggests that West array 1 is not necessarily over designed, but in fact the households on this array are using less heat than expected.

It is likely that the ground loops were designed to accommodate the peak flow rates from all the connected heat pumps simultaneously to ensure that all residents can have instantaneous heating as required, however the utilisation figures suggest that these peaks occur so infrequently, leaving the majority of the ground loops operating a much lower capacities for large periods of time. This may not be the optimum design in terms of cost and time and instead the arrays could perhaps be designed to meet less load, with the residents utilising the thermal battery to meet the peak needs if and when required. However, the fact that East array 1 however has prolonged periods of high utilisation during the winter months provides an interesting contrast to the others. In this case, there are only 8 heat pumps connected, 2 of which are on the lower ground floor. This could suggest that more heat is being lost through the ground for these properties, and as such less heat is being transferred upwards into the 6 heat pumps on the floor above, driving higher heat requirements and thus higher utilisation of the ground loop. This may also be due to the lower diversity on this array, as it is more plausible to think that 8 heat pumps may be frequently on at the same time over the winter period than say 16 as with arrays 2 and 3.

The low flow rates have two implications to the upfront design of the system. Firstly, they suggest that not all heat pumps on a given array are running simultaneously, indicating that the amount of borehole heat exchanger installed in the ground is likely more than required. This means a greater initial cost to the system owners. Secondly, the low flow rates seen, would result in a lower pressure drop across the hydraulic system than originally designed for. This could mean that smaller diameter pipework could have been used in the design, saving on the upfront costs.

The entering water temperature (EWT) from the ground loop into the heat pumps was designed to be 0°C after 20 years of operation. As can be seen from Figure 72 to Figure 79, the temperature of the fluid returning to the ground loop was consistently higher than this due to the system only being a few years into its design life. It is expected that the ground temperature will slowly drop to the design condition over the many years of operation of the heat pump system, before reaching an equilibrium with the ground, as no heat is actively being rejected to the ground from the building to recharge it. Some natural recovery of the ground temperature is expected as utilisation in the summer months decreases, however this is accounted for to an extent in the original design.

Continued underutilisation of the arrays will lead to increased efficiencies at the heat pumps representing a better return on investment for the end user. However, this comes at the expense of the contractor who has potentially paid for an overdesigned ground array.

4.7.3 Usage patterns

The analysis of the monitored flats highlighted a number of differing usage patterns for the heat pump and Sunamp, supporting the conclusion found in the original study (Fletcher, Gorse and Miles-Shenton, 2021). The original design intention was that the heat pump be used for space heating and charging the Sunamp, with the immersion on the Sunamp unit only being used as a backup. Flats I, J, K, Q and as far as can be told Flat R, all appear to be following this regime. Whilst it is unknown whether Flat A uses the immersion or not, the flow temperatures from the heat pump indicate it is also using the heat pump to charge the heat battery. When looking at the behaviour on a daily scale, it is noted that there is a difference in behaviour between these flats as well, with some, such as Flat A, appearing to use the heat pump based on a timer control, and others such as Flats I and J appear to be a bit more sporadic in their usage.

Flats E, G, and L on the other hand are frequently using the immersion heater to charge the heat battery. Additionally, the heat pump in Flat L is frequently operating constantly for several weeks at a time, whilst the remaining heat pumps are being used cyclically, typically once or twice per day.

In the sample weeks shown in the summer, winter, and assumed generation of domestic hot water in Figure 136 to Figure 138, Flats I and J are shown to have higher system performance factors than Flat G, indicating that the intended usage pattern, limiting the use of the immersion, is the most effective when the heat pump is not required for long time intervals, and should be the adopted in these cases. This is supported in Table 40, showing an average MPF1+ of 2.91 for flats I, J, and K compared to 2.68 for Flat G.

Flat K in isolation, however, does have a lower PF than that of Flat G. Figure 117 suggests that this occupant is comfortable at a lower internal temperature than many of the other flats, so it is possible that the heat pump has shorter cycle times as the room will reach the required temperature much quicker. This will reduce the efficiency of the system as a larger percentage of the heat pump “on time” will be covered by the low efficiency ramp up of the compressors.

This may indicate the heat pump is oversized and installing the 3kW version to be run for longer periods may have been the more efficient solution.

Fletcher, Gorse and Miles-Shenton (2021) originally put forward that these various usage patterns may be down to the varying levels of instructions and guidance the residents received when the heat pumps were installed, excessive noise from the heat pumps causing a nuisance, or potentially that the heat pump alone was not sufficient in meeting the demand of the flat. The further analysis provided in this thesis provides more rigor to the conclusion that many users are not operating these systems as intended, and the continuation of these patterns suggest that the underlying issues have not been addressed.

4.7.4 Performance

As highlighted above, the different usage patterns lead to different performance levels in the heat pumps.

Of all the flats, Flats I, J and L, all achieve any average system performance factors greater than 3 once the immersion is accounted for. Whilst flat G achieves heat pump performance factors (boundary level 1*) above 3, these drop significantly when the heat battery is taken into account at boundary level 1+*, again highlighting the efficiency gains to be made by using the system as designed. This may not always be possible, as with Flat L, in which the heat pump is running almost constantly to raise the internal temperature to higher than seen in the other flats. Similarly, differing hot water requirements across different flats are likely to alter the usage across the flats, however this should be accounted for when designing the system. The reduced system performance seen here will have an impact on any potential bill savings expected for the residents as well as reducing the emissions savings achievable.

This raises a wider question on the design of such systems. If a flat has a higher demand than typical for the same size/archetype of flat, as with Flat L, a shared ground loop system with distributed heat pumps may not provide the best solution. For example, if the person is vulnerable or works from home, the desired internal temperature will be potentially higher than the design condition. This could result in the heat pump being undersized, and the user might then be forced to use an auxiliary system to meet the additional heat demand. This means the user is then personally penalised for the reduced efficiency, despite the fact that this increased demand may be unavoidable. A centralised heat pump system feeding the multiple properties, however, would be able to run at high efficiencies despite individual changes in usage such as this, and thus the end user would not be penalised in the same way. Of course, centralised systems have other challenges such as metering individual usage, and heat losses in distribution, but nevertheless this could be a drawback of distributed systems. Accounting for these variations in the initial design is naturally the best way of eliminating these individual penalties, however through monitoring such as this, additional commissioning or training could now be provided for users experiencing such additional costs, allowing for greater efficiencies. Of course, not all such variations can be accounted for, for example additional heat losses may be incurred through a shared wall with a colder flat, either because the users are attempting to reduce their bills or have a lower comfort temperature. However, attempt should be made to understand the likely use cases of the systems where possible.

Whilst there are no shared ground heat exchange systems to directly compare against, Figure 146 to Figure 148 compare the performance factors to similar systems highlighted in the literature review. The details and references for the comparative case studies can be found in Table 41. It is worth noting again that for the Heights systems, as per the Annex 52 boundaries, SPF1 = SPF2 = SPF4 as there are no additional circulation pumps. This is shown in the following figures as just SPF and does not include the immersion.

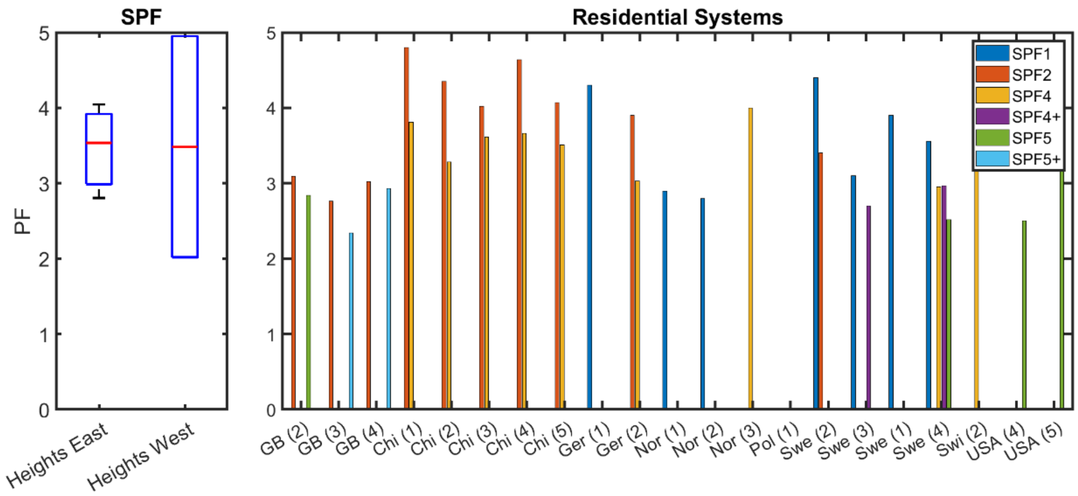


Figure 146 - SPFs of Residential Systems

Figure 146 demonstrates the range in individual performance factor for the Heights East and West compared to other residential systems found in the literature. For the Heights, a boxplot has been used to show the average and the range for the three monitored systems in each building. This has produced SPFs comparable to those installed elsewhere, with the mean in each building being higher than the others in Great Britain.

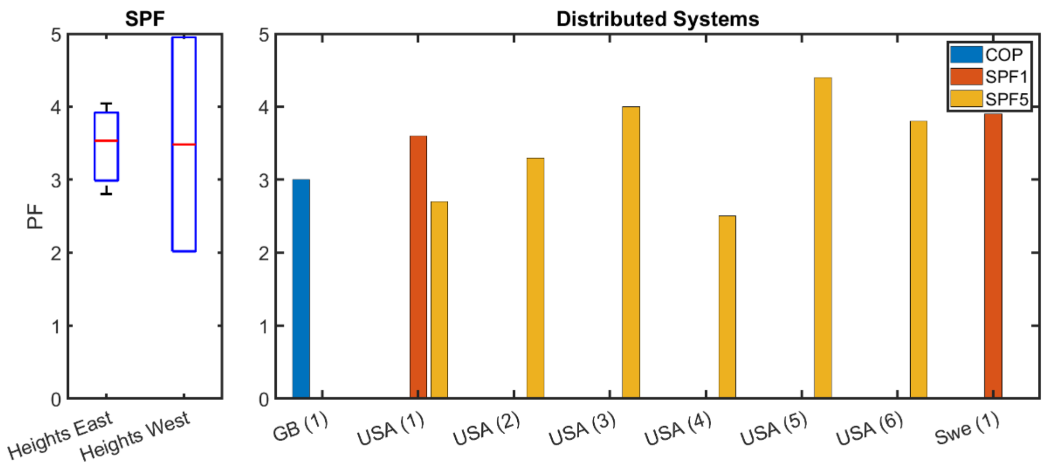


Figure 147 - SPFs of Distributed Systems

Figure 147 shows a comparison of the Heights systems to six other distributed systems noted in the literature, one in the Great Britain, six in the USA and one in Sweden. Once again, the Heights values appear similar to these other systems, however it is worth noting that the USA based systems are generally distributed water-to-air heat pumps rather than water-to-water as with the Heights.

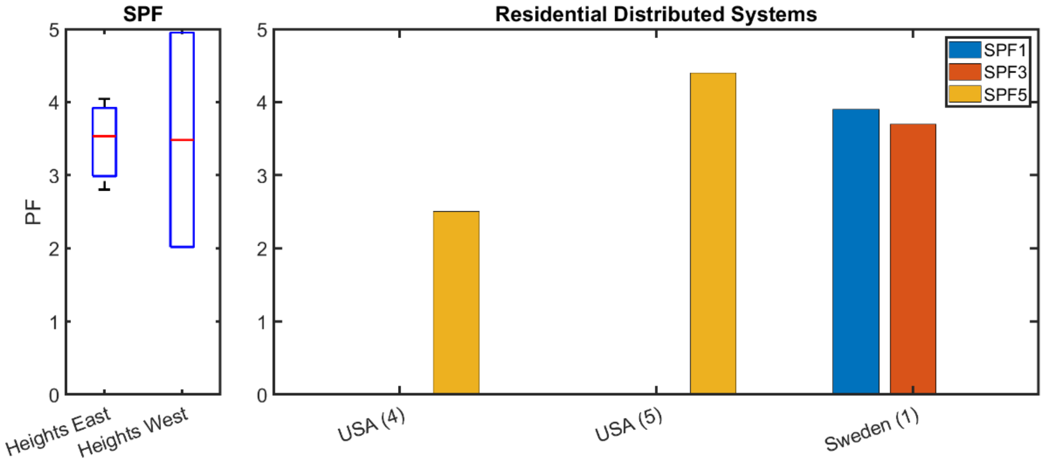


Figure 148 - SPFs of Distributed Residential Systems

Figure 148 shows the three other distributed, residential systems identified in the literature.

The comparison of the performance figures across multiple boundaries, depending on the data available, means that the high performance factors of the systems installed at the Heights may be partly attributable to the lack of any additional circulation pumps. Essentially, the circulation pumps are internal to the shoebox heat pumps, with each one only activating if that heat pump is turned on. This is the equivalent of having a large, centralised circulation pump with the same number of stages as heat pumps connected and so it is likely that this distributed method of circulating fluid through the ground loop is more efficient. It would be of interest to compare the performance factors of the heights to the other systems, if the circulation pump energy could be discounted from the Shoebox heat pumps, as this would provide a PF more strictly aligned with the boundary level 1 definition.

Table 41 - The Heights Comparative Case Study References

Identifier	Country	System Capacity	Building Type	Citation
GB (1)	Great Britain	225	Office & Warehouse	(Witte, van Gelder and Serrão, 2002)
USA (1)	USA	1540	University	(Im and Liu, 2015a)
USA (2)	USA	812	High School	(Liu, Malhotra and Im, 2017)
USA (3)	USA	300	Office	(Liu *et al.*, 2016)
USA (4)	USA	1253	Student Apartments	(Liu *et al.*, 2015)
USA (5)	USA	2153	Student Apartments	(Liu, Malhotra and Im, 2017)
USA (6)	USA	111	Office	(Spitler, Southard and Liu, 2021)
Swe (1)	Sweden	1900	Residential	(Walfridson, 2022a)
GB (2)	Great Britain	54	Uni Accommodation	(Hughes, 2018b)
GB (3)	Great Britain	71	Hotel	(Hughes, 2018b)
GB (4)	Great Britain	23	3 Dwellings & Office	(Hughes, 2018b)
Chi (1)	China	1040	Residential	(Deng *et al.*, 2019b)
Chi (2)	China	1986	Residential	(Deng *et al.*, 2019b)

Chi (3)	China	2600	Residential	(Deng *et al.*, 2019b)
Chi (4)	China	5680	Residential	(Deng *et al.*, 2019b)
Chi (5)	China	2160	Residential	(Deng *et al.*, 2019b)
Ger (1)	Germany	110	Apartments	(Bauer *et al.*, 2010)
Ger (2)	Germany	30	Residential	(Bockelmann, 2021b)
Nor (1)	Norway	76	Flats & Supermarket	(Stene and As, 2021)
Nor (2)	Norway	252	Flats, Library, Kindergarten	(Stene and As, 2021)
Nor (3)	Norway	320	Conference Hotel	(Midttømme *et al.*, 2021)
Pol (1)	Poland	10.4	Residential & Office	(Pater and Ciesielczyk, 2017)
Swe (2)	Sweden	100	Apartments	(Delattre, 2018)
Swe (3)	Sweden	80	Residential	(Ekestubbe, On and Ab, 2021)
Swe (4)	Sweden	180	Residential	(Pallard, 2021)
Swi (1)	Switzerland	96	Residential	(Kohl, Brenni and Eugster, 2002)
Swi (2)	Switzerland	63.6	Residential & Office	(Wemhoener *et al.*, 2017)

4.8 Conclusions

The analysis in this chapter presents some of the first data on the utilisation rates of shared ground heat exchange systems in the UK. The key conclusions to be drawn from the analysis of this system are:

- A clear instrumentation plan is required in advance, to be agreed by all parties, where possible to ensure the quality and timeliness of data when monitoring systems such as these. This not only encompasses equipment but also logistics and programme.
- Given its definitive upper limit, the SEI can be a useful proxy for data quality as well as a key performance indicator.
- The use of the SEI in this way, along with statistical analysis techniques such as change point analysis can help to automate the cleaning of problematic data
- Where possible, data should be recorded at time intervals smaller than 15 minutes as this would reduce the interpolation and filtering required to effectively analyse and interpret the data,
    - This is less important if the main interest is overall system performance rather than troubleshooting
- The utilisation rates of the ground loop arrays attempts to quantify the diversity present in systems using multiple heat pumps connected to a single ground loop
    - The low utilisation rates of the majority shared ground loops suggest the diversity factor is likely under predicted, however one circuit, East array 1, suggests the contrary. Further research will be need on how to account for this appropriately in design.
- Shared ground heat exchange systems with distributed heat pumps can provide performance factors greater than four for the end users and are performing at comparable efficiencies to similar systems found in the literature.
- The additional data on individual flat heat demands further supports the conclusion from the original study (Fletcher, Gorse and Miles-Shenton,

2021) that some users are not using the heat pump and thermal battery system in an optimal way, leading to losses in efficiencies, greater emissions, and higher costs for the end user. This could indicate the need for greater training or instruction on how to use these systems effectively.

  - In particular, the excessive use of the immersion heater in the Sunamp has been a common deviation from the intended usage pattern. It is possible this could be avoided if the heat pumps were upsized, for example in Flat L from 3kW to 6kW.
  - Conversely, the end user in Flat K appears more comfortable at a lower internal temperature and is potentially oversized with a 6kW heat pump.

- Some of these sub-optimal usage patterns could potentially have been addressed through a greater understanding of each user’s requirements at the design phase, rather than assigning 120 flats into one of four archetypes.
- For example, a simple survey on usage needs, and understanding occupancy could allow for upsizing or downsizing of heat pumps as appropriate, to ensure minimal usage of auxiliary systems, whilst maintaining a robust design for the overall system.

4.9 Future Work

Future work on this system could look at how the ground loop for this system might have been designed to reduce the significant upfront cost and labour for any potential similar projects in the future. This may involve reducing the number or the depth of the boreholes in each array or perhaps reducing the number of arrays required. Further monitoring of this and other shared ground heat exchange systems will be required to inform this work.

Additionally, further monitoring of this system would provide a useful insight into the longer-term effects of use. Namely, how does ground recover during the summer months?

The data available could also be further interrogated, attempting to fill any gaps in the heat output by correlating the electricity usage with the heat pumps manufacturers IPF data or vice versa where heat output is available and electricity usage is not.

5 Case Study #3 – Grangetown Nursery

The following chapter will investigate the long-term performance of an open loop ground source heat pump supplying a nursery school in Cardiff. The main objectives of this chapter are to:

- Using available data sets, calculate heat delivered to the building on a smaller timescale than previously available from infrequent manual readings,
- Use the calculated heat to determine the system's performance at multiple system boundaries,
- Compare the system performance to similar systems in the literature.
- Identify any markers for system underperformance that may be present.

This chapter will follow a similar format to the previous two case studies: a description of the system, the instrumentation installed, and the data available for analysis, followed by a description of the data cleaning required and the analysis methods. The results of the analysis will follow before a discussion on the system performance and overall conclusions are then drawn for this system.

5.1 System & Instrumentation

5.1.1 Context

In 2015 the Grangetown Nursey School in Cardiff was retrofitted with an open loop ground source heat pump system as part of an InnovateUK feasibility study into groundwater heat from shallow aquifers.

As part of this retrofit, various instrumentation was installed by the British Geological Survey working in partnership with assistance from Cardiff City Council, who have been monitoring and maintaining the system since the end of the original project in 2016. The aim of this instrumentation was to monitor the performance not only of the heat pump system, but of the aquifer. The original findings for the first three years of this case study were reported in

Boon *et al.* (2019). As noted in the literature review, however, due to various data issues the reporting on the heat pump system itself and its performance was limited. As such, to maximise the learning and outputs from the wealth of data that is available, this chapter investigates the datasets in more depth, applying additional models and making reasonable assumptions to map the behaviour of the system on a more granular level.

5.1.2 The building

The Grangetown Nursery School in Cardiff, Figure 149, built in the late 1980's and extended in 2011, is a single storey building with a potential occupancy of close to 100; up to 80 children and up to 18 members of staff. Table 42 provides a summary of the building.

Figure 149 - Grangetown Nursery (Boon *et al.*, 2019)

Table 42 - Summary of the building features

Location	Cardiff, United Kingdom
Year of building construction	Late 1980's
Ground source system operation start date	2015
Building Type	School – Classrooms, Offices, Communal Areas,
Building floor area (net, gross)	280 m² gross (Footprint)
Analysed monitoring start date	2016
Analysed monitoring end date	2021

5.1.3 The Ground Source Heat Pump System

The GSHP system was intended to replace the existing gas boiler, to provide the space heating and hot water demand of the building. However, the pre-existing gas boiler system remained installed to provide redundancy in case of any problems with the heat pumps. The heat pump system was encapsulated completely within a powder coated aluminium housing within the school grounds, meaning that in theory, it could be disconnected and relocated to another site if necessary. This is shown in Figure 150. No changes were made to the existing system of radiators for the switch to a heat pump.

Figure 150 - GSHP Equipment in Outdoor Container (Boon *et al.*, 2019)

The system was designed to meet the worst-case demand of 22kW at minus 3°C outdoor air temperature, as per heat loss calculations undertaken at the design stage, and consists of 2 centralised Dimplex SIH 11ME heat pumps. The heat pumps have a heating capacity of 11kW each and principally operate in a duty assist manner, meaning that for large parts of the year when the heat demand is less than 11kW, only one heat pump will need to be in operation.

The heat pumps are part of a groundwater system and are connected to a well doublet of one 22m deep abstraction well and one 18.6m deep reinjection well. As noted in the previous reporting on this system, the production well had a PVC well casing lining, and was screened between 8 and 17 meters below ground level with the remaining 5 meters from 17 to 22 meters below ground level being grouted (Boon *et al.*, 2019).

The reinjection well is 18.6 m deep with the pipe outlet located 10m below ground level, screened throughout, and located approximately 20 meters downstream of the abstraction well. The spacing between the two wells was restricted by the available space on the site, however the initial idea was that the wells could swap operation if too much thermal breakthrough was observed, with the abstraction becoming the reinjection well and vice versa.

These wells pass through a number of geological layers, including made ground, tidal flat deposits, sand and gravel aquifer, and Triassic Mercia mudstone, though the water is being abstracted from the sand and gravel aquifer. The wells have an external diameter of 200mm and the two pipes in the wells are constructed from 40mm diameter HDPE.

In the abstraction well, a single, fixed rate submersible pump was installed at 15m below ground level; a suitable depth to remain submerged year-round and avoid the seasonal temperature fluctuation zone. This pump was originally reported as a Nastec 4H 06/02 but through examination of the provided information, data, and images, this was found to be incorrect. The actual pump installed is a WPS 07/03.

A summary of these wells and the ground layers can be seen in Figure 151.

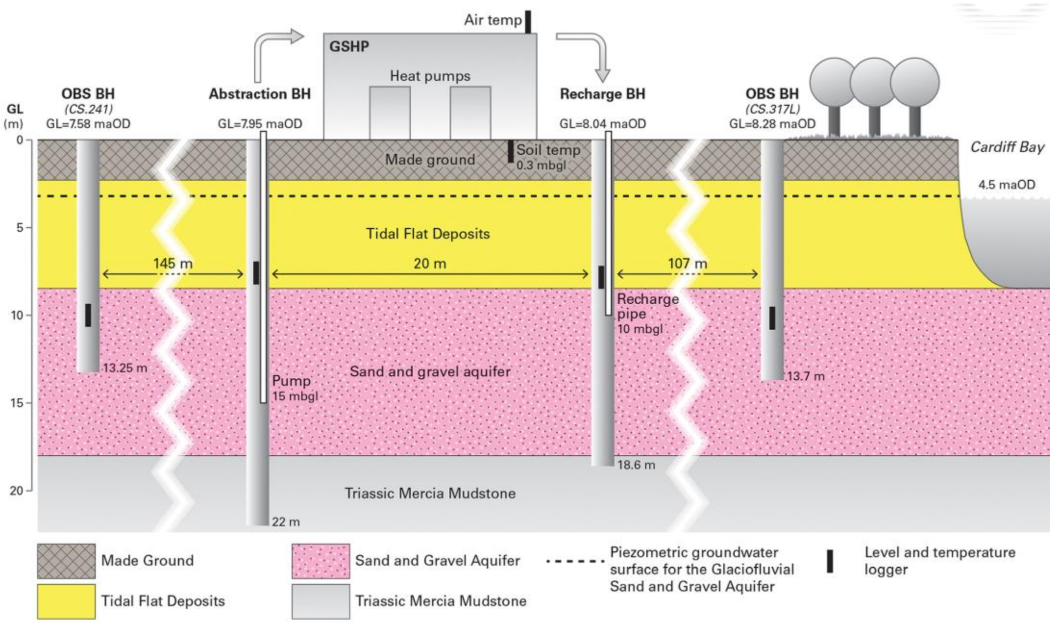


Figure 151 - Summary of the ground layers (Boon et al., 2019)

Table 43 and Table 44 provide further details on the ground source. The minimum and maximum heat exchanger fluid temperatures presented have come from monitored data rather than design conditions.

The water from the extraction borehole passes through a particulate water filter and then on to a single stainless steel plate heat exchanger. The heat is then transferred to an intermediary brine loop and the cooled groundwater is then rejected back to the reinjection well.

Table 43 - Summary of the ground source and sink

Ground source	X1 Well Doublet
Loop type	Open loop
Ground composition	See figure 150
Maximum Groundwater level [m]	~4 m
Annual mean air temperature (measured)	11.28°C
Undisturbed ground temperature	12.8°C (Ambient Ground water Temp)
Minimum ground heat exchanger exiting fluid temperature ($ExFT_{min}$)	4.73°C
Maximum ground heat exchanger exiting fluid temperature ($ExFT_{max}$)	31.15°C

Table 44 - Summary of the ground heat exchanger - Groundwater

Number of production wells	1
Number of injection wells	1
Well depth	22 m Production, 18.6m Injection
Distance between production and injection wells	20 m
Type of aquifer	Shallow superficial
Aquifer thickness	~-10m
Groundwater pumping rate, heating	0.93 l/s (Calculated)
Anti-fouling/scaling/corrosion measures	Intermediary brine loop & PHE to separate ground loop from heat pumps

A simplified schematic is shown in Figure 152 and Table 45 provide details on the main characteristics of the GSHP system.

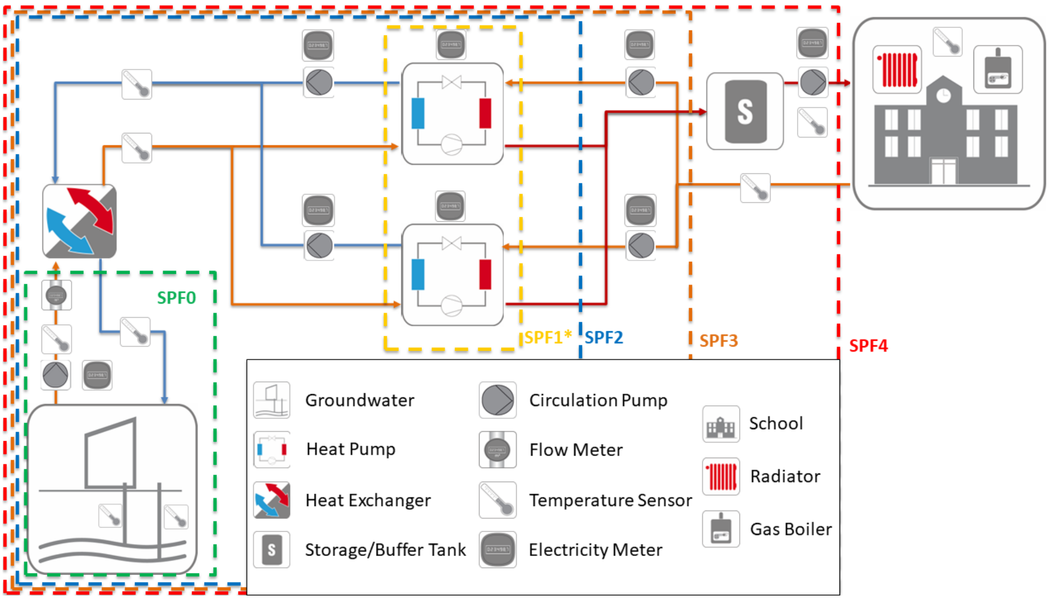


Figure 152 - Grangetown Nursery School System Schematic: Pictograms by TU Braunschweig IGS, used with permission within the course of IEA HPT Annex 52

Two Wilo Yonos Pico 25/1-8 pumps are used to circulate the brine from the plate heat exchanger to the two centralised heat pumps evaporators.

On the building side, another two Wilo Yonos Pico 25/1-8 pumps are used to circulate the heated water from the heat pumps to a Gledhill 210 litre buffer tank. Finally, one Wilo Yonos Maxo D 35/0.5-11 pump is used to circulate the fluid from the buffer tank to the buildings heating system.

Table 45 - Summary of the system configuration

Heat distribution	Pre-Existing Radiators
Heating load	32.5 MWh/year
Heat pump type	Water-to-Water
Reversible	No
Compressor type	Scroll
Speeds	Single Speed
Heat pump system	Centralized
Number of heat pumps	2
Nominal total heat pump heating capacity	22 kW_{th} (2x 11 kW)
Refrigerant	R134a

The heating load provided in Table 45 is the mean yearly delivered heat of the building over the monitoring period as opposed to the design loads as the yearly design load was not available.

5.1.4 Instrumentation & Monitoring

The flow and return fluid temperatures throughout the system have been monitored at a typical interval of 15 minutes since February 2016, with electricity data for the heat pumps and each of the circulation pumps also being recorded every 15 minutes, from April 2016. In November 2017, the data recoding interval was changed from every 15 minutes to every minute.

Table 46 details the relevant data sets available. Unfortunately, there is no information regarding which sensors were used for the data collection at this time and as such the information on calibration and uncertainties in these values is also unavailable.

Additionally, a heat meter was installed to record the total heat to the building and a flow meter to monitor the total flow from the extraction borehole, however both of these meters must be read manually, and this has not been achieved on a regular basis. As such there are only 10 values for the cumulative heat, and 11 values for the cumulative water abstraction over the monitoring period at irregular intervals. Similarly, the electricity used by the borehole submersible pump has only been recorded at manual intervals, providing 14 cumulative totals. All the manual readings available can be found in Table 47, with the red cells denoting no reading available.

Despite the system providing both space heating (SH) and domestic hot water (DHW) to the building, only the total heat to the building is provided by the available data. Therefore, it is not possible to investigate how the split of SH to DHW affects the performance of the system.

Additional parameters, beyond those reported in Table 46, were monitored for the system, but have not been included in this chapter as they are not pertinent to the analysis conducted at this point. These include parameters such as soil moisture at various depths.

The analysis of this data covers the period of February 2016 through to December 2017 and January 2019 through to December 2020. 2018 has been omitted from the analysis due to an inability to calculate the heat produced by the heat pumps, as discussed further in Section 5.3.1.4

Table 46 - Summary of the system monitoring

Measurement	Recorded Unit	Typical Interval	Comments
Brine Flow Temp	°C	15 min	
Brine Return Temp	°C	15 min	
Borehole Abstraction Temp	°C	15 min	
Borehole Return Temp	°C	15 min	
Building Flow Temp	°C	15 min	
Building Return Temp	°C	15 min	
Abstraction Well Water Temp	°C	15 min	
Rejection Well Water Temp	°C	15 min	
Outdoor Air Temp	°C	1 min	
Heat Pump Room Indoor Temp	°C	15 min	
Heat Pump 1 Power	W	1 min	
Heat Pump 1 Voltage	V	1 min	
Heat Pump 1 Current	A	1 min	
Heat Pump 2 Power	W	1 min	
Heat Pump 2 Voltage	V	1 min	
Heat Pump 2 Current	A	1 min	
Building to HP1 Circ Pump Power	W	1 min	
Building to HP1 Circ Pump Voltage	V	1 min	
Building to HP1 Circ Pump Current	A	1 min	
Building to HP2 Circ Pump Power	W	1 min	
Building to HP2 Circ Pump Voltage	V	1 min	
Building to HP2 Circ Pump Current	A	1 min	
Heat Exchanger to HP1 Circ Pump Power	W	1 min	
Heat Exchanger to HP1 Circ Pump Voltage	V	1 min	
Heat Exchanger to HP1 Circ Pump Current	A	1 min	
Heat Exchanger to HP2 Circ Pump Power	W	1 min	
Heat Exchanger to HP2 Circ Pump Voltage	V	1 min	
Heat Exchanger to HP2 Circ Pump Current	A	1 min	
Buffer Tank to Building Circ Pump Power	W	1 min	
Buffer Tank to Building Circ Pump Voltage	V	1 min	
Buffer Tank to Building Circ Pump Current	A	1 min	
Borehole Submersible Pump Power	W	-	Cumulative values manually read at irregular intervals
Heat to the Building	MWh	-	Cumulative values manually read at irregular intervals
Water Abstracted from the Borehole	m^3	-	Cumulative values manually read at irregular intervals
Water Level	m	1 min	Head of water above pressure sensor datum

Table 47 - Manual Readings

	Date	Groundwater abstracted (m3)	Heat generated (MWh)	Borehole pump (kWh)	Heat pump 1 (kWh)	Brine pump HP1 (kWh)	Heat pump return 1 (kWh)	Heat pump 2 (kWh)	Heat pump return 2 (kWh)	Brine pump HP2 (kWh)	Main circ pump (kWh)
2016	28-Apr			939	1953	45	75				326
	05-May			978	2110	50	111				341
	04-Oct	9638	31	1049	2291	56	162	1993	133	50	367
2017	02-Mar	17950	38.4	2271	7107	174	372	5547			872
	11-Jul			2868	9157			6379			
	09-Aug	21994	97.48	2889	9193		513	6415	415		
	14-Sep	22238		2927							
2018	13-Mar	30099	129	4085	10686		760	12082	628		1454
	16-Apr	31148	135	4339	10990		805	13135	683		
	30-Oct	36430	157.5	4988	13987	385	1058	13205	743		1788
2019	17-Jan	40309.65	181.65	5587.82	17270	468.19	1195.76	13434.93			2140.3
	27-Mar	43571.44	201.508	6066.97	19806.04			13440.24	865.99		
	30-Jul	44322.38	206.506	6177.81	20374.55			13440.24			
	05-Sep	44322.38	206.506	6177.81	20374.55			13440.24			
	29-Oct	44919.03	211.304	6273.51	20857.07		1377.75	13476.44	898.17		
2021	28-Oct	55076.7	301.093	7870.49				13820	908		

5.1.5 Previous Analysis & Reporting

A number of aspects for this system have already been investigated and reported (Boon *et al.*, 2019). The analysis and conclusions, along with remaining knowledge gaps are summarised below.

The focus of the original paper is how the heat pump system affects the aquifer over the first three years of operation alongside numerical modelling of groundwater flow and heat transport. As such the primary analysis in the paper focuses on the temperatures within the aquifer and abstraction and rejection wells and how they respond to heat pump operation. The heat pump system itself was only briefly investigated. Firstly, to rationalise an unexpected lack of aquifer thermal rejuvenation in the summer months of 2018 the heat pump energy usage was interrogated, noting that the flow temperature set point had been increased, and the heat pumps left on over the summer unnecessarily. Secondly, the system SPF at SEPEMO boundary four was reported to be 4.5 for the whole monitoring period and the total heat extracted from the aquifer for a one-year period between March 2017 and 2018 (77MWh) was reported. Finally, it was concluded that thermal interference was occurring between the abstraction and reinjection wells, causing a loss in efficiency, and it was noted that continuous high-resolution monitoring of such systems is required to manage their development.

Through conducting the analysis detailed in this chapter, a number of inaccuracies were found in the specification of the system in Boon *et al.* (2019). These have been detailed in Table 48.

The analysis that has been conducted in this thesis will look to build on this original research, with a greater focus on understanding the operation and performance of the heat pump system itself.

Table 48 - Inaccuracies in Original Reporting

Inaccuracy	**Originally Reported in Boon et al (2019)**	**Correction**
Borehole pump	Nastec 4H 06/02	WPS 07/03
Borehole pump abstraction rate	Up to 35m^3/day (0.42l/s)	- Pump capable of 5 l/s - Estimated abstraction rate 0.93 l/s (Section 5.3.2)
Buffer tank	100 litre (Dimplex PSP100E)	210 litre (Gledhill Stainless Lite)
Main circulation pump	Wilo Yonos Maxo 25/05-12	Wilo Yonos Maxo D 32/05-11

5.2 Data Processing & Cleaning

Whilst there are a number of datasets for this system, typically producing high frequency readings, there are also a number of data challenges present, making analysis difficult.

Specifically, there are a number of desirable data sets that either are not available at all or are limited to a number of sporadic manual readings. For example, the heat meter only has manual readings, which means that it is difficult to know how the heat output is affected by the weather or time of year, or even how much heat is being produced on small, regular timescales. Similarly, there are no measurements at all for flow rates for the groundwater, brine, or water in the building side loop to aid in calculating heat transfer. As well as data sets, there are also a number of system parameters that are not readily available that would aid the analysis, such as the set point temperatures, design loads, pump head set points etc.

In addition, there a number of gaps in many of the datasets, making it difficult to build a clear picture and calculate accurate annual values for heat provided or other such metrics. This also makes it difficult to validate any attempts to distribute the values between any manual readings as there is often incomplete data between the two readings.

The following section details the methods applied to overcome some of these data limitations to allow for a more detailed understanding of the system.

5.3 Data Analysis & KPIs

The performance factors are a key performance indicator for any heat pump system. In order to calculate the performance factors, reliable data on the energy used by the heat pump and heat produced is required.

Similarly, the energy exchanged with the ground is of great importance for a GSHP system. This would require either data from a heat meter or data from a combination of a flow meter and temperature sensors.

Unfortunately, this data is not readily available at small timescales from the monitoring conducted, with only the manual readings shown in Table 47 being recorded.

The following Sections 5.3.1 to 5.3.3, detail the methods developed for calculating these parameters from the available datasets

Section 5.3.1 shows how the manual heat meter readings have been backfilled by calculating the flow rate through the building loop.

Sections 5.3.2 and 5.3.3 describe how the heat extracted from the ground is determined, by calculating the flow rate through the borehole, using the borehole head as a proxy for when the circulation pump is turned on.

5.3.1 Calculating Heat Delivered to the Building

The infrequent heat meter readings means that the determination of the performance factors of the heat pumps is difficult, instead only allowing calculations over long, irregular time periods. However, as shown in Table 46, a number of other parameters were recorded at regular, smaller time intervals for most of the monitoring period. This included the fluid temperature to and from the building.

Therefore, if the flow rate of heated water to the building could be determined then the heat could be calculated using the equation (31), where Q is the heat in kWh, $\dot{m}$ is the mass flow rate of the fluid in kg/s, c is the specific heat capacity in kJ/kg.K, and ΔT is the difference between the flow and return temperatures in °C or °K.

$$Q = \dot{m}c\Delta T \tag{31}$$

The power to the building side circulation pump was also monitored continuously. Utilising the manufacturer's data for the circulation pump, shown in Figure 153, the power to this pump was used to calculate the flow rate.

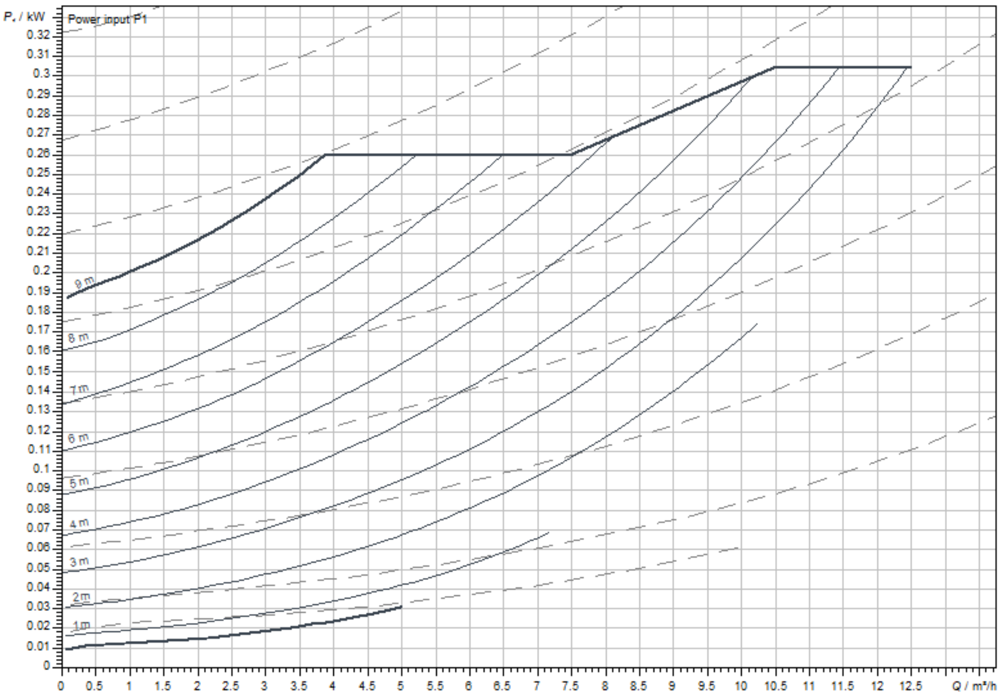


Figure 153 - Wilo Yonos Maxo D 32/05-11 Power to Flow Curves (Wilo, 2022)

However, as a site visit was not possible due to COVID, a number of key parameters of the system were unknown at the time of analysis, namely the head set point and the operating mode of the circulation pump. Figure 150 shows the main circulation pump and indicates the pump is set up in 'Constant Differential Pressure Mode', so this has been assumed for the remainder of the analysis. Each of the head set points in the assumed operating mode of the pump, shown in Figure 153, were then modelled, producing flow rates which when combined with the temperature data produced continuous data on the heat from the heat pumps. This was compared to the available manual heat measurements recorded from the heat meter on site. The head set point that most closely aligned with the measured data was then selected.

Upon interrogating the available data, it became clear that due to component malfunctions and unknown control strategies, analysis of the heat pumps would not be possible for 2018. This is explained in greater detail throughout the chapter, however this meant that any assumptions and models applied to back fill data would have to be validated for both the period from 2016-2018 and from 2019 onwards as it is not possible to assume the consistent operation and control strategies through this period.

Once chosen and validated, these parameters were assumed constant for the remainder of the analysis, unless otherwise explicitly stated. The detailed process of this parameter selection is included below.

1) Assume operating mode of circulation pump is constant differential pressure, as highlighted above
2) Read the power curve for each head set point and convert the curves into a series of linear equations.
3) Apply each set of equations to the power data provided, calculating the flow rate to the building.
4) Use the calculated flow rate along with the recorded temperatures to calculate the heat to the building, as per Equation (31)
5) Sum the calculated heat between each manual reading of the heat meter and compare the value against the manual reading.
6) Repeat steps 2-5 for each head set point.

The equations and results associated to each circulating pump head set point that has been investigated have been referred to as “head set point models” or simply “models” throughout the following analysis.

5.3.1.1 Known Main Circulation Pump Issues

The approach described in 5.3.1 relies on the main circulation pump as the primary source of data, therefore it is useful to set out known issues with this pump (D Boon 2021, personal communication, 31st March 2021).

- December 2017 – Main circulation pump malfunctioned.
- December 2017 – Main circulation pump replaced.
    - High running temperatures after pump replaced.
- Early 2018 – engineer visit & settings adjusted.
- Spring 2019 – system controls adjusted.

Unfortunately, no dates for these visits or details on the adjustments are available, so assumptions are made based on what the available data shows. These assumptions will be clearly indicated when made during the analysis.

5.3.1.2 Head Set Point Selection - Post 2018

The large gaps in power data for the primary circulation pump, as shown in Figure 154, makes it difficult to validate the approach in 5.3.1 as without continuous data between any two manual heat meter readings, the calculated heat would not necessarily align with the recorded value.

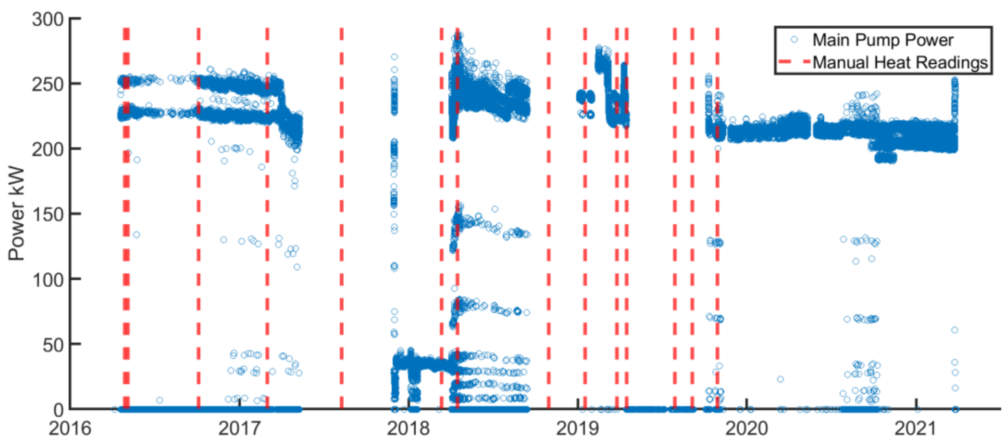


Figure 154 - Main Circulation Pump Power over Whole Monitoring Period

The period between the 27th of March and the 17th of April 2019 was used as the validation period as it has 93% of the circulation pump power data available. Only one period contained more continuous data, from March to April 2018, however the system is not operating correctly during this period. This is demonstrated in Section 5.3.1.4.

Figure 155 shows the data for the validation period chosen.

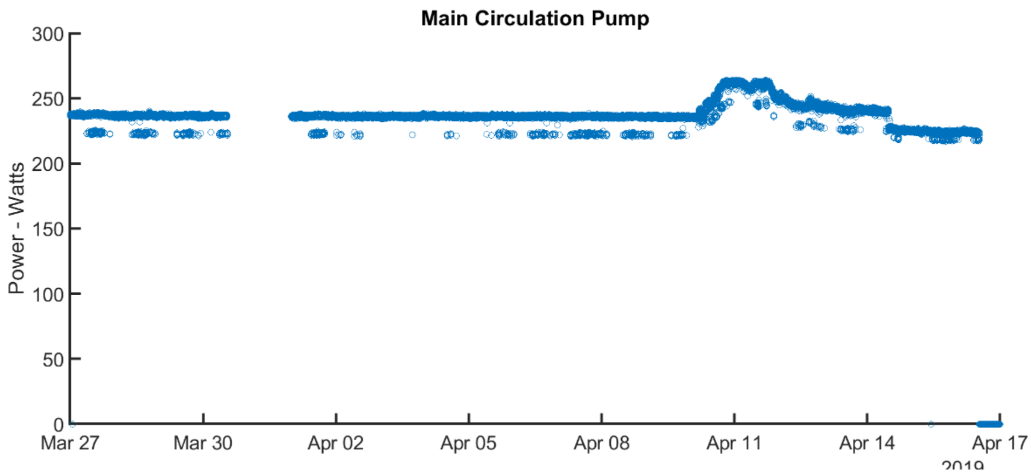


Figure 155 - Main Circulation Pump Power During Validation Period

This shows a predictable, almost constant, usage pattern indicating that the pump was likely in operation during the period of missing data, with the pump only turning off right at the end of this period.

Figure 156 shows the difference between the heat delivered to the building calculated using the approach in Section 5.3.1 at different pump head set points, and the value recorded at a manual reading for the same period.

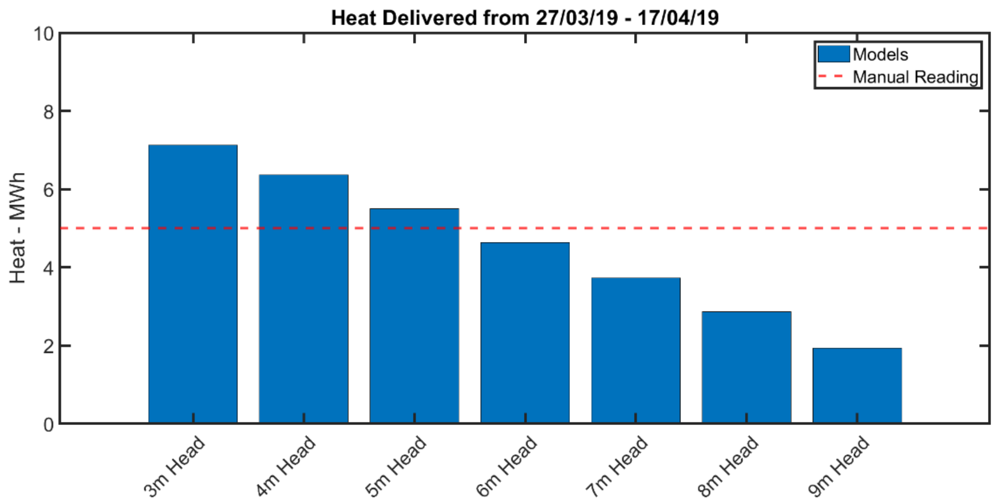


Figure 156 - Heat Delivered – Head Set Point Models vs Measured

From Figure 156 it can be seen that the 5m and 6m head set points for the constant differential pressure operating mode of the circulation pump most closely matches the recorded heat measurement of 5.002MWh for the validation period. As Figure 155 shows, it is likely that the pump is operating for the 7% of the time for which there is no data, and as such it is expected that the model would underpredict the recorded heat by approximately 7%. Therefore, the 6m head set point is the most appropriate model to be used.

However, given the aforementioned limitations of the power data set, and therefore inability to validate against the other heat measurement points, additional analysis centred around heating degree days was conducted. This was to ensure that the chosen model was still the most appropriate at smaller timescales.

5.3.1.3 Head Set Point Validation - Heating Degree Day Analysis

This analysis uses heating degree days (HDD) to correlate the outdoor air temperature to the expected amount of heat delivery to the building. As a result, it is independent of the main circulation pump power used to calculate the heat in the previous method and therefore free of the limitations associated with that dataset.

As discussed in Section 5.2, the outdoor air temperature was one of many datasets recorded by the remote monitoring system had some large data gaps present. These gaps have been backfilled using data from a local weather station, located approximately 2 miles away from the station (CEDA, 2020)

A more detailed explanation of heating degree days can be found in Appendix C1. However, it is worth noting that for this analysis a base temperature is required. This is the outdoor air temperature below which heating is required for the building. As this is not known for this building, it was calculated through regression analysis through the method detailed below:

1) Set the base temperature = 15.5
2) Calculate the HDD from the outdoor air temperature at minutely intervals.
3) Sum the HDD for each time interval between 2 heat meter readings, excluding days where it is known that heat is not being provided e.g. April-October 2019 (Figure 157)
4) Divide the cumulative HDD by the number of days in the time period, again excluding days where it is known that heat is not being provided, to give HDD per day for each time interval

5) Divide the measured heat delivered in that time period, provided by the manual readings, by the number of days to give MWh per day for each time interval
6) Perform a weighted regression analysis to correlate the input (HDD per day) to the output (MWh per day) using the number of days in each period as the weighting factor
7) Record the intercept, R^2, and RMSE values for the regression
8) Repeat steps 1-7 for base temperatures increasing in half-degree increments from 15.5°C to 23°C

For step 5 of this process, the number of days the heating system was operational is required. Figure 157 plots the power data available for the main circulation pump over the monitoring period, to highlight any periods where the heat pumps were turned off.

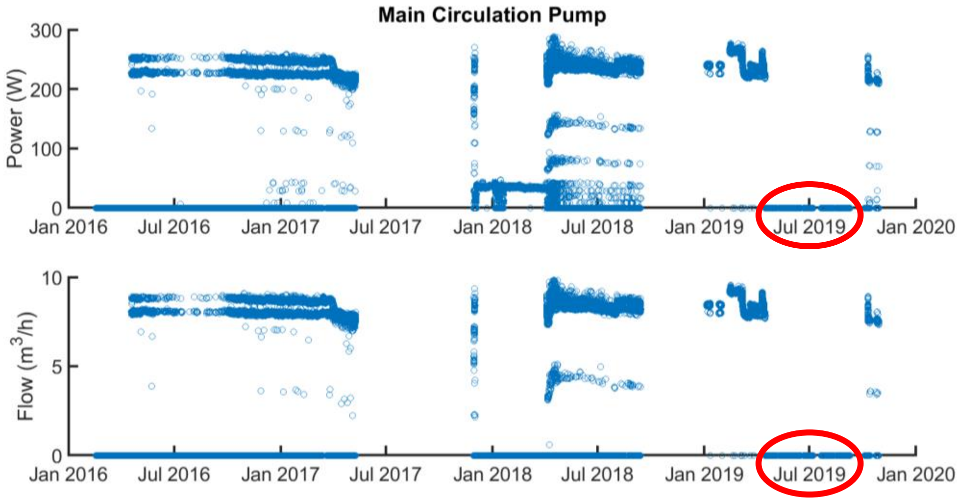


Figure 157 - Main Circulation Pump Power and Flow

In some cases, such as April to October 2019, it is clear that no heat is being delivered to the building from the heat pumps, as the main circulation pump is turned off, as shown by the ringed sections in the figure. If the control system is working correctly, this will mean that the heat pumps are also turned off. In this instance, a large portion of the time the heat pumps are turned off coincides with the school holidays whilst the building is unoccupied. However, the lack of continuous power data for the main circulation pump in a number of these time intervals mean it is often impossible to know whether heat is being delivered on these days. This means a decision must be made as to whether or not to include these days, and associated HDD, in this regression analysis or not. Unfortunately, these periods cannot simply be removed as it is unknown how long, if at all, no heat is being delivered in each period and thus the number of days and HDD cannot be adjusted accordingly. As such the options are to assume that heat is being delivered correctly during these periods, and include them in the regression, or conclude that there is not enough information to assume correct operation and exclude these points from the regression.

The inclusion/exclusion justification for each period can be found in Table 49

Table 49 - Manual Reading Periods - HDD Regression Inclusion and Exclusion

Period #	Start of Period	End of Period	Included? (Y/N)	Justification
1	17/02/2016	28/04/2016	N	No heat measurements
2	28/04/2016	05/05/2016	N	No heat measurements
3	05/05/2016	04/10/2016	N	First heat measurement 04/10/2016 - baseline
4	04/10/2016	09/08/2017	Y	2nd March heat reading removed as too small to be credible
5	09/08/2017	13/03/2018	N	Main circ pump broken – no heat delivered – no temperature data either
6	13/03/2018	16/04/2018	N	No missing data BUT Main Circ Pump not delivering flow
7	16/04/2018	30/10/2018	Y	Only missing small period of data towards end of period
8	30/10/2018	17/01/2019	Y	Temperatures indicate HP still running
9	17/01/2019	27/03/2019	Y	<25% data missing & indication of continual usage

10	27/03/2019	17/04/2019	Y	<25% data missing & indication of continual usage
11	17/04/2019	30/07/2019	N	No heat being delivered
12	30/07/2019	05/09/2019	N	No heat being delivered
13	05/09/2019	29/10/2019	Y	Most of missing data when HPs off – temperatures indicate consistent use during gap in data when HPs on

The results of a sample of the regression calculations can be seen in Table 50. For brevity, not all of the base temperature iterations have been included.

Table 50 - HDD Regression Results for Different Base Temperatures

Base Temperature	**Intercept**	**R^2**	**RMSE**
15.5	0.0600	0.9422	0.2085
17.5	0.0369	0.9514	0.1911
19	0.0148	0.9539	0.1863
19.5	0.0066	0.9543	0.1854
20	-0.0020	0.9546	0.1847
21.5	-0.0296	0.9553	0.1833

From Table 50 it can be seen that base temperatures above 19.5°C are not suitable as the regression intercept becomes negative. This indicates that at zero heating degree days i.e. at the base temperature, there will be a need for cooling. This is not the case in this system as it is a heating only system. Thus, the most appropriate base temperature is 19.5°C, as this provides the highest R^2 value and the lowest RMSE for the regression whilst having a positive intercept as close to zero as possible.

This means that at an outdoor temperature below 19.5°C, it is expected that the heat pump system will be operational to provide space heating to the nursery. Given that a 3.5-degree rise is typically applied (EnergyLens, no date) to such analysis to account for internal gains of people and machines within a building, this analysis suggests that the internal thermostat is set to around 23°C for this nursery. This initially seems a little high but is within the realms of possibility, given that the 3.5°C addition is an estimate and may be affected by insulation levels, movement within the building, amount of IT equipment etc.

With the base temperature selected, the HDD analysis was rerun. This time however, regression analysis was not used, and instead each time interval was modelled separately, with a simple linear regression and an intercept of 0. The reason for this was two-fold: Firstly, an intercept of zero more closely aligns with what is expected from the building which has no active cooling, i.e., above the base temperature no heating is assumed, and below the base temperature heating is assumed, thus the intercept should be at zero. Secondly, the HDD analysis is being used to validate the circulation pump head set point model. This is only comparable to the measured heat data for one time interval due to the circulation pump data quality, and thus using a simple regression for this period would be more accurate than using a more complex regression that includes other periods for which less circulation pump data is available and thus system behaviour is less well known.

Using a base temperature of 19.5°C there was a cumulative HDD of 227.2 between 27th March 2019 and 17th April 2019. Thus, the multiplication factor would be calculated as in Equations (32) to (34).

$$HDD\ per\ day = \frac{227.2}{20.55} = 11.0585 \quad (32)$$

$$MWh\ per\ day = \frac{5.002}{20.55} = 0.2435 \quad (33)$$

$$\frac{MWh\ Per\ Day}{HDD\ Per\ Day} = \frac{0.2435}{11.0585} = 0.022 \quad (34)$$

This multiplication factor can now be applied to the daily data within that time period to determine the estimated heat produced at a smaller timescale, based on the outdoor temperature. This provides a useful measure to validate the output of models that convert the circulation pump power to the flow rate.

Figure 158 shows this estimated heat for the period in question, based on the HDD analysis, alongside heat predicted by the models based on the circulation pump at 3 head set points.

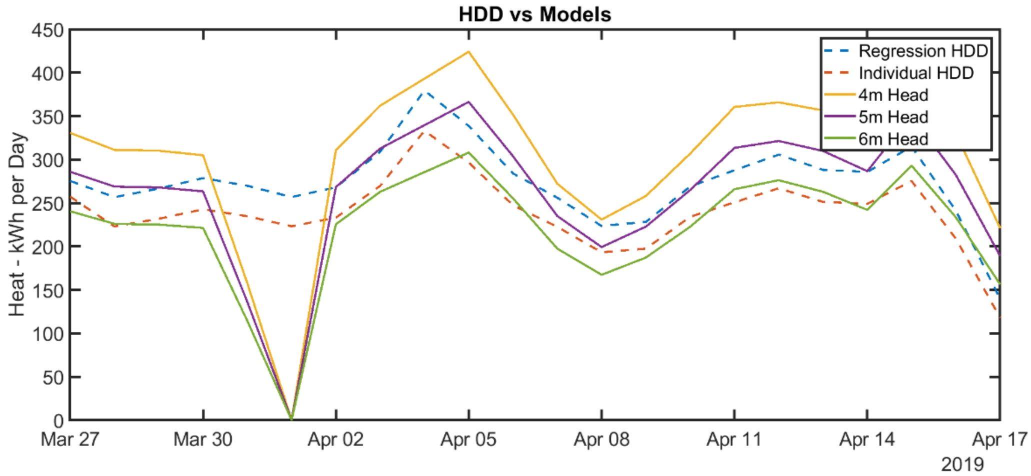


Figure 158 - HDD Models vs Heat Calculations for Validation Period

Calculating the RMSE between the daily output of heat from the differing flow models and the HDD estimate provides a measure by which to select the most appropriate model. Naturally, when calculating the RMSE, the days for which there are no pump power data are discounted to avoid the skewing seen in Figure 158.

A summary of results to determine the most appropriate model can be seen in Table 51. As the period being analysed is missing ~1.5 days of circulation pump data, the model cannot simply be compared to the manual reading. Instead, it will be compared to the manual reading minus the estimated heat load for these 1.5 days as estimated by the HDD analysis. The days in question are 30th March 2019 13:08 to 31st March 2019 23:59, a total of 13.4868 HDD. This, multiplied by the slope determined to be 0.022, gives the estimated load for this period in MWh.

This is shown in Equation (35).

$$\begin{aligned}&Heat\ Load\ for\ Available\ Data =\\&Heat\ load\ for\ whole\ period\ (manual\ reading)\ -\\&Estimated\ heat\ load\ for\ missing\ data\ during\ period\ (HDD\ analysis)\end{aligned}$$

$$= 5.002MWh - (13.4868 * 0.022)$$

$$= 5.002MWh - 0.297MWh$$

$$= 4.705MWh \quad (35)$$

Alongside this measure, Table 51 shows the RMSE for that model compared to the estimated daily heat from the HDD analysis.

Table 51 - Model vs HDD Analysis for Validation Period

Model	Head Set Point	Value for 27/03/2019 – 17/04/2019 (% diff)	Daily RMSE vs HDD for same period
Success Criteria		Closest to Manual Reading of 4.705	Smallest RMSE
1	4m	6.363 **(+35.2%)**	87.5 kWh
2	5m	5.5 **(+16.9%)**	43.2 kWh
3	6m	4.627 **(-1.7%)**	1.62 kWh

From this it is clear that not only does the 6m head set point model most closely match the measured heat value for the whole period, but it also produces heat values that most closely match the HDD estimated heat on smaller timescales. As such this model will be taken forward in the analysis of the system post 2018.

5.3.1.4 Model Selection - 2018

As previously noted in Section 5.3.1.1, the main circulation pump malfunctioned in December 2017 and was replaced. The power data for this pump suggests this malfunction occurred on the 25th of December, following which the pump was drawing minimal power, roughly 35W, until April 4th, 2018. This is shown in Figure 159. This power draw is not high enough to control the flow rate through the pump at the head set point found to be applicable in Section 5.3.1.2. This means that either no heat is being delivered to the building for this period, or that the heat pump return pumps are controlling the flow through the building loop.

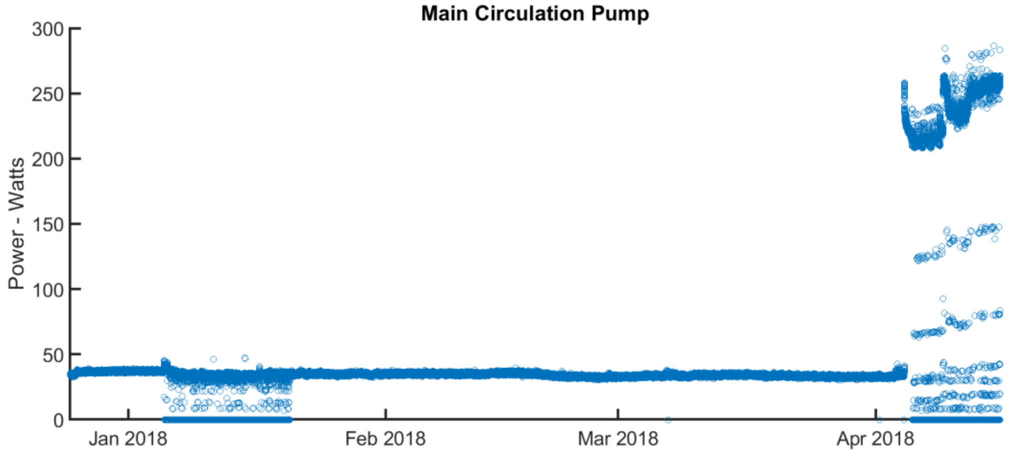


Figure 159 - Period of Main Circulation Pump Malfunction

Figure 160 shows a comparison of the HDD regression against the various head set points for this period up until the next manual reading in October 2018.

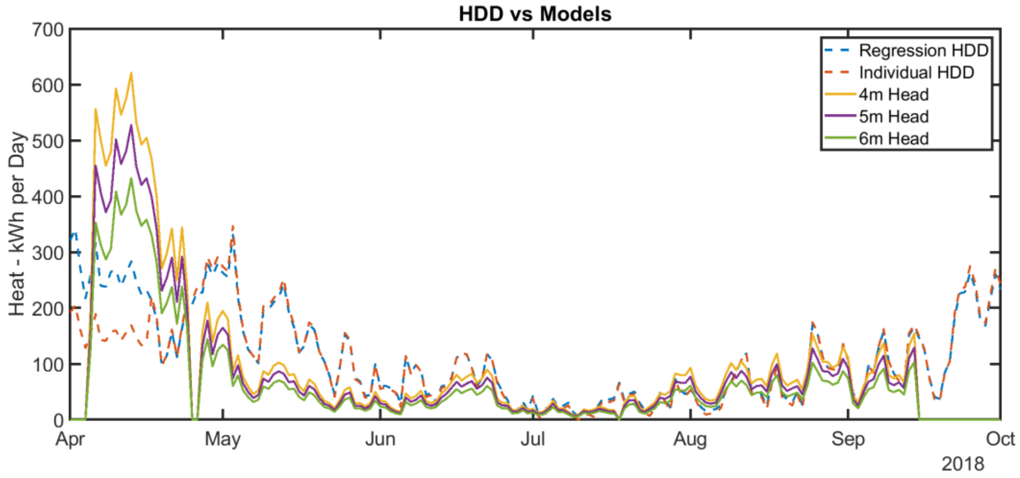


Figure 160 - Comparison of HDD vs Different Head Set Point Models

The settings appear to have been adjusted to induce flow again from the 4th of April, however none of the head set points for the main circulation pump align with the expected heat output as predicted by the heating degree day analysis. This suggests that the controls may have been adjusted multiple times. However, due to the inability to determine the flow rate in early April and the missing circulation pump energy data in September and October, the appropriate model cannot be selected by comparison with the manual readings either.

As such, for the data available in 2018, no model is applied to convert the power into flow rate and therefore no heat data is available for 2018 except that provided by the manual readings.

5.3.1.5 Model Selection - Pre 2018

Given the settings for the replacement pump installed in December 2017 cannot be determined, as per Section 5.3.1.4, it cannot simply be assumed that the original pump settings were the same as those determined for the period in 2019. As such, similarly to Section 5.3.1.2, the pump models need to be compared to the manual readings and validated against the HDD analysis to determine the most likely head point setting, prior to the pump failure. As the majority of the data available for this period, up until November 2017, was recorded at intervals of 15 minutes rather than minutely, this required interpolation.

5.3.1.5.1 Backfilling 15-minutely data

To accurately report the heat and performance factors across the whole monitoring period the value of each reading was assumed constant for the previous 15 minutes. This method of interpolation was chosen as it would better represent the actual operation of the pumps, quickly ramping up to full power and maintaining this level before quickly ramping down again, rather than applying a linear interpolation which would show the pump ramping up to full power over 15 minutes. Figure 161 shows the comparison of the manual readings for the energy used by the three pumps, to the summed data before it is backfilled. Figure 162 shows the same comparison after the data has been backfilled.

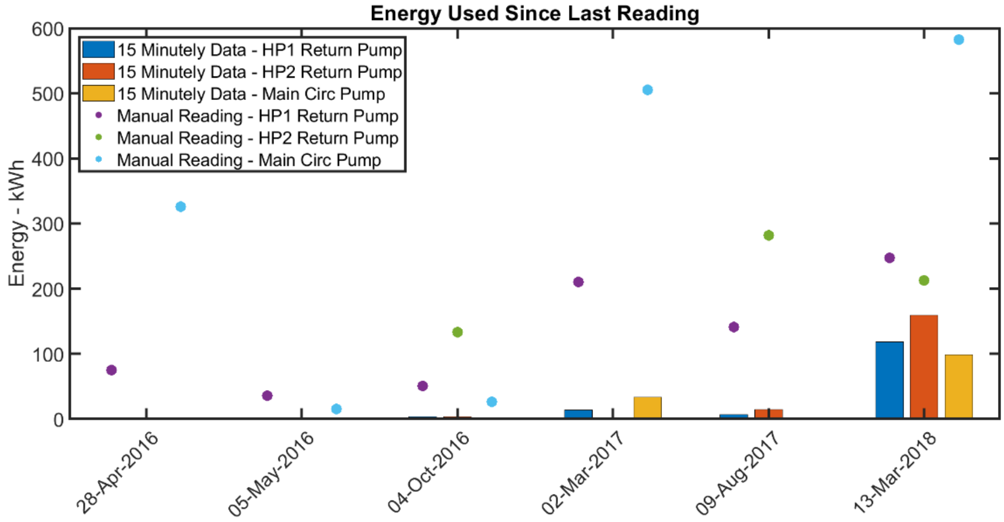


Figure 161 - Circulation Pump Energy Usage - Continuous vs Manual Readings Pre-Backfill

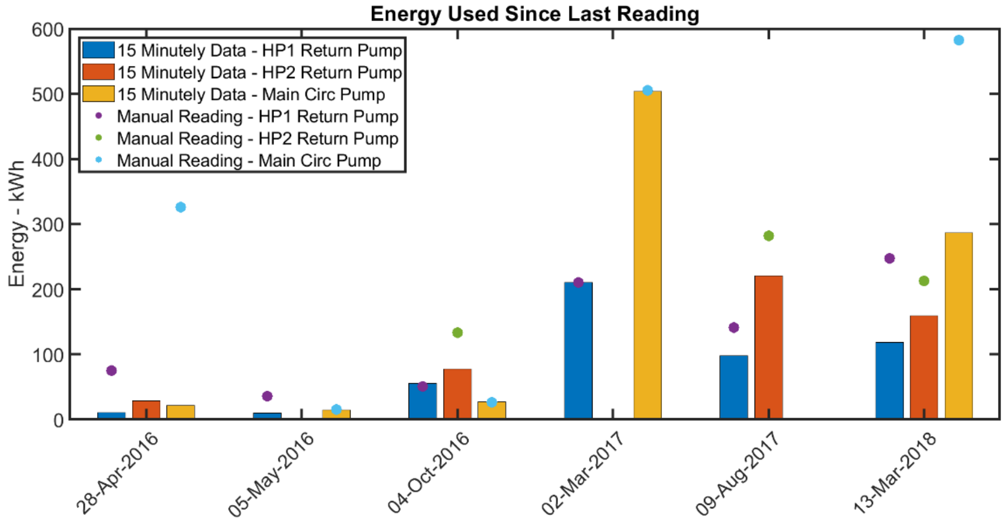


Figure 162 - Circulation Pump Energy Usage - Continuous vs Manual Readings Post-Backfill

The missing data during each period means that the interpolated data does not match with the manually recorded energy readings exactly for each time period, however Figure 162 shows this approach to provide suitable estimates. This allows the flow rate, and thus heat delivered to the building, to be calculated over each period. This heat can then be compared against the manually recorded heat at these intervals as an additional validation of the approach, as in Figure 163.

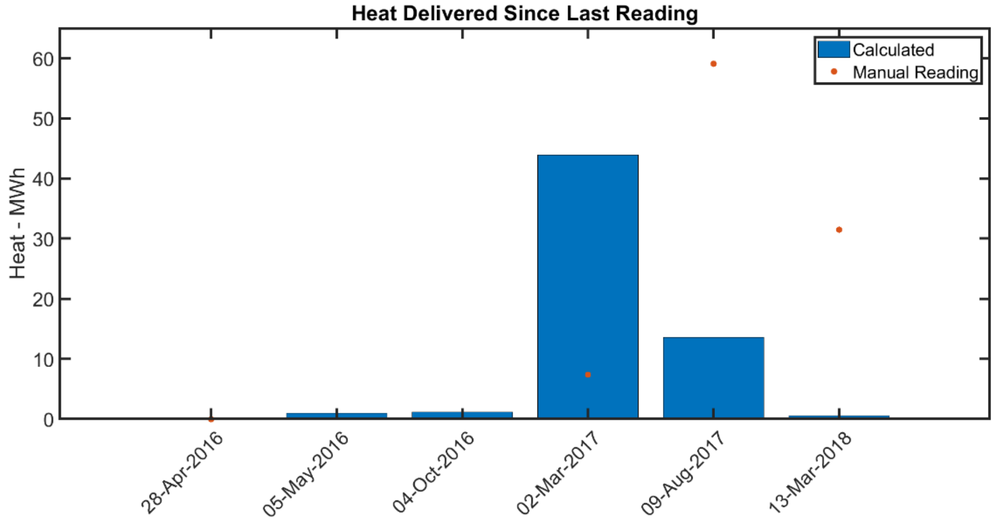


Figure 163 - Comparison of Calculated Heat and Manual Readings

The calculated and manually recorded heat values do not align completely. In particular the two periods from October 4th, 2016, to March 2nd, 2017, and from March 2nd to August 9th, 2017 show significant differences, warranting additional investigation.

The manually recorded values suggests that 7 MWh was delivered over a 5-month period spanning the winter months between October 2016 and March 2017. This value seems small when compared with similar periods in 2017-18 (31.52 MWh) and 2018-19 (44.01 MWh). Similarly, the recorded values also suggest that over the following 5-month period through spring and summer, ~60 MWh was used, which seems excessive. Figure 164 shows the main circulation pump power over these periods, along with the flow and heat as calculated by the model applied.

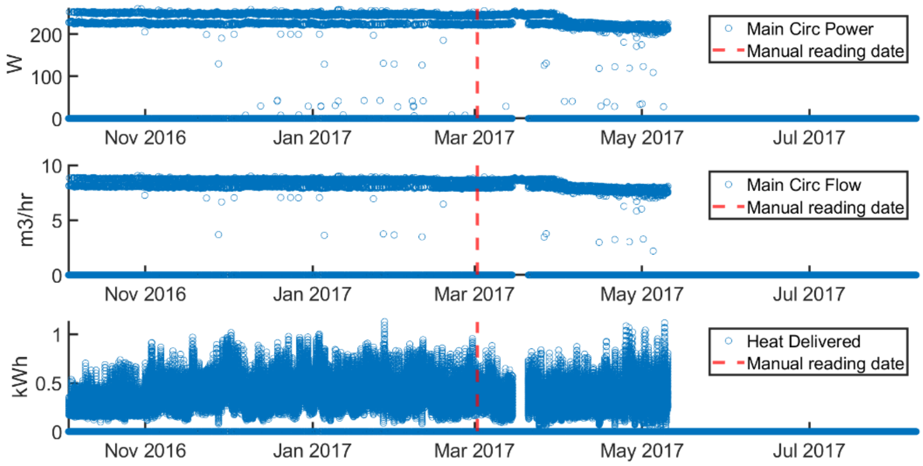


Figure 164 - Main Circulation Pump Power, Flow Rate, and Heat Calculated for Period of Inconsistency Between Calculations and Manual Readings

As expected, Figure 164 indicates a much higher heating load over the period spanning the heating season compared to the summer period, further refuting the manual readings provided. If the March 2nd manual reading is omitted, leaving a comparison of model and manual readings between the 4th of October 2016 and 2nd of March 2017, the values align much more closely as shown in Figure 165.

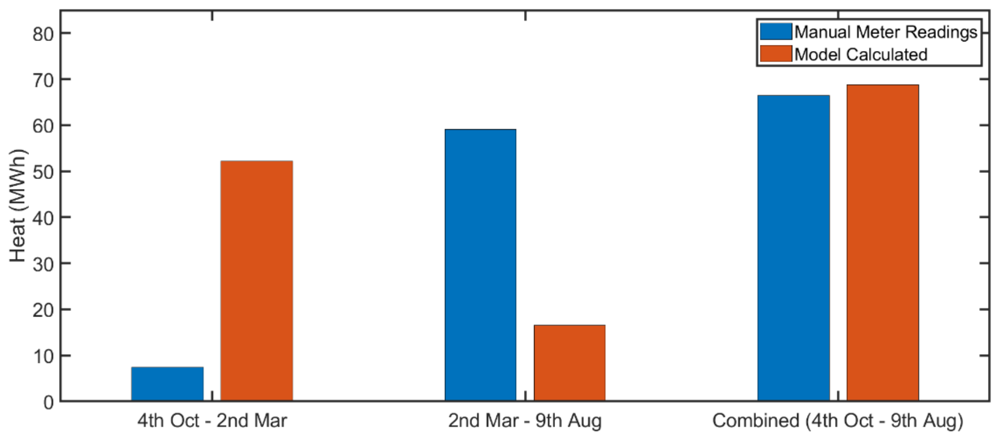


Figure 165 - Calculated Heat vs Manual Readings October 2016 to August 2017

This further supports the conclusion that the 2nd of March reading was likely mis-recorded and so the value for heat delivered as reported on the 2nd of March 2017 is deemed to be erroneous.

Ignoring the erroneous reading, the remaining manual readings all provide values of heat greater than those predicted by the model, which is to be expected given the levels of data availability for the main circulation pump. This suggests that the interpolation method applied to the 15-minutely data is valid.

5.3.1.5.2 Model Selection and Validation

With the exclusion of the erroneous heat meter reading, the period from the 4th of October 2016 to the 9th of August 2017 can be compared against the different pump head set point models to determine the most appropriate for the period before the pump malfunction. This is demonstrated in Figure 166.

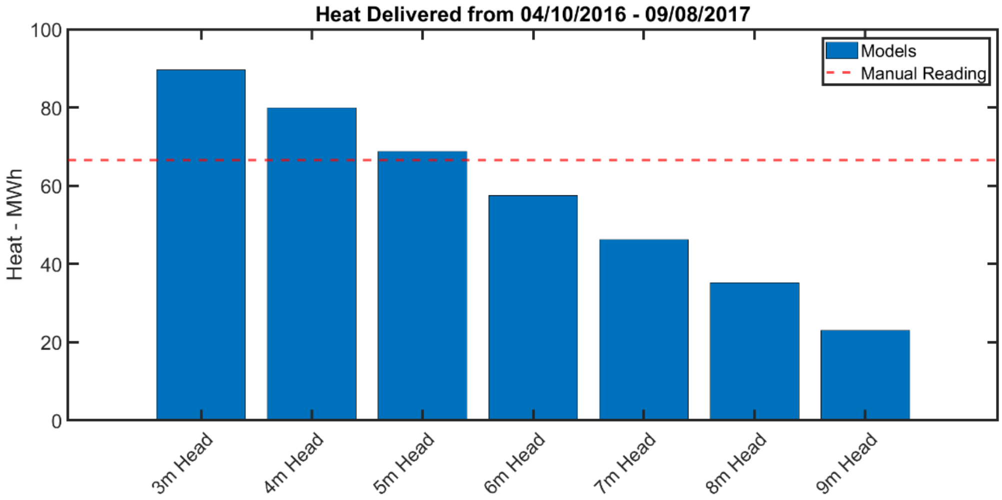


Figure 166 - Calculated Heat Vs Manual Readings Post Removal of Erroneous Reading

Whilst the 5m head model provides the closest total heat to the manual reading, data for the main circulation pump power is not available for ~29 % of the validation period. Consequently, it is expected that the appropriate model will undershoot the target value, though it is unclear by how much due to the large portion of data missing. This adds extra significance to the validation against the HDD for this period which is shown in Figure 167 up until the data is no longer available: the 12th of May 2017.

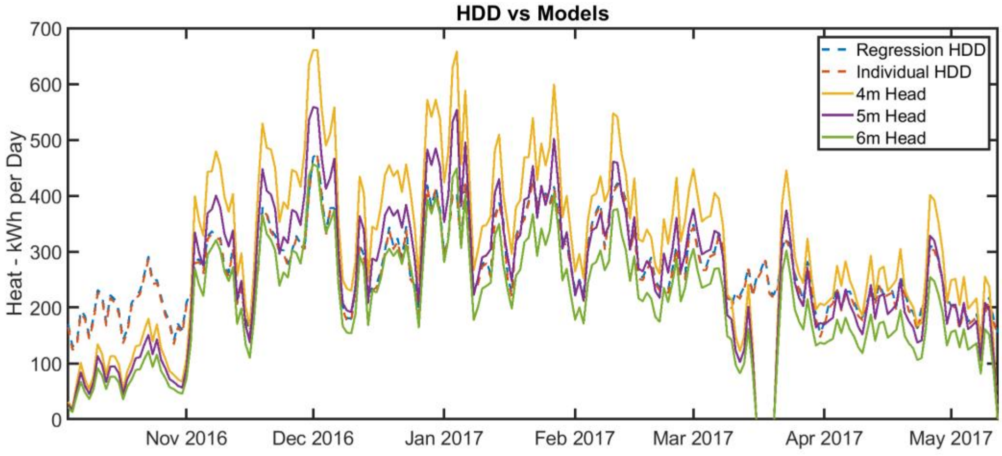


Figure 167 - HDD Heat vs Calculated Heat for Period Spanning the Erroneous Manual Reading

Table 52 shows the RMSE for various models against the individual HDD analysis for this period, once again ignoring the days during which data is not available.

Table 52 - HDD vs Calculated Heat Post Removal of Erroneous Manual Reading

Model	**Head Set Point**	**Value for 04/10/2016 – 09/08/2017 (% diff)**	**Daily RMSE vs HDD for same period**
Success Criteria		Closest to Manual Reading of 66.48	Smallest RMSE
1	5m	68.75**(+3.4%)**	46.01 kWh
2	6m	57.5 **(-13.5%)**	5.07 kWh
3	7m	46.16 **(-30.57%)**	56.58 kWh

The RMSE suggests that the 6m head set point model is the most appropriate for the initial pump settings, as it was for the replacement pump from 2019 onwards. It is also conceivable that the missing 29% of data in this instance only accounts for 13.5% of the total heat, as the missing data occurs from 12th of May to the 9th of August, spanning the warmest months with the lowest heat demand.

As such, the model with the head setpoint of 6m is applied to the data up to the point of the main circulation pump breakdown. It is worth noting that this is the same set point that was validated for the period from 2019 onwards in Section 5.3.1.2.

5.3.2 Calculating Groundwater Abstraction Flow Rates

To investigate the behaviour of the groundwater source as part of the heat pump system, the heat extracted from the aquifer is required. As can be seen in Table 47, manual measurements for the volume of water abstracted were taken at irregular time intervals. The electrical energy used by the borehole pump was also manually recorded at these times.

As the pump used is a constant flow submersible pump, with no variable frequency drive it can be assumed that for a given system head, the flow rate produced would be the same.

The total dynamic head for a system is a combination of the static head, the friction loss in the system, and the velocity head. Of these variables, the friction loss should be essentially constant for a constant flow rate as the pipes and route for the flow is unchanging. The only potential exception to this could be friction losses due to the filter clogging, however as no information has been provided on this, it is initially assumed that the filter does not affect the flow over the monitoring period. Therefore, the water level in the abstraction borehole is the only variable that should affect the system head for the pump to overcome.

Figure 168 shows the water level measurements available from the OTT Pressure Level Sensor. It was intended that these measurements would provide the depth of the groundwater from the ground datum, however the sensor was never calibrated and thus the data shows the uncalibrated head from the water above the sensor datum. Despite this, the change in the water level can still be discerned from the available data.

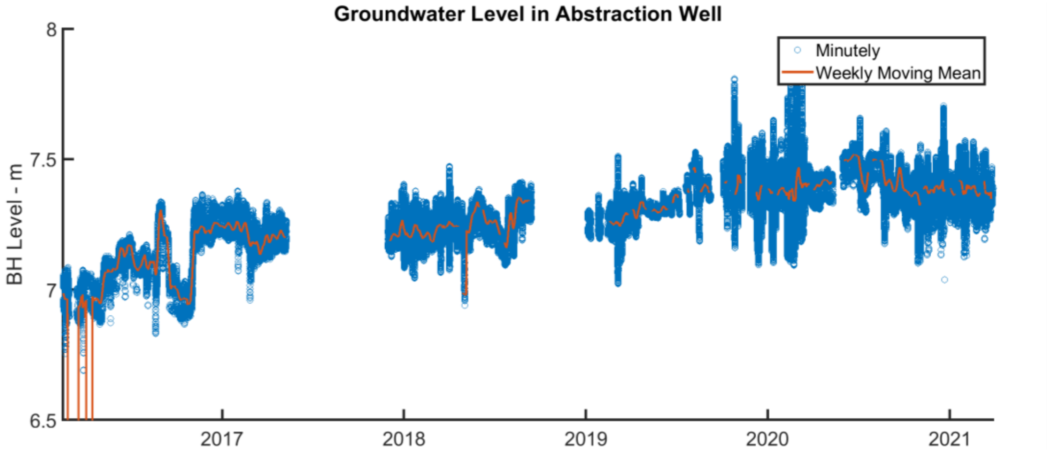


Figure 168 - Groundwater Level Raw Data

As the sensor was never calibrated, it is not possible to determine the absolute value of head, and thus convert it to flow rate through the manufacturer's data. Without a reference value from which to start, the small changes in head highlighted in Figure 168 cannot be accounted for. However, the weekly moving average shows that from late 2016 the groundwater level remains fairly constant throughout the monitoring period. Therefore, it is assumed that the borehole pumping system head can be taken as constant, and thus, when in operation, the pump will be pumping at a continuous flow rate.

To determine this flow rate, and in the absence of small timescale power data, it is necessary to define a proxy for when the pump is in operation.

Figure 169 displays the groundwater level data again, at a further reduced timespan of just 12 hours on the 1st of January 2017, a period selected at random to show the pattern of the data.

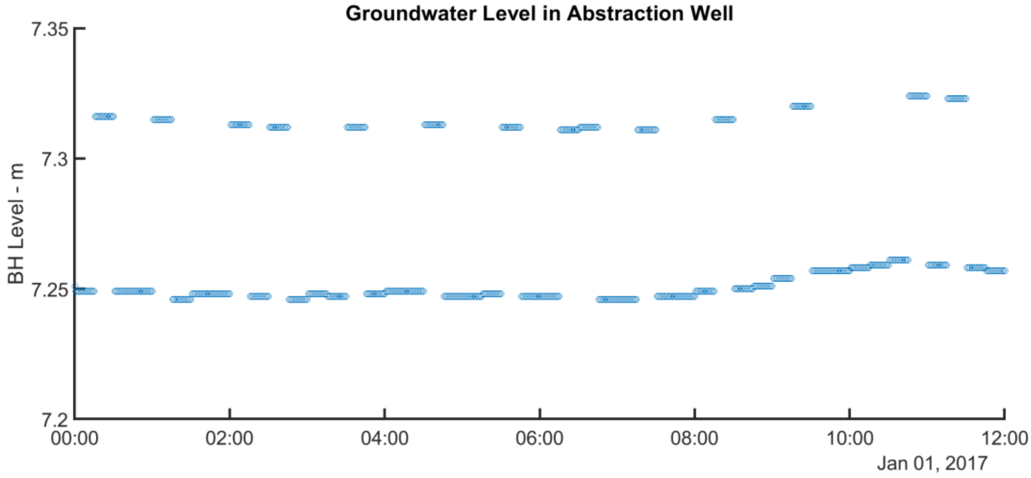


Figure 169 - Groundwater Level Raw Data – 12-hour period

It can be seen that there is a cyclical pattern, with the level dropping roughly seven cm and then reverting back to the previous level. These changes are likely drawdown from the pump being switched on, providing a useful indicator as to when the borehole abstraction pump is being turned on and off. As with much of the analysis however, the borehole level data has some large gaps in it as seen in Figure 168, meaning it is only possible to discern whether the borehole pump was operational or not for the portions of the monitoring period when this data is available.

Table 53 shows the percentage of data available for this proxy between each of the manual flow readings, as well as the manual readings themselves, the total time between the readings, and the time it is assumed the pump spent on between these readings as predicted by the water level changes. By dividing the total volume abstracted, in m^3, by the time spent on, in hours, an average flow rate is also produced.

Two periods of time have 100% of the borehole level data between manual readings, however the first of these is interpolated from data every 15 minutes to data at the minutely interval. This means only one period has 100% of the minutely data and that is the period from 13th March to 16th April 2018.

Table 53 - Borehole Pump Operation Using Water Level Change as a Proxy for Borehole Pump Operation

Time Stamp	Time Delta from Previous Manual Reading (hours)	Percentage of Water Level Data Available	Manual Reading – Total Flow during period (m^3)	Time On (hours)	Flow rate (m^3/h)
02-Mar-2017	3576 (from start of monitoring)	100 (Backfilled)	8312	2193.8	3.79
09-Aug-2017	3840	43.5 (Backfilled)	4044	909.5	4.45
14-Sep-2017	864	0	244	0	-
13-Mar-2018	4320	57.0	7861	1507.5	5.21
16-Apr-2018	816	100	1049	488.2	2.15
30-Oct-2018	4728	74.4	5282	755.1	7.00
17-Jan-2019	1896	8.80	3879.65	120.5	32.19
27-Mar-2019	1656	67.6	3261.79	574.5	5.68
17-Apr-2019	504	93.1	750.94	208.6	3.60
30-Jul-2019	2496	80.8	0	0	-
05-Sep-2019	888	85.2	0	0	-
29-Oct-2019	1296	37.1	596.65	93.2	6.40

5.3.2.1 Borehole Abstraction Rate – March to April 2018

The average flow rate calculated for this period was then applied to the whole monitoring period, provided the proxy indicates the borehole pump is on. From this the total volume flow in each period can be calculated and compared to the manual readings. As not each period has 100% of the data available, it is logical that this will not account for the total flow in each period, but the remaining value of flow to be accounted for by the missing data can be calculated.

For example, applying the flow rate of 2.15 m^3/h to the 43.5% of data available for the period from 2nd March to 9th August 2017, as seen in Table 53, gives a total *known* volume abstracted for this period of 1954.3 m^3. The manual reading for this period was 4044 m^3. This means the remaining 2089.7 m^3 must have occurred during the 56.5%, or 2171 hours, of the time, for which there is no proxy data.

As the flow rate is assumed to be constant, this approach can be validated by calculating the maximum volume of abstracted water possible during the time period and comparing it to the manual reading.

Continuing the previous example, the *known* volume abstracted from the data available is 1954.3 m^3, and if the pump was running at the same rate of 2.15 m^3/h for the 2171 hours for which data is not available, the maximum additional volume abstracted would be 4667.7 m^3. This makes the maximum total volume possible for this time period 6622 m^3.

This can then be compared to the manual reading for the volume abstracted, showing that for this period, the maximum possible volume (6622 m^3) is greater than the actual volume abstracted (4044 m^3) and therefore the flow rate of 2.15 m^3/h is possible for this time period.

Figure 170 shows this validation for each of the periods between the manual readings once the flow rate of 2.15 m^3/h has been applied.

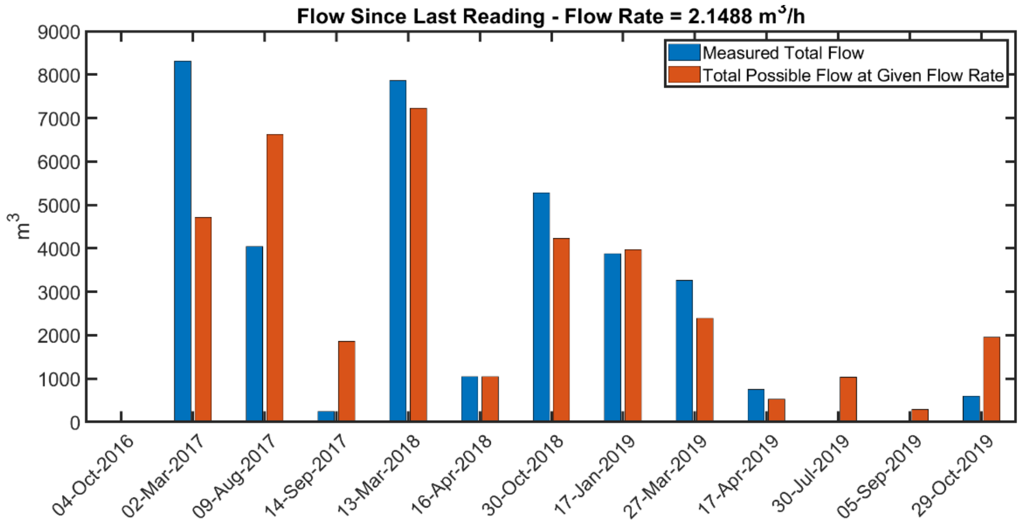


Figure 170 - Validation of Borehole Pump Flow Rate @ 2.15 m^3/h

Figure 170 demonstrates that this flow rate is not suitable to be applied across the whole monitoring period as in many of the cases, the maximum volume possible is less than the actual volume abstracted, accounted for by the missing proxy data.

Given the water level shown in Figure 168, does not vary significantly for this period compared to the other monitoring periods, it is suggested that there must be a change in the system causing an inflated head resistance to the pump and reducing its flow rate. This is investigated further in section 5.3.2.3.

The calculated flow rate of 2.15 m^3/h is therefore applied to the time period between the 13th of March 2018 and the 16th of April 2018, however, it is clearly not applicable for the remaining time periods.

5.3.2.2 Borehole Abstraction Rate – Majority of Monitoring Period

To determine a more appropriate value for the borehole pump flow rate, the period with the next highest percentage of proxy data was taken: 27th of March to 17th April 2019. This period has 93.1% of the minutely proxy data available, shown in Figure 171, and this produces a flow rate of 3.6 m^3/h, as shown in Table 53. However, as it is likely that the borehole pump will have been in operation at some point during the remaining 6.9% of this period, this needs to be accounted for in calculating the average flow rate.

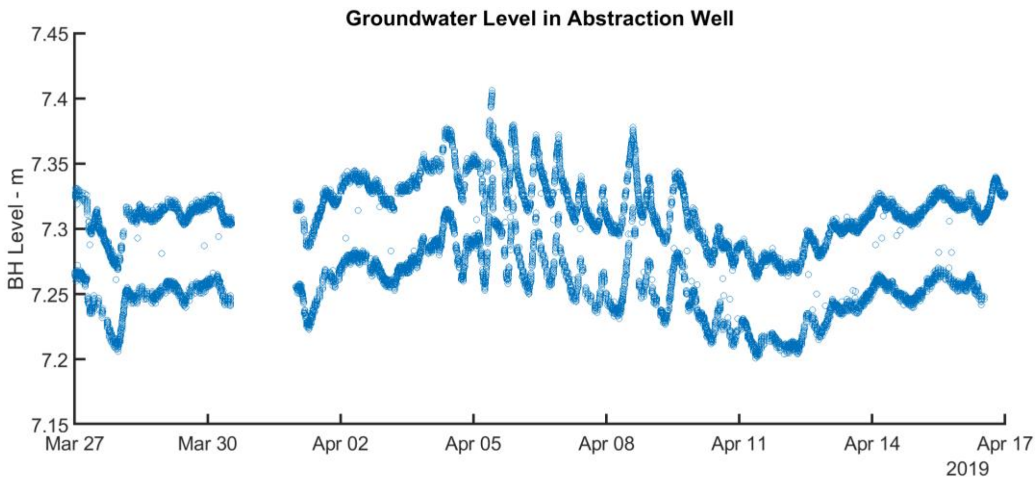


Figure 171 - Groundwater Level During Validation Period

As such the proportion of time spent switched on was calculated during the 93.1% of the period for which data is available. This “On factor” was then applied to the whole time period to produce an estimate for the total amount of time spent switched on during this window. This new value of time spent switched on was then used to calculate a revised average flow rate for this time period. This is shown in Equations (36) to (38).

$$On\ Factor = \frac{On\ Time\ in\ hours}{No\ of\ hours\ of\ data\ available} = \frac{208.5}{504*0.931} = 0.444 \quad (36)$$

$$Revised\ Time\ On = On\ Factor\ \times Total\ No\ of\ hours$$

$$= 0.444\ \times 504\ = 223.95\ hours \quad (37)$$

$$Revised\ Flow\ Rate = \frac{Total\ Volume\ Abstracted}{Revised\ Time\ On} = \frac{750.943}{223.95} = 3.35\ m^3/h \quad (38)$$

As before, the new flow rate was validated by comparing the calculated volume abstracted against the maximum possible volume extracted at that flow rate for each of the time periods between manual readings. The results of this validation are shown in Figure 172.

This shows that this flow rate is appropriate for each of the periods of data, with the exception of the initial period from October 2016 to March 2017. This period contained 15-minutely data which has been interpolated rather than minutely recorded data and so is less accurate which could explain the discrepancy.

As such, the flow rate of 3.35 m^3/h was deemed suitable and applied across wherever the borehole water level proxy suggested the pump was on, with the exception of the period specified in Section 5.3.2.1.

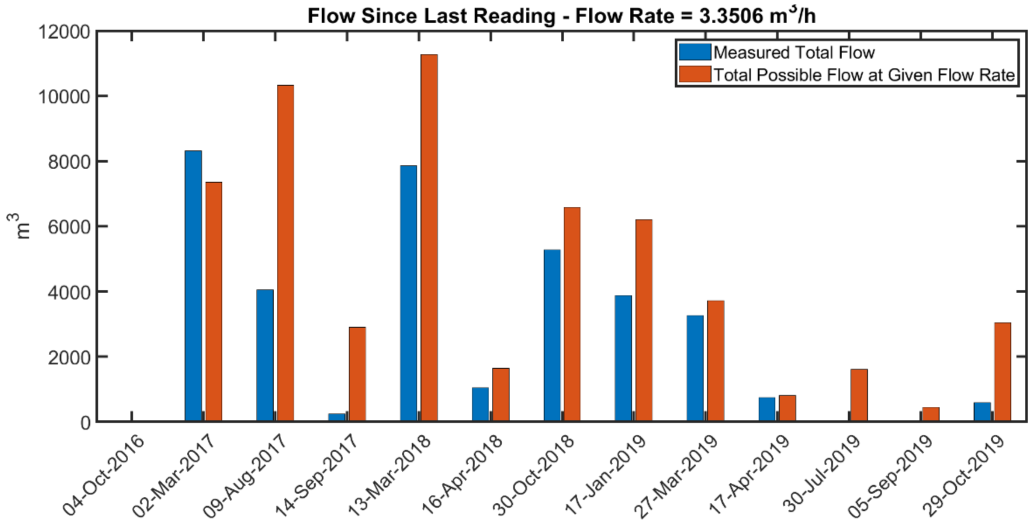
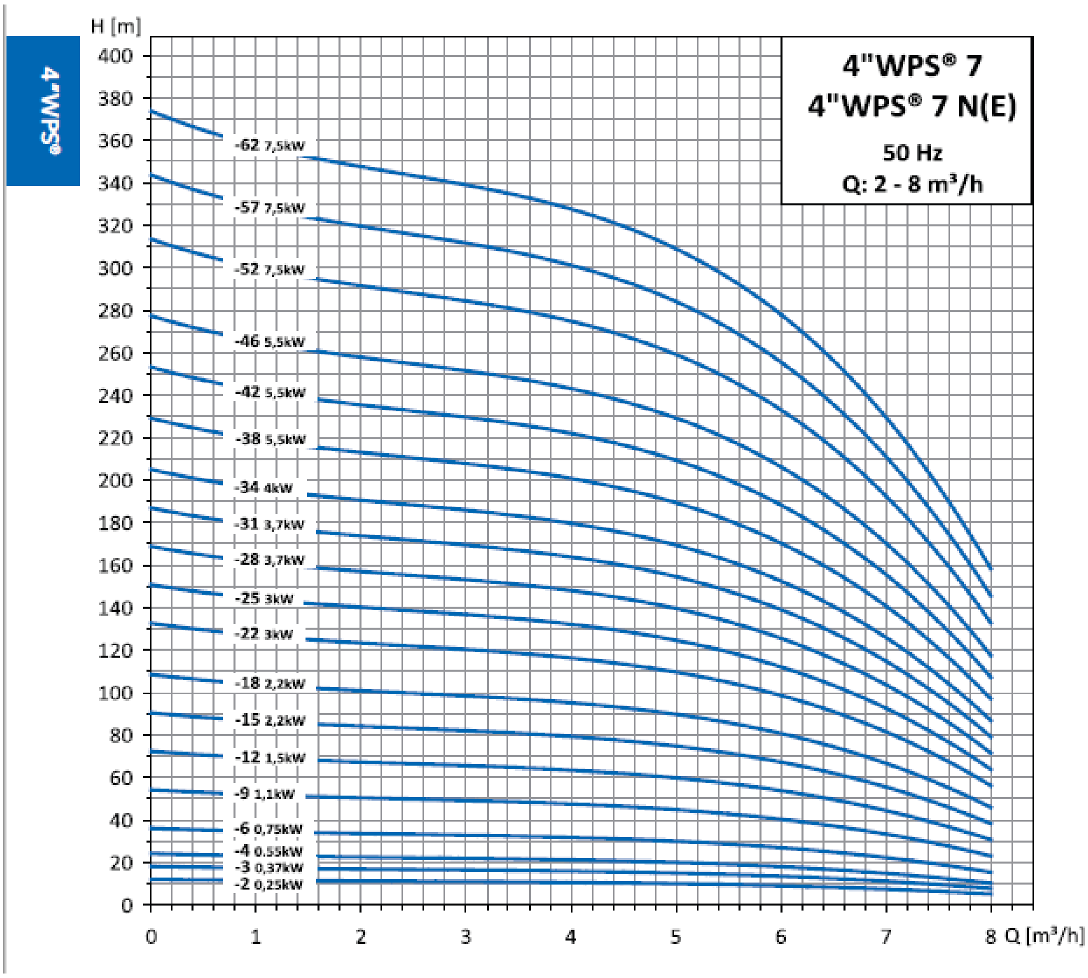


Figure 172 - Validation of Borehole Pump Flow Rate @ 3.35 m^3/h

5.3.2.3 Comparison of the two abstraction rates

Comparing the two flow rates to the manufacturer's data, Figure 173, the drop in the flow rate for the period in 2018 equates to a change in head of the system of around 0.7m, or 6.7kPa of pressure.

Whilst it is not clear what caused this, the reduced flow rate does occur during the same period in which the wider system appears to be operating incorrectly and so it is possible this could be attributed to a clogged filter, which was then cleaned whilst the wider system was being investigated and in early 2018. Alternatively, in the same way that the main circulation pump settings appear to have been incorrectly changed during 2018 before reverting back to the original setup, the borehole pump settings may also have been adjusted.



Selection Chart 4"WPS® 7 and 4"WPS® 7 N(E)

Pump Type	Pump Power P_2		Flow [m³/h]									Full load current	
	[kW]	[HP]	0	1	2	3	4	5	6	7	8	1x230V	3x400V
4"WPS® 7-2	0,25	0,33	12	12	11	11	11	10	9	7	5	2,4	0,7
4"WPS® 7-3	0,37	0,5	18	17	17	16	16	15	14	11	8	3,3	1,1

Figure 173 - Borehole Pump – Manufacturer's Data (WP Well Pumps, no date)

5.3.3 Calculating BH Pump Power

With the borehole pump flow rates determined, the power being used by the pump had to be calculated. This was done in a similar fashion to the flow rate, by using a simple regression between the total electrical energy used over each period and the time the pump spent on. However, whilst the change in head that occurs in early 2018 would affect the flow rate, it is unlikely to affect the power input. As such the power calculated for this period with 100% of the proxy data, 0.52kW, is applicable to the whole monitoring period. This was again validated by ensuring the energy not accounted for by the data available, could be accounted for in the remaining time in each period. This is shown in Figure 174.

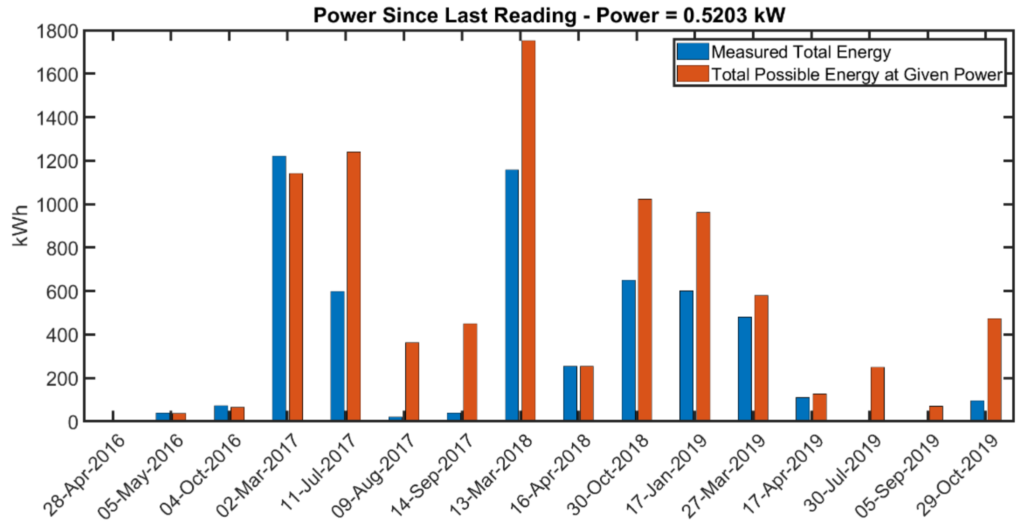


Figure 174 - Validation of Borehole Pump Power @ 0.52 kW

As with the flow rate, there are minor discrepancies where the 15-minutely data has been interpolated, however the power appears appropriate for all periods of minutely data.

A further validation exercise was carried out to ensure these calculated values of flow rate and power would be applicable across the monitoring period, using the total volume of groundwater abstracted and energy consumed by the borehole pump from the 4th of October 2016 to the 28th of October 2021. These values are found in Table 47 and the validation is shown in Equations (39) to (42).

$$Total\ electricity\ consumed = 7870.49 - 1049 = 6821.49\ kWh \quad (39)$$

$$Number\ of\ Operating\ Hours = \frac{Total\ Elec}{Power} = \frac{6821.49}{0.5203} = 13110.7\ hours \quad (40)$$

$$Total\ Volume\ Abstracted = 55076.7 - 9638 = 45438.7 m^3 \quad (41)$$

$$Average\ Flow\ Rate = \frac{Total\ Volume\ Abstracted}{Number\ of\ Operating\ Hours} = \frac{45438.7}{13110.7} = 3.47\ m^3/h \quad (42)$$

This calculated flow rate is less than 4% off from the flow rate calculated using the smaller sample data set, suggesting it is fit for purpose across the period to be analysed.

Despite the drawbacks, there is merit to conducting this analysis, as these estimation methods allows for a greater understanding of the operation of the system at smaller timescales. For example, the estimation of the groundwater abstraction rate will allow for a calculation of the heat extracted from the ground. Similarly, without the power for the borehole pump, it would not be possible to calculate the SPF at Annex 52 boundaries 0, 2, 3, or 4, limiting the ability to compare the performance of the whole system with other such systems and instead leaving only the performance factor for the heat pumps in isolation at boundary 1.

Figure 175 and Figure 176 show the resulting data sets for the borehole pump power and flow, which will be taken forward in the analysis.

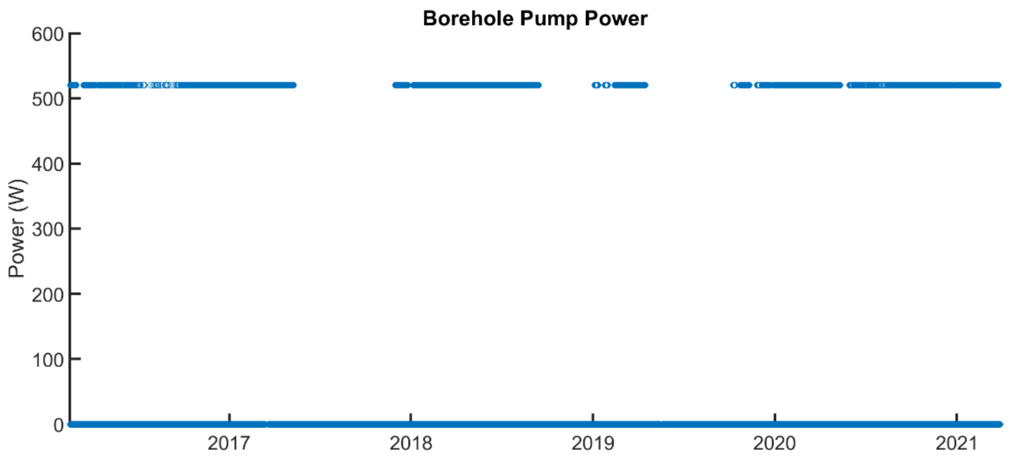


Figure 175 - Borehole Pump Power Over Monitoring Period

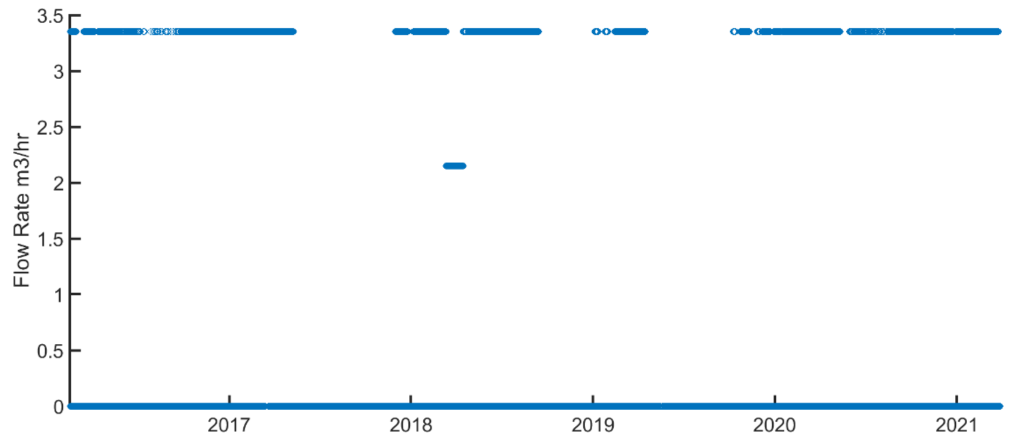


Figure 176 - Borehole Pump Flow Rate Over Monitoring Period

5.3.4 Summary

A summary of the assumptions applied to each period of data is included in Table 54.

Table 54 - Summary of Assumptions Used in Analysis

Equipment	Timeframe	Assumption	Needed for	Comments
Main Circ Pump	Start – Dec 2017	Head set point = 6 m	Converting pump power to flow rate and subsequently calculating heat delivered to the building	Validated separately from post-2018
Main Circ Pump	Dec 2017 – Jan 2019	No model applied to power data – no analysis conducted		Models applied did not match data
Main Circ Pump	January 2019 - End	Head set point = 6 m		Validated separately from pre-2018
BH Pump	Start – April 2018	Flow rate = 3.3 m^3/h	Calculating heat extracted from groundwater	
BH Pump	April – May 2018	Flow rate = 2.14 m^3/h		Flow rate too small to be applied to other periods – possible filter clogging or control adjustment
BH Pump	May 2018 - End	Flow rate = 3.3 m^3/h		

5.4 Results

Due to the nature of the data and the exclusion of the 2018 values from the detailed analysis, the results are provided in two sections: manual readings, and smaller timescale investigations. This is because excluding the heat provided in 2018 would, for example, mischaracterise the overall load statistics when high level data is available for how much heat was provided. This will also provide a useful comparison of what can be learned from the two analyses.

Due to the dates available for the manual readings, these analyses will cover slightly differing timespans.

Whilst data is available for the system until March 2021, and a manual reading was provided for October 2021, the heat pump was turned off due to a malfunction in November 2020 until early 2022. As such the manual reading analysis will cover October 2016 to October 2019, and the in-depth analysis will cover from February 2016 to November 2020.

5.4.1 Results - Manual Readings

Table 55 shows the overall load of the building during the time period spanned by the manual meter readings.

Table 55 - Overall load characteristics

Start of evaluation period	October 4th 2016
End of evaluation period	October 29th 2019
Building space heating load met by system [MWh_{th}]	180.3
Groundwater Abstracted [m^3]	35281
Electricity Used – Heat Pump 1 [MWh]	18.57
Electricity Used – Heat Pump 2 [MWh]	11.48
Electricity Used – Borehole Pump [MWh]	5.22
Electricity Used – Circulation Pumps [MWh]	>4.64

Unfortunately, as seen in Table 47, the final readings for the main circulation pump and the brine side circulation pump were taken in January 2019 rather than October and so only a minimum value can be provided for the total energy used by the circulation pumps.

These readings allow the calculation of some performance factors over irregular time periods. Figure 177 to Figure 180 show these performance factors where possible at system boundary level 1,2, 3 and 4 respectively,

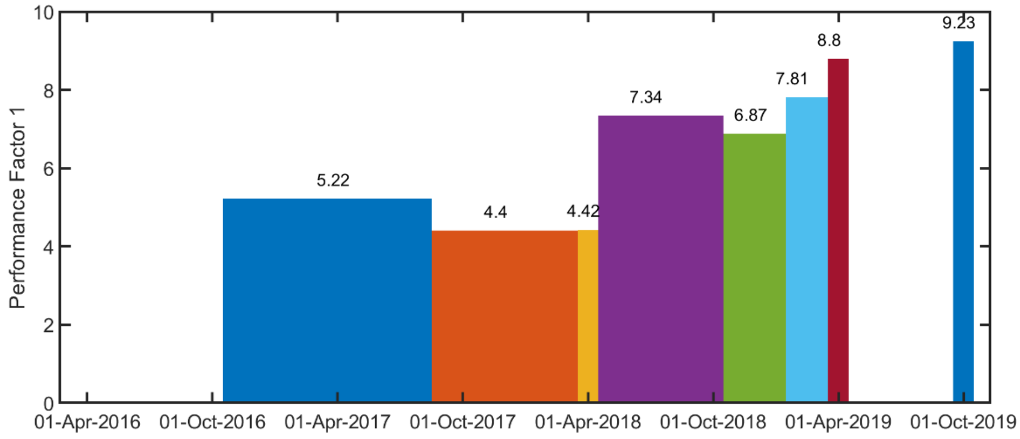


Figure 177 - PF1 over Periods Between Manual Readings

Figure 177 shows the performance of the heat pumps is increasing with time, but due to the coarseness of the analysis periods, the reasons for this are unclear.

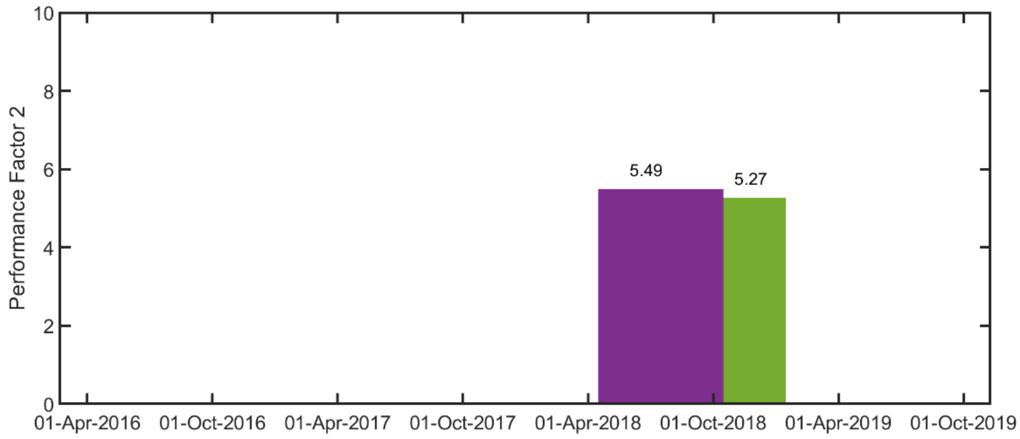


Figure 178 - PF2 over Periods Between Manual Readings

As can be seen in Figure 178, only two time periods have all the necessary manual readings to calculate the performance factor at system boundary 2, though the values still appear to be relatively high.

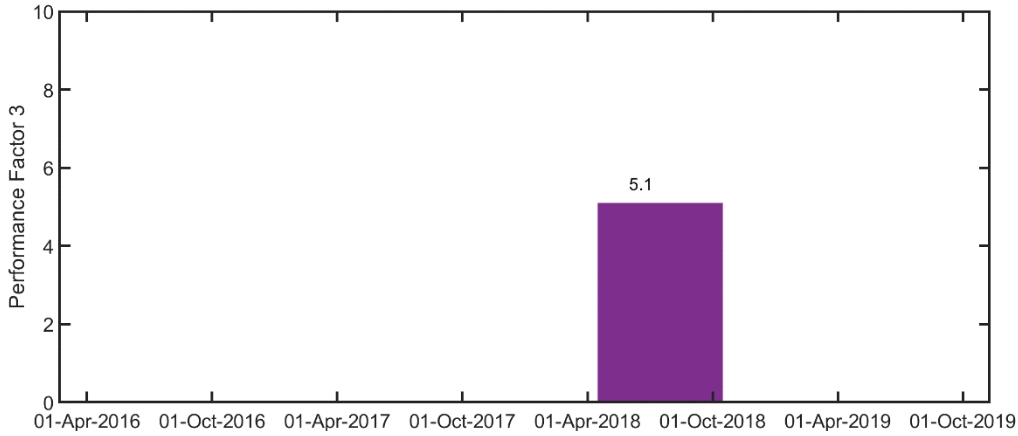


Figure 179 - PF3 over Periods Between Manual Readings

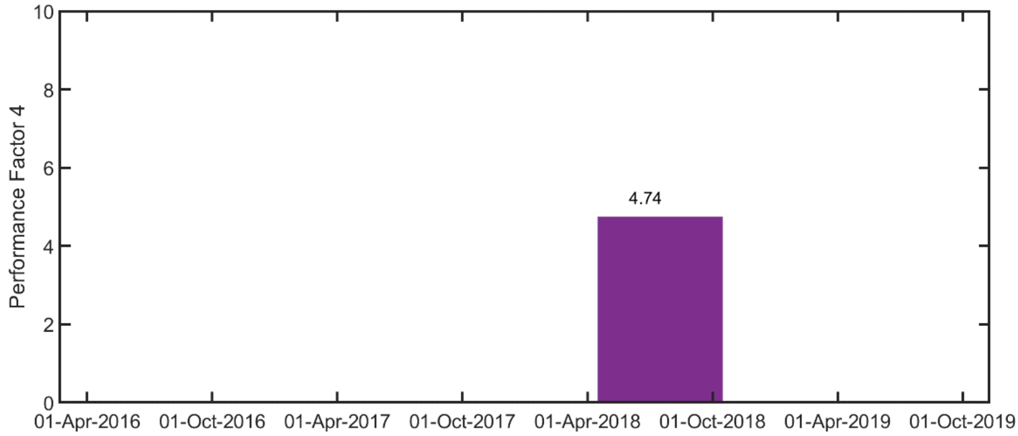


Figure 180 - PF4 over Periods Between Manual Readings

Figure 179 and Figure 180 show the PF at boundaries 3 and 4 for the only time period possible using the manual readings.

Figure 177 to Figure 180 show that due to the number of missing readings, performance factors are only possible to be calculated for very few timesteps at very few system boundaries, with the exception of system boundary one. This provides insight into the performance of the heat pumps themselves but not a great deal of information as to how the wider system is performing, except for in mid to late 2018.

Figure 181 to Figure 184 shows the same performance factors but this time rather than excluding any timesteps with missing readings, the performance factors have been calculated with any available data, meaning the values shown are the maximum the performance factor could be for that time period. For example, there is no reading for the the circulation pump on the return pipe for heat pump 2 in the period from the 30th October 2018 to the 17th January 2019, however the other parameters required have been recorded, so the performance factors has been calculated using without accounting for the energy used by this pump.

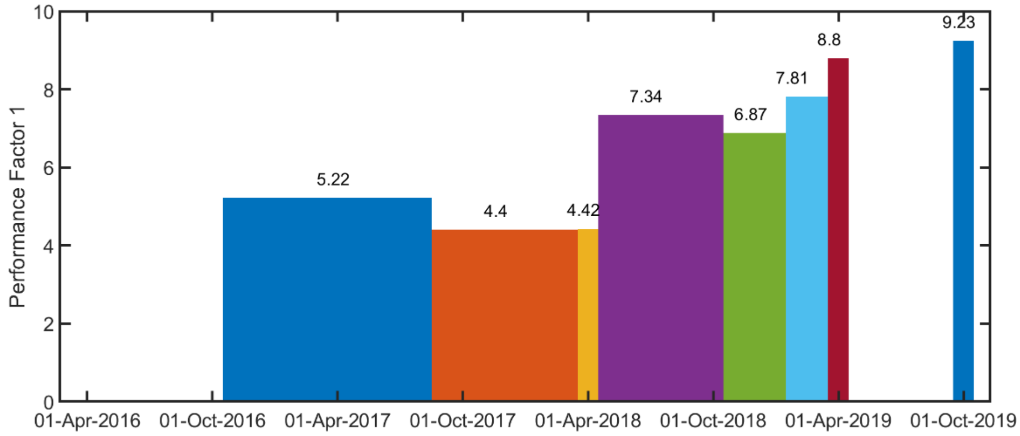


Figure 181 - Maximum PF1 over Periods Between Manual Readings

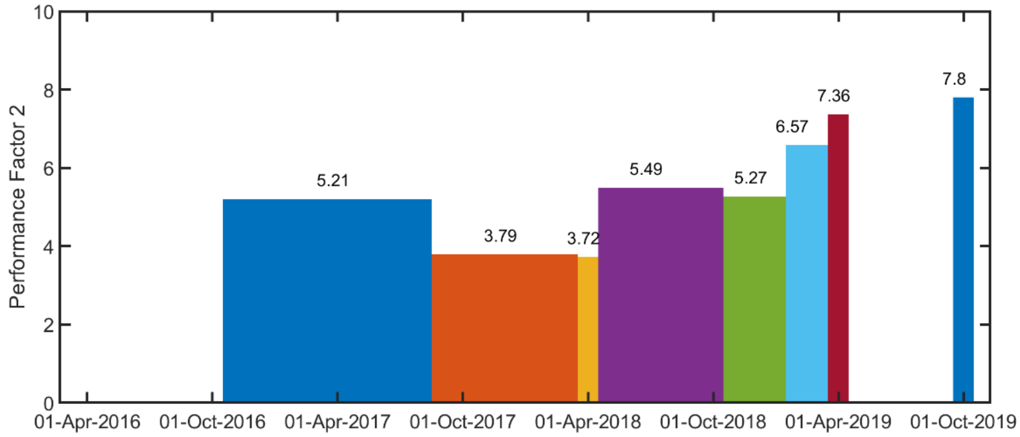


Figure 182 - Maximum PF2 over Periods Between Manual Readings

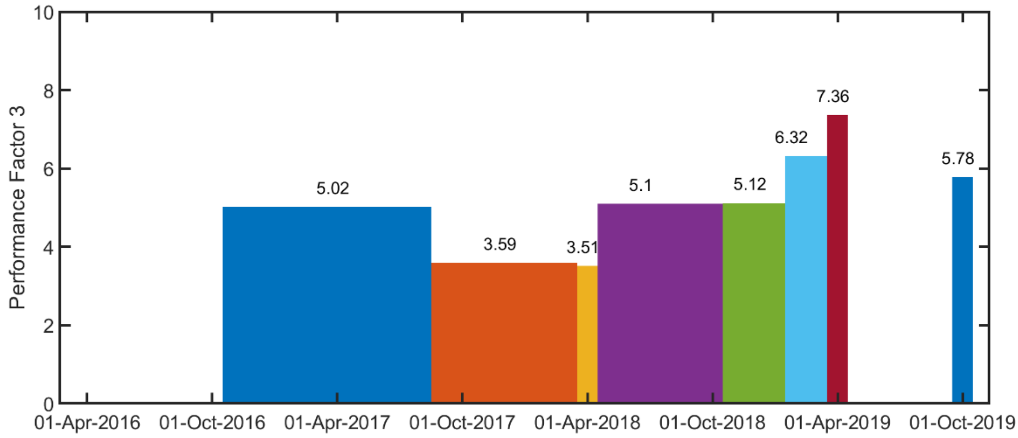


Figure 183 - Maximum PF3 over Periods Between Manual Readings

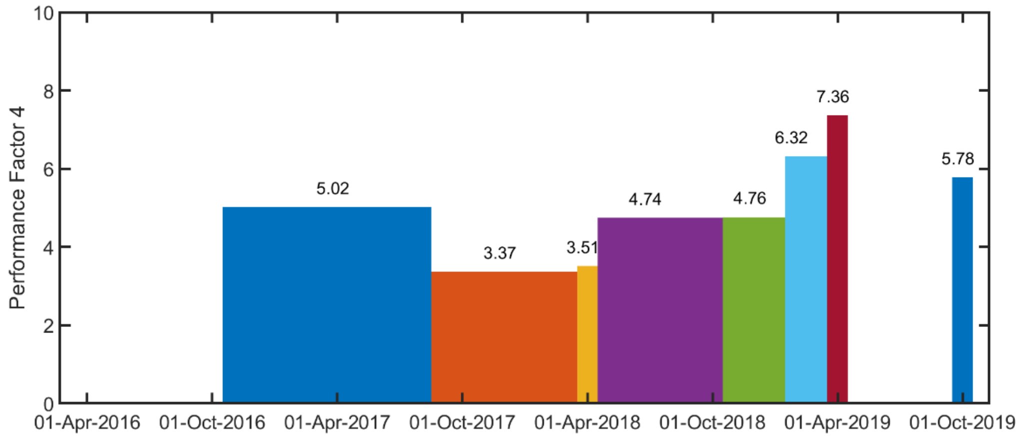


Figure 184 - Maximum PF4 over Periods Between Manual Readings

These figures show that despite the fact that the manual readings were taken at irregular intervals and for different meters each time, they can still provide useful insights. For example, the evolution of the PF over time and the drop in performance between system boundaries is still evident, despite Figure 181 to Figure 184 only showing the maximum theoretical PF.

5.4.2 Results - In-Depth Analysis

As per the assumptions stated in Table 54, any analysis regarding heat delivered to the building in 2018 is not included in the following analysis and the only available performance factors for this period can be found in the previous section. That is not to say that 2018 is not investigated as other data sets are available such as the power consumption of the various heat pumps and circulation pumps and system temperatures, just that an appropriate model to calculate the heat delivered to the building could not be found.

5.4.2.1 Building Heat Demand

It is also worth reiterating at this point that the data for the heat delivered to the building is limited by the power data available for the main circulation pump. Figure 185 shows the data for calculated heat delivered to the building for each of the calendar years of monitoring.

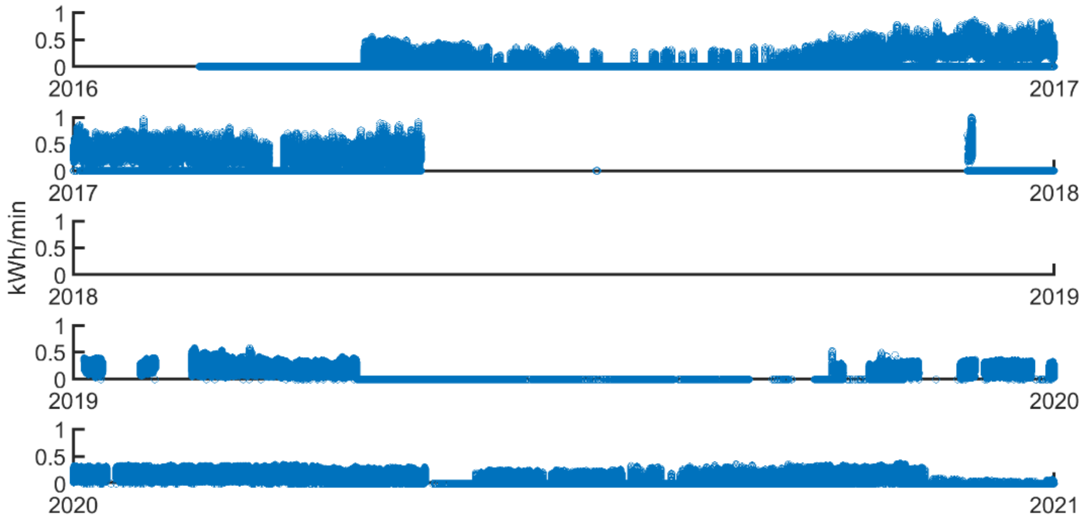


Figure 185 - Yearly Comparison of Heat Delivered Calculated from Minutely Readings

It can be clearly seen from this that comparisons across the years of operation will have to be carefully considered as data is available at different times of each of the monitoring years for this system, and no two years are directly comparable with one another.

Figure 186 shows the mean hourly heating load binned into the hourly average outdoor temperature bins, providing an energy signature for the building.

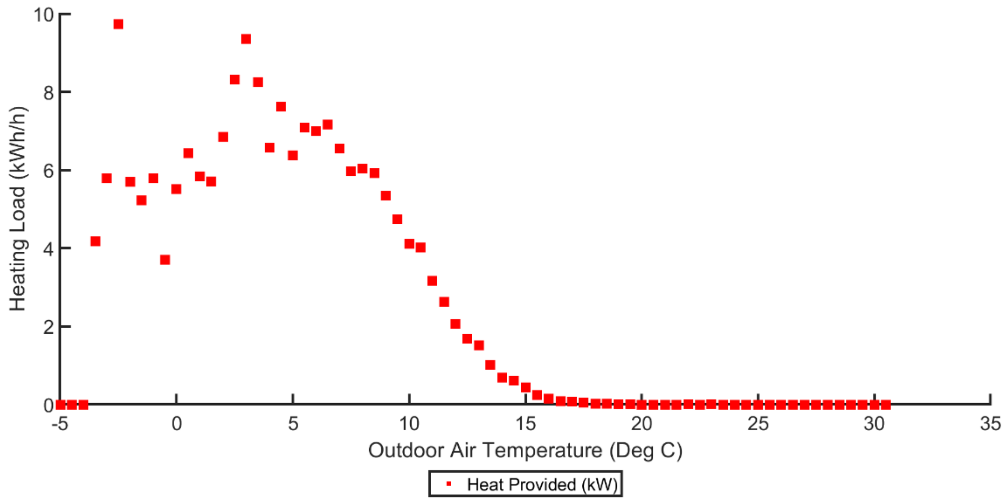


Figure 186 - Building Energy Signature

The heating load decreases with temperature for the most part, as expected, however at outdoor temperatures of less than 5°C, the heating load decreases again. This could be due to the comparatively small number of hours spent at these temperatures as seen in Figure 187. The building profile could also be influenced by the school holidays, potentially limiting the data points available at these lower temperatures over the winter, as well as the greater temperatures during the summer months.

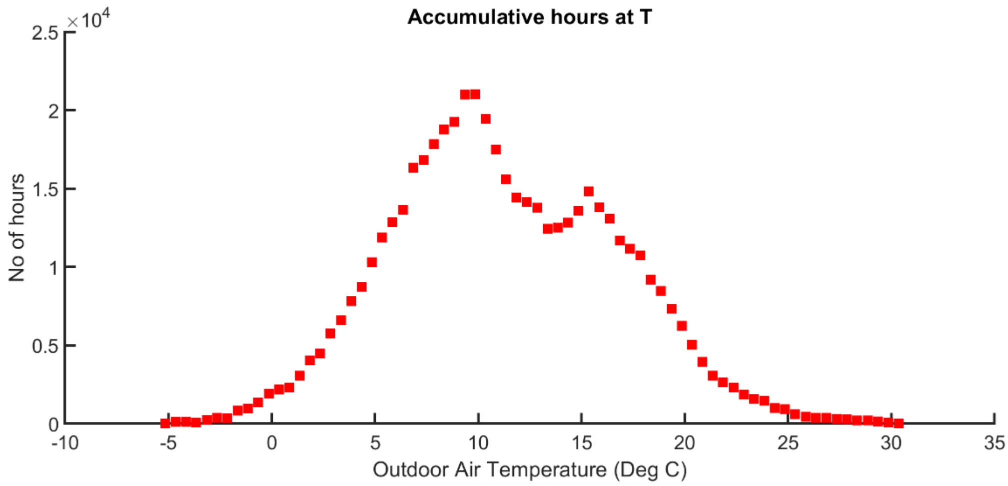


Figure 187 - Hours Spent at Outdoor Air Temperatures

Figure 188 and Figure 189 show the annual and monthly heat provided by the heat pump system to the building. As previously discussed, it was not possible to calculate the heat at every time interval due to data availability issues and as such the percentage of data available per timestep has been included in the monthly breakdown to provide some context for the values shown.

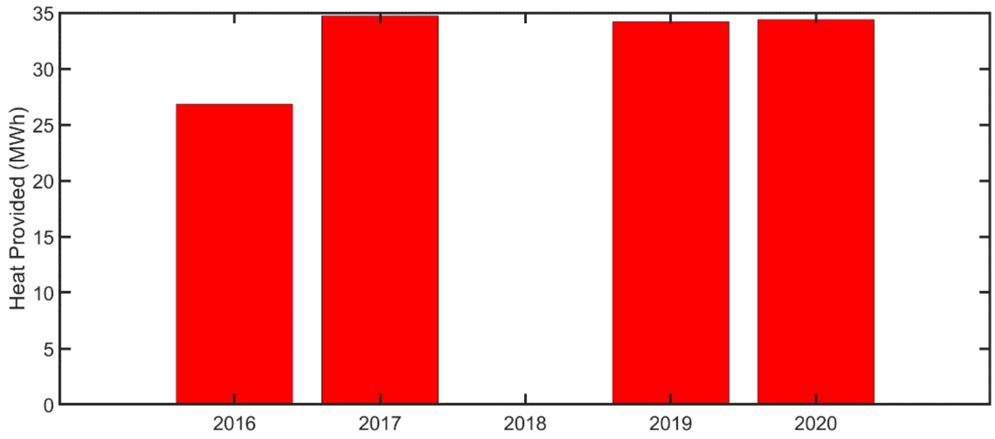


Figure 188 - Annual Heating Load

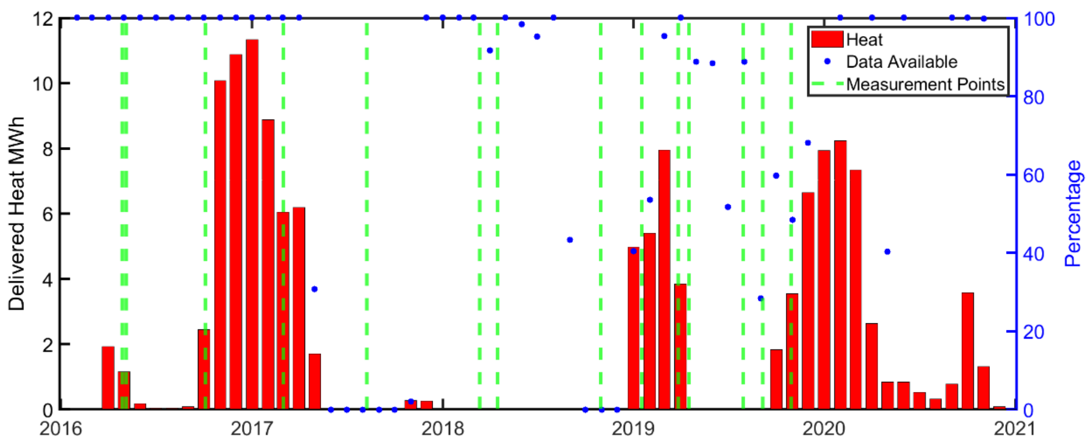


Figure 189 - Monthly Heating Load

This clearly highlights the additional heat being wasted whilst the system is left on during the summer months in 2020. These figures also demonstrate a reduction in heat delivered from the first winter that was monitored, 2016-2017, to the following heating periods, though these overall figures may again be due to data losses.

Figure 190 shows the minutely and the weekly moving mean flow and return temperatures to and from the building respectively.

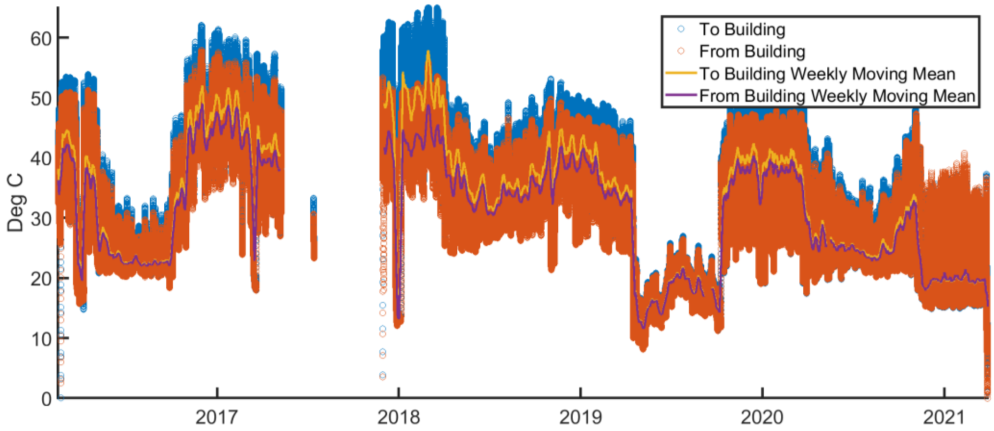


Figure 190 - Heat Pump Flow and Return Temperatures

This shows a higher flow temperature was targeted by the heat pumps in 2017 and early 2018, between 50°C and 60°C. There is a marked drop in flow temperature from the end of April 2018 to between 30°C and 40°C. This figure also clearly shows where the system is turned off over the summer months in 2019. Figure 191 isolates the difference in temperature between the flow and return.

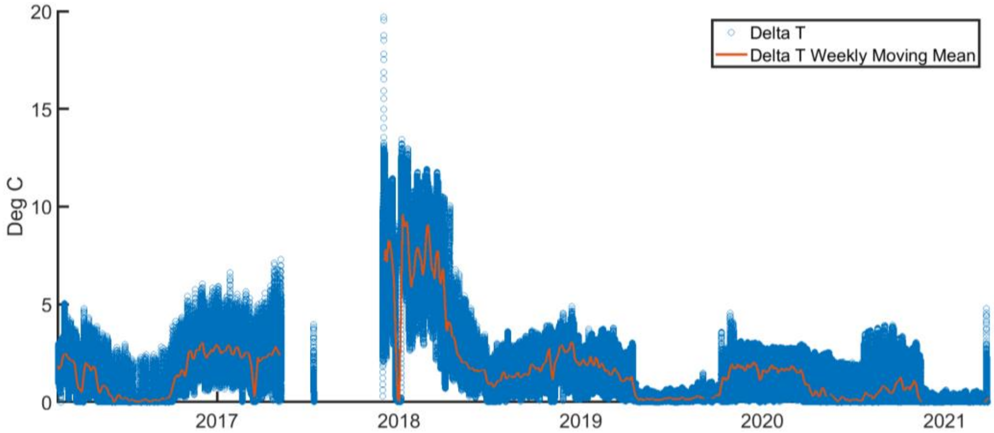


Figure 191 - Heat Pump Delta T

It can be seen that typically a delta T of between 0°C and 5°C is maintained, however during early 2018 the temperature difference is significantly larger than the rest of the monitoring period. This is likely caused by decreased flow rate through the system due to incorrect commissioning of the replacement circulation pump, however this can’t be confirmed through the data available.

5.4.2.2 Ground heat exchanger performance

Figure 192 demonstrates the average weekly values for the borehole flow and return temperatures leaving and entering ground loop temperatures along with the flow rate and outdoor air temperatures.

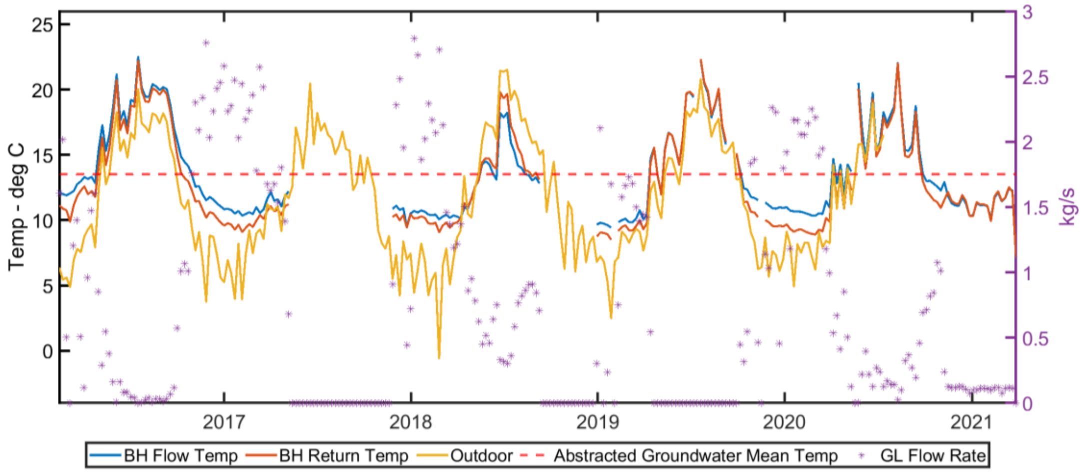


Figure 192 - Average Weekly Ground Heat Exchanger Data

This highlights the potential benefits of using a ground source system, with the groundwater temperatures remaining several degrees above the outdoor air temperature over the winter months. This system, however also closely matches the outdoor air temperature over the summer months, thus reducing the temperature lift required in both cases. The large temperature fluctuation at greater than 10m depth is unusual and is likely due to the close proximity of the river. This suggests the aquifer is in hydraulic contact with the surface water, as assumed in the original reporting (Boon *et al.*, 2019), and this is leading to these elevated temperatures with strong seasonal fluctuations. The abstracted water is likely gaining additional heat from the borehole pump, and in the summer, marginal heat gains from elevated air temperatures in the heat pump enclosure.

Figure 193 however, includes the temperatures of the brine filled intermediary loop, between the groundwater and the heat pumps. This shows that the use of this additional loop negates this potential gain to some degree, with the brine temperatures falling between the groundwater temperatures year-round. This means that the brine is generally closer to the cold air temperatures in the winter, and further from the warm air temperatures in the summer.

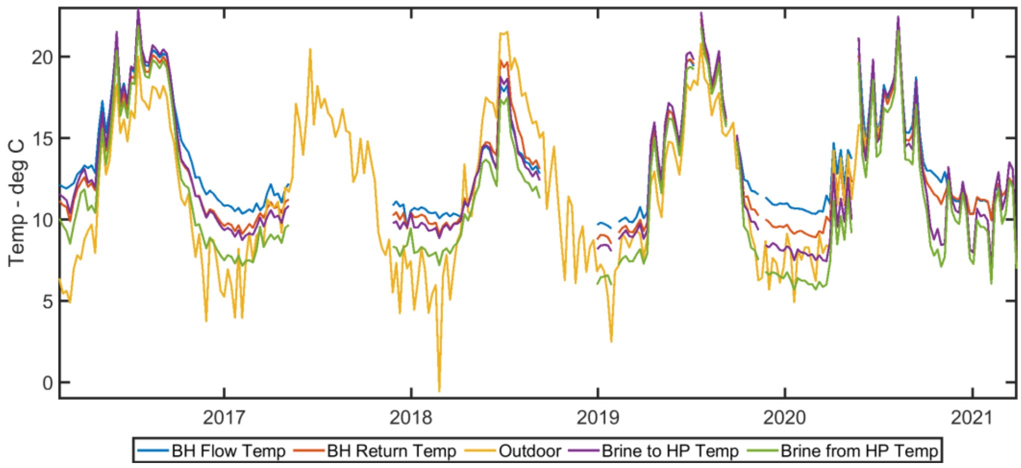


Figure 193 - GHE & Brine Loop Temperatures

Figure 194 and Figure 195 demonstrate the annual and monthly net ground heat exchange, again with the percentage of available data in the monthly figure.

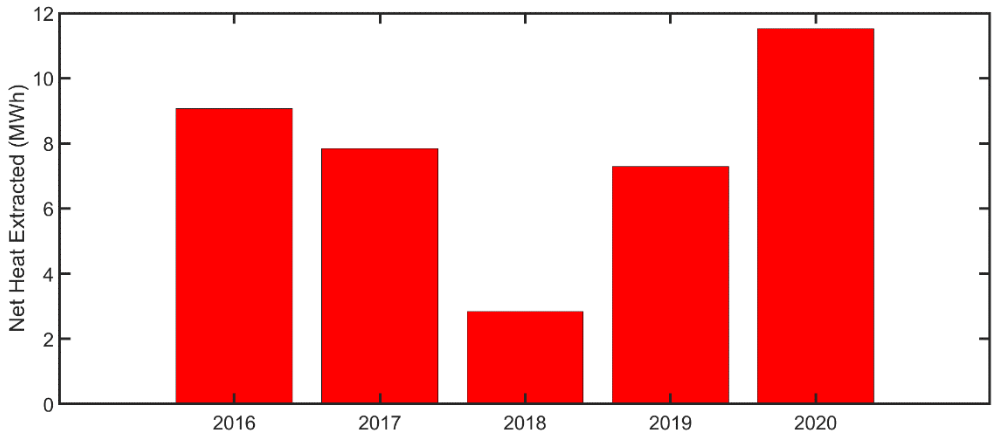


Figure 194 - Annual Net Heat Extracted from Aquifer

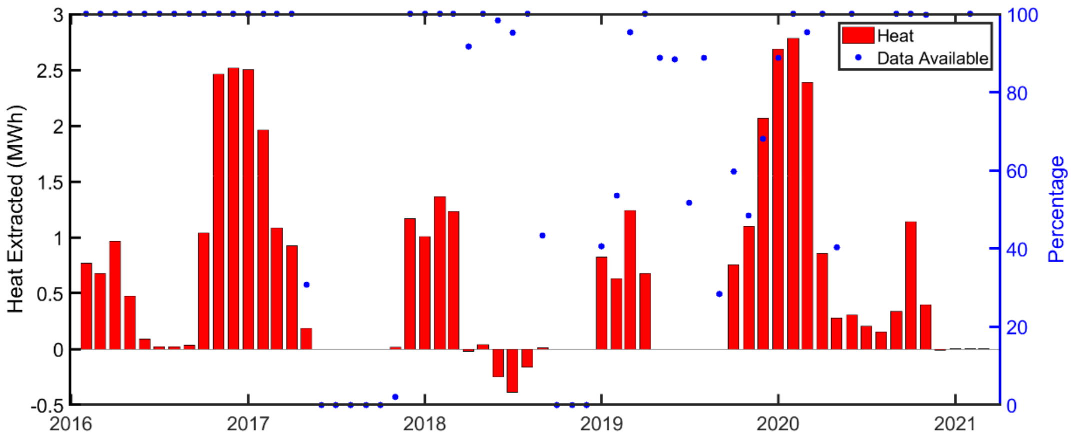


Figure 195 - Monthly Net Heat Extracted from Aquifer

This system is not set up for active cooling, so it is not expected to reject heat to the ground at any point during its operation. It is clear from Figure 194 that the annual heat exchanged in 2018 is affected by the heat that appears to have been rejected to the ground during the summer months.

This period of heat rejection has been investigated further. Figure 196 shows the electrical energy consumption for both the borehole pump, noted to be operational as determined by the drawdown in water level measurements, and the brine side circulation pump, indicating that both pumps are operational during this period and as such any heat from the groundwater should be being transferred to the brine via the plate heat exchanger.

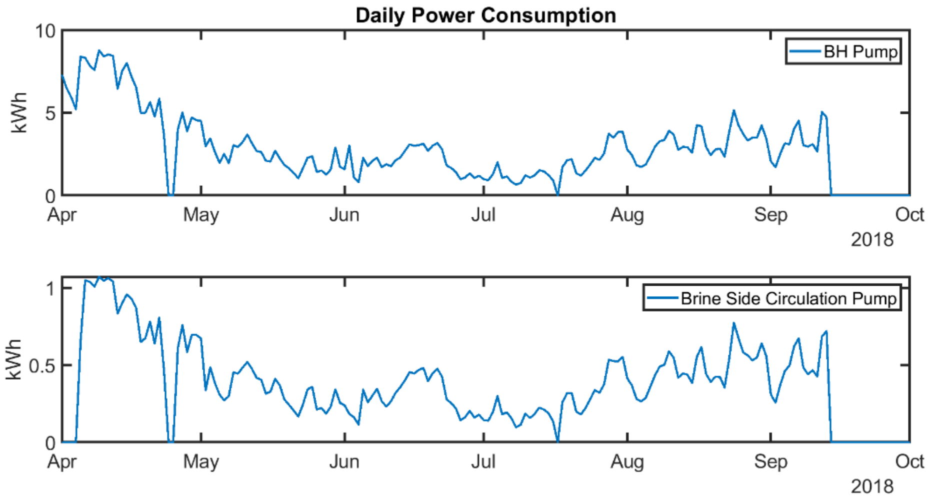


Figure 196 - Pump Energy Usage During Heat Rejection Period

Figure 197 shows the daily mean flow and return temperatures to the and from the borehole, i.e. the ground water temperatures, and to and from the heat pumps, i.e. the brine temperatures, respectively.

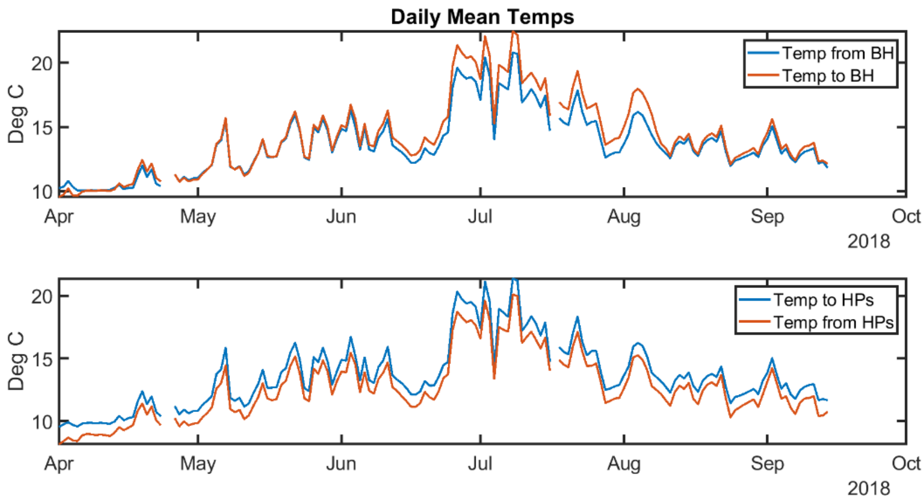


Figure 197 - Temperatures During Heat Rejection Period

The return temperature to the borehole is noted to be larger than the extracted temperature from the borehole, despite the temperatures on the other side of the heat exchanger indicating that the brine is absorbing heat from the heat exchanger to deliver to the heat pump. This suggests that the temperature of the water being returned to the ground loop is increasing after the heat exchanger, potentially due to poor insulation and/or an external heat source being located nearby. This temperature difference could also be a result of a sensor issue which is subsequently rectified, though this seems unlikely as the temperatures provided are within the expected range and there is no clear loss of signal for when a sensor could have been removed and replaced.

As such, it is unlikely that this is actually heat being removed from the system and so rather than showing the net heat extraction, Figure 198 and Figure 199 separate out the “rejected heat” and heat extracted separately.

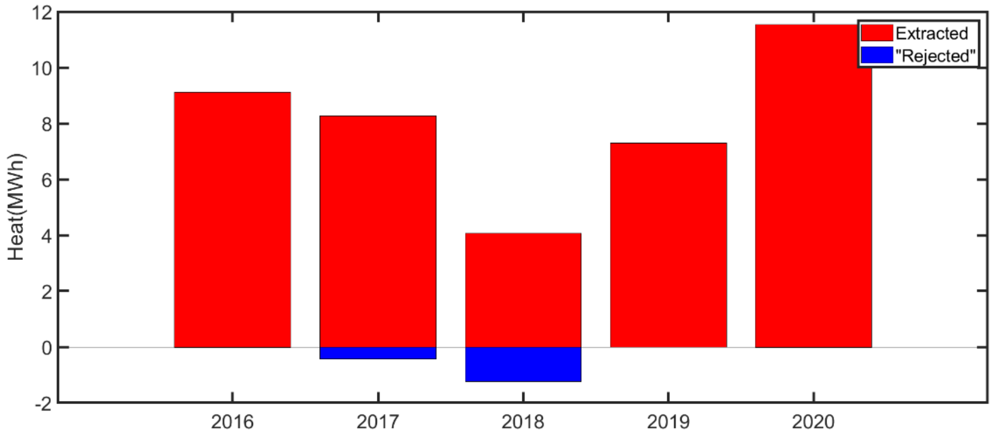


Figure 198 - Gross Annual Heat Extracted and Rejected from Aquifer

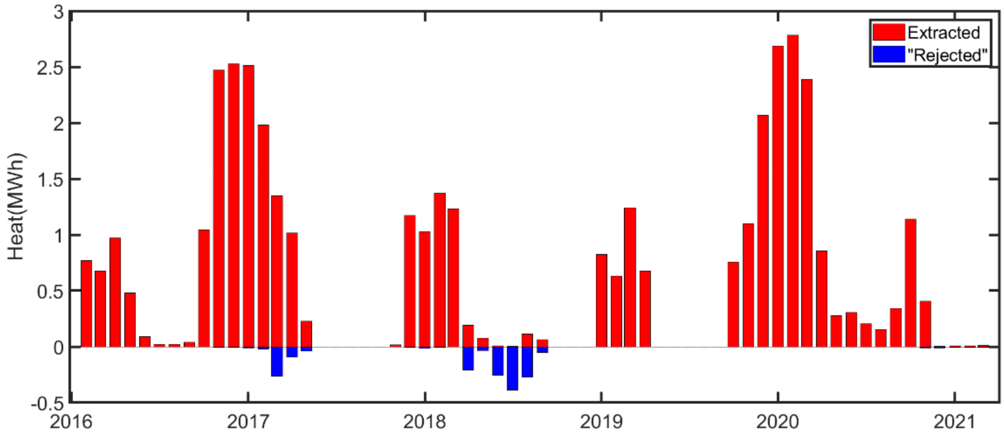


Figure 199 - Gross Monthly Heat Rejected from Aquifer

The heat "rejection" is also present in 2016 and 2017, though at a small enough scale so as not to tip the monthly net heat extracted into negatives. If it is the case that the "rejected heat" is in fact simply an external heat source artificially raising the temperature of the groundwater after the heat exchanger, the values of extracted heat presented in these figures would only represent a minimum.

To investigate how the ground loop changes with the weather, Figure 200 shows the correlation of the borehole flow temperature to the outdoor air temperature.

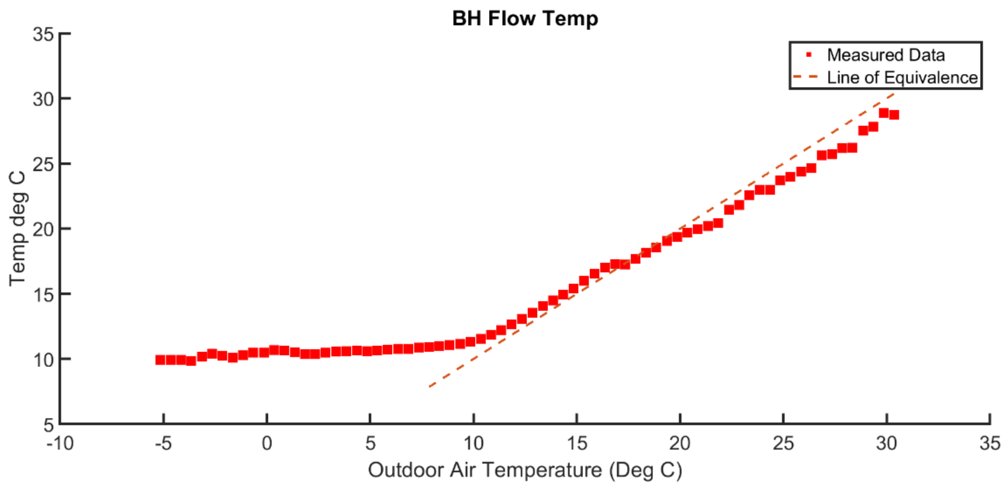


Figure 200 - Outdoor Air Temperature vs BH Flow Temperature

The leaving groundwater temperatures in this correlation are particularly high. Figure 201 shows the same correlation, but only including the temperatures when the borehole pump is assumed to be running.

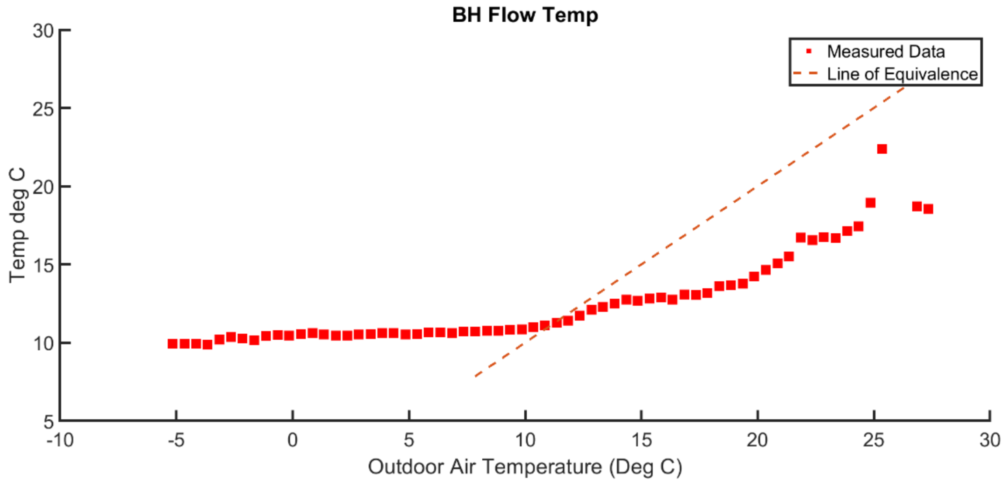


Figure 201 - Outdoor Air Temperature vs BH Flow Temperature - Adjusted

These values in Figure 201 appear more realistic, suggesting the elevated temperatures in Figure 200 are likely due to additional heat transfer from the air in the heat pump enclosure when the fluid is not circulating. Figure 201 does still show relatively higher temperatures, however, and highlights the potential benefits of a groundwater system compared to an air source system, as the flow temperature from the borehole is relative stable at around 10°C for any air temperature below 5°C, thus allowing for a potentially higher heat pump performance factor when the largest amount of heating is required. The additional heat transfer from the enclosure air to the stationary fluid, could also be providing a temporary boost to the heat pumps performance, as when the pump starts up again, the evaporator will be receiving even higher entering water temperatures.

This warmer water effect, with the temperature sensors providing higher temperature readings for the borehole return than the borehole flow, is likely transient meaning that only a very small amount of heat is actually being rejected back to the aquifer. This is a limitation of the 15-minutely temperature readings, as the pump appears to be cycling on and off again at shorter intervals than this. Thus, the interpolation between two temperature readings is missing the actual temperatures of the fluid whilst it is flowing and only capturing the static, elevated temperatures.

5.4.2.3 Minutely Performance Factor & SEI

Given the minutely power data available for the heat pumps, along with the calculated minutely heat output (based on the minutely circulation pump power data and minutely temperature data), the minutely performance factor for the system can be calculated. This allows for the SEI to be calculated for the "instantaneous" measurement, rather than having to average temperatures over a time period. As with the previous case study, this thesis adopts the proposed definitions in Gehlin *et al.* (2022) that COP refers to controlled lab conditions, and PFs are used for field measurements.

Minutely data, being at such as small timescale is particularly susceptible to errors such as misaligned timestamps which could drastically skew the results, and as such the SEI has been used as a filter for bad quality data from this system. As per Lane *et al.* (2014) systems operating at SEI above 0.45 are deemed excellent and systems with an SEI of 0.35 and above are deemed good. Gehlin *et al.* (2022) suggests that the best operating systems will not exceed 0.55 at their most efficient. Any PF and SEI values that correspond to an SEI of 0.55 or greater have therefore been omitted from this analysis.

Due to the method used to calculate the heat, only the heat provided to the building is available, and not the heat provided by each of the heat pumps. As such, the initial PF values were calculated for each heat pump when only one heat pump was running at a time. Figure 202 show the effects of the outdoor air temperature on the average PF of heat pump one and two when operating in isolation.

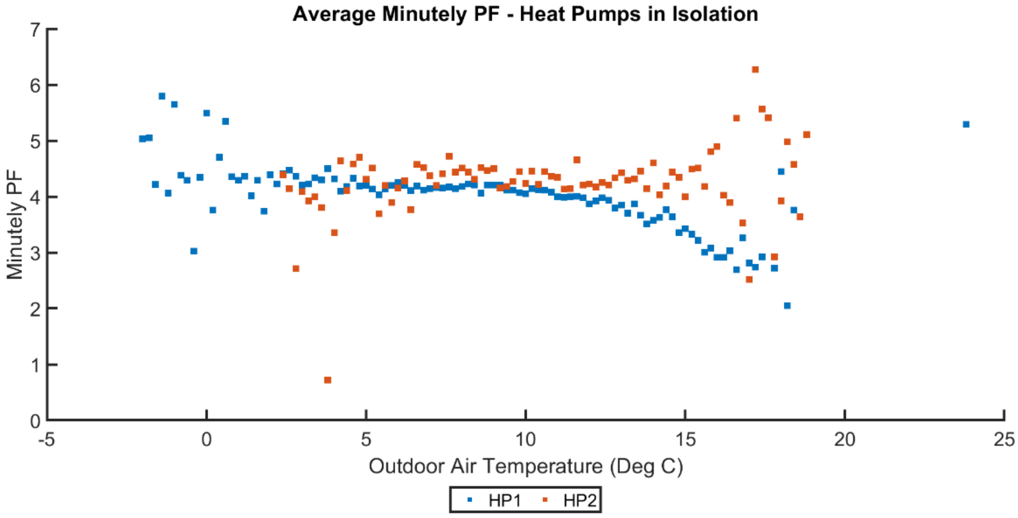


Figure 202 – Minutely PF1* vs Outdoor Air Temperature for Heat Pumps Working in Isolation

The difference between the PFs can be partially attributed to the difference in sample size of the data sets. There are 145,389 valid PF readings for heat pump 1 operating in isolation, whereas there are only 12,544 for heat pump 2, only 9% that of heat pump one. This means that for each temperature bin, there are likely less samples for heat pump 2 and this will skew the relationship somewhat.

Figure 203 shows the heat provided by each of the heat pumps when operating in isolation.

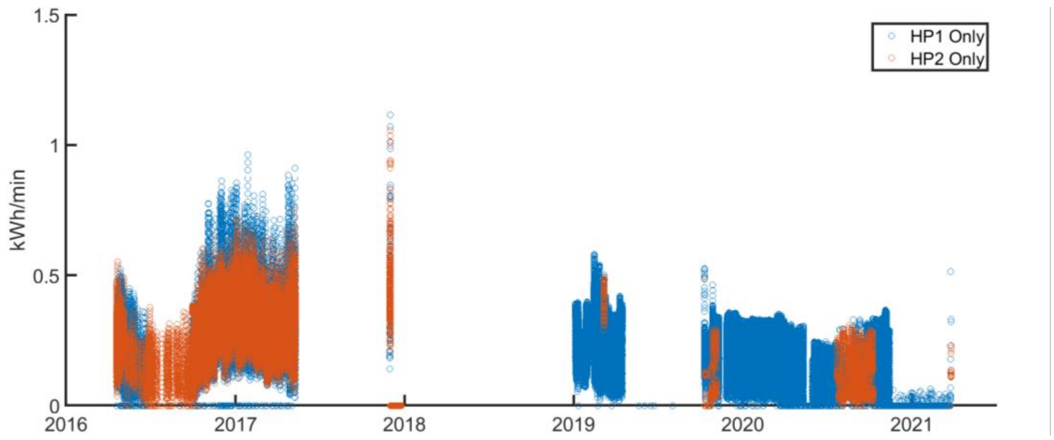


Figure 203 - Heat Provided by Each Heat Pump Working in Isolation

This shows that the majority of the timesteps in which heat pump two was operating in isolation occurred before the main circulation pump was replaced and the controls adjusted.

To calculate the PFs for each heat pump throughout the monitoring period it was necessary to apportion the heat delivered to the building when both heat pumps were in operation to the individual heat pumps.

Figure 204 shows the electrical energy to heat relationship for each of these heat pumps operating in isolation.

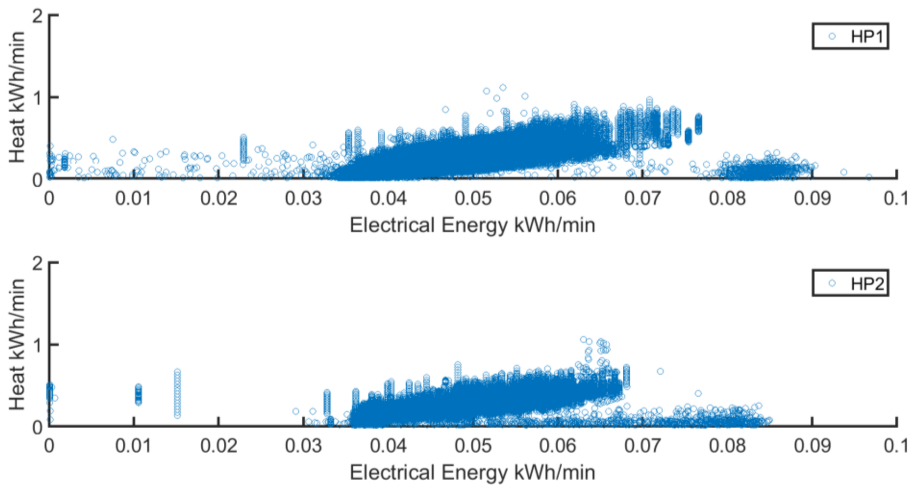


Figure 204 – Electrical Energy vs Heat for Heat Pumps Operating in Isolation

Both heat pumps are exhibiting very similar behaviour, as expected, and as such when both heat pumps are in operation simultaneously the power being consumed by each heat pump is used as a ratio to allocate the heat produced.

This allows for the calculation of the individual heat pumps PFs whilst both are running.

It is worth commenting that as the heat pumps are single speed, it is expected that the energy used by each would be the same if they are both operating simultaneously. The main difference in these values would be caused by the compressor ramping up and down as the assist heat pump is turned on or off.

Figure 205 and Figure 206 show the average PF for each heat pump as the outdoor temperature varies. Unlike Figure 202, this includes the data from when both heat pumps are in operation at the same time to provide a more complete picture of how the heat pumps are operating in certain conditions. These figures also display how the average SEI varies for each heat pump, again omitting the PFs and SEIs which have SEIs greater than 0.55.

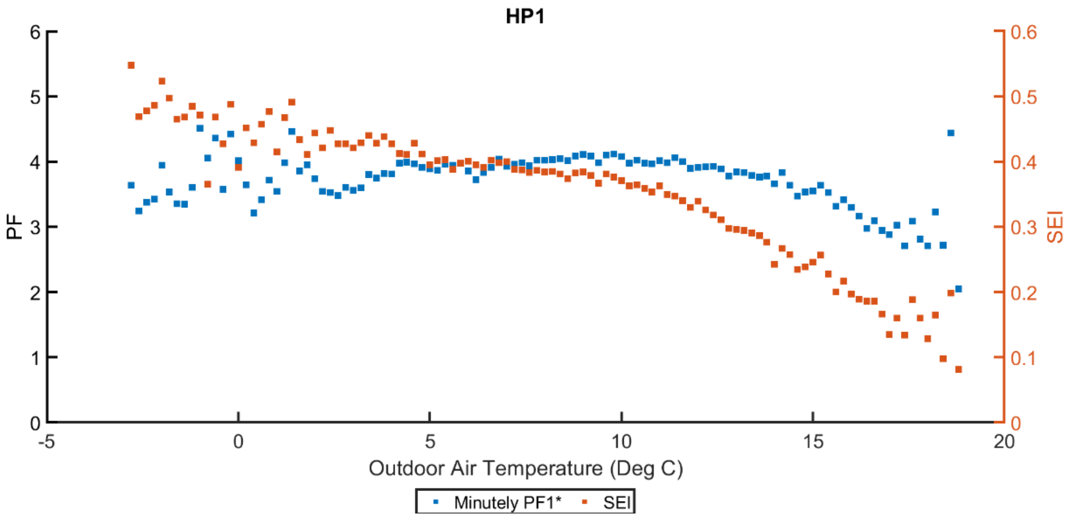


Figure 205 - Heat Pump 1 PF1* and SEI vs Outdoor Air Temperature

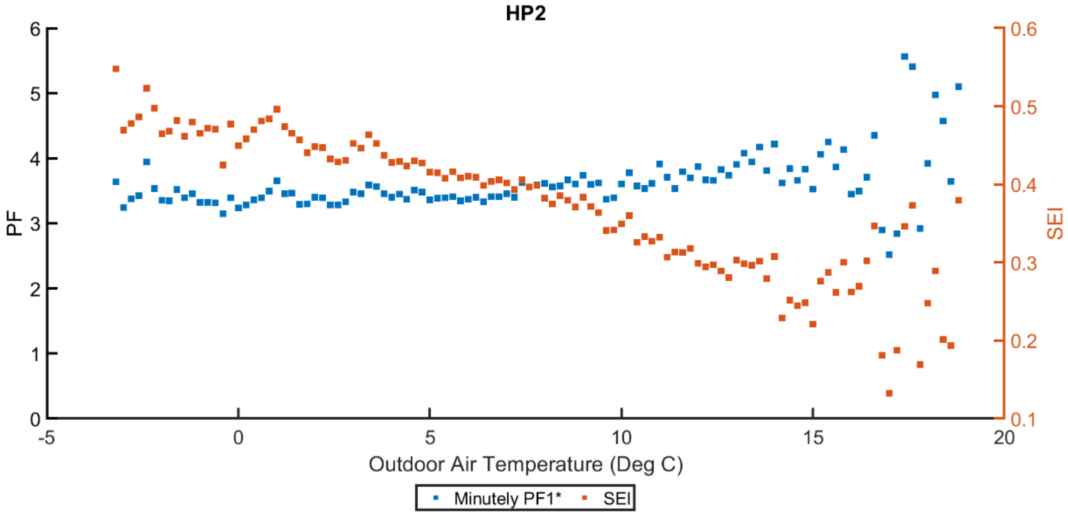


Figure 206 - Heat Pump 2 PF1* and SEI vs Outdoor Air Temperature

These figures show that when the outdoor air temperature increases, the performance of heat pump 1 initially increases before degrading from about 10°C onward. Heat pump 2 on the other hand generally increases in PF before the correlation disappears above around 15°C. Both heat pumps generally produce PFs greater than 3, however, the SEI for both drops away significantly with increasing outdoor temperature, indicating they are not achieving close to the theoretical maximum PF for the given conditions. This is likely due to the shorter cycles the heat pumps are running at for the higher outdoor temperatures, as less heat is required in the buildings. The PF drop off for heat pump 1 is potentially also due to the cycle times of the heat pumps as heat pump 1 has been found to be the duty heat pump more often than heat pump 2. This is investigated in Section 5.4.2.7.

5.4.2.4 Monthly & Seasonal Performance Factors

The analysis conducted allows for the performance factors to be calculated at much more regular timesteps than the manual readings. Figure 207 shows the annual performance factor at each of the four available system boundaries: 1*, 2, 3, and 4. Again, these performance factors are limited by the data availability for the required parameters and so for each *year*, only *months* that contained data for both the heat delivered to the building and energy used by at least one of the heat pumps have been included in the calculations. Similarly in calculating the *monthly* performance factors, only *weeks* in which the power to the heat pumps and heat data is available have been included.

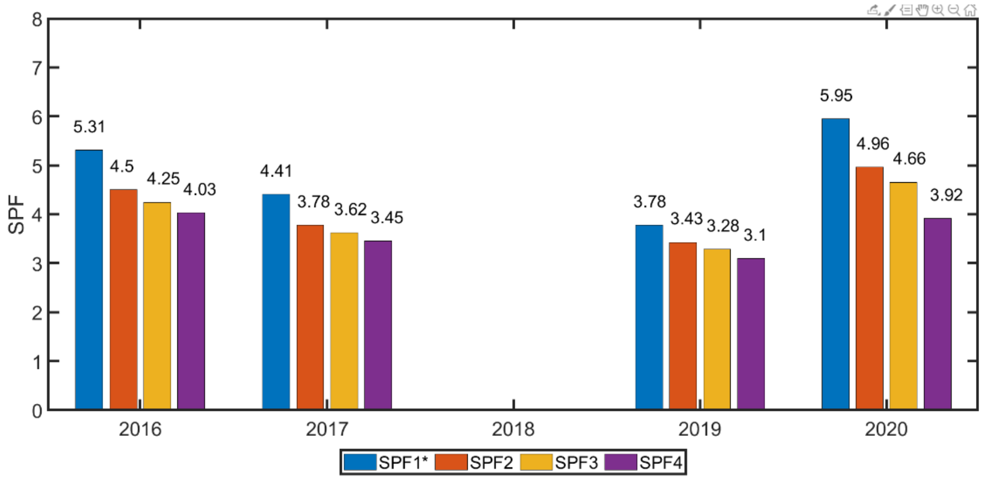


Figure 207 - System SPF at Multiple Boundaries

The system SPF doesn't drop below three in the four years of the monitoring period available. The SPF at boundary level one reaches close to 6 in 2020, which is a marked rise from the 3.78 recorded in 2019, highlighting the variability of the performance level for this system. The drop in PF between boundary level 1* and 2 shows that the brine circulation and borehole pumps are using a significant amount of energy. This represents the additional electricity that would not be needed in a traditional heating system or an air source heat pump and so it is important that this is not overly draining on the systems efficiency.

Figure 208 to Figure 211 show the monthly performance factors at each month. It was not possible to report a value for every month of the monitoring period due to data availability. Each figure represents a calendar year for ease of comparison, and 2018 has been omitted as previously discussed.

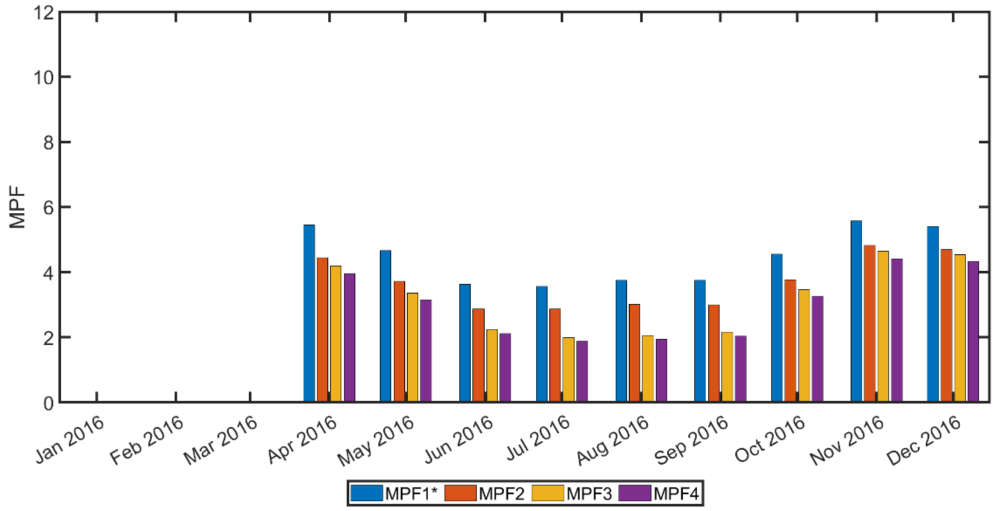


Figure 208 - MPF at Multiple Boundaries - 2016

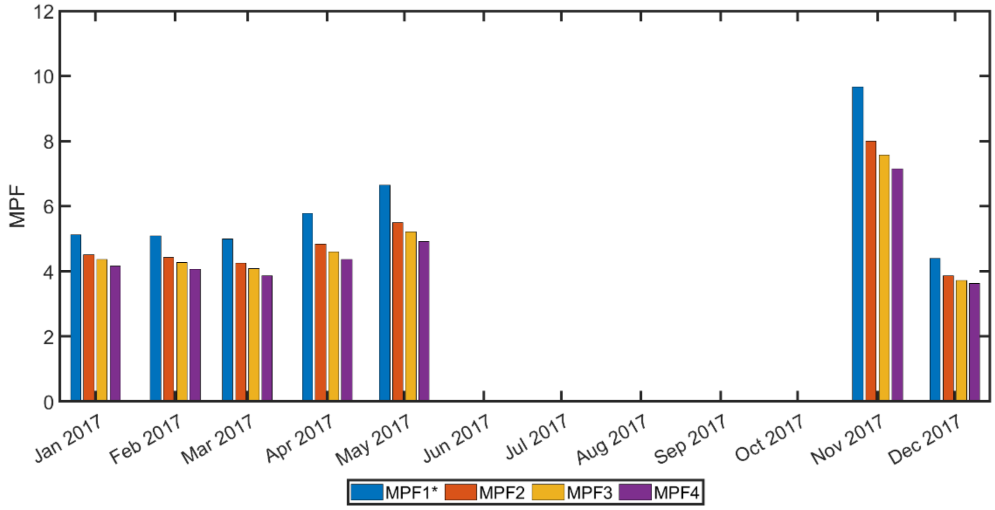


Figure 209 - MPF at Multiple Boundaries - 2017

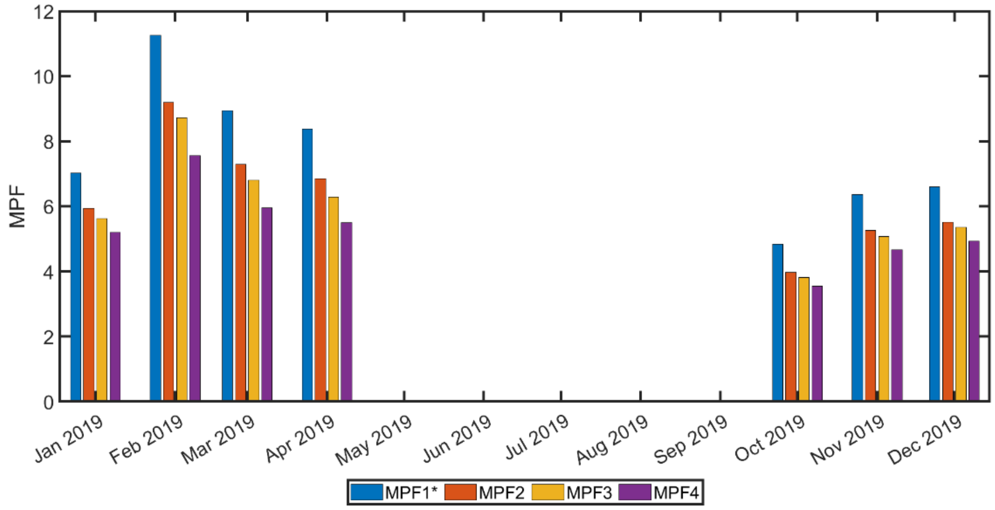


Figure 210 - MPF at Multiple Boundaries - 2019

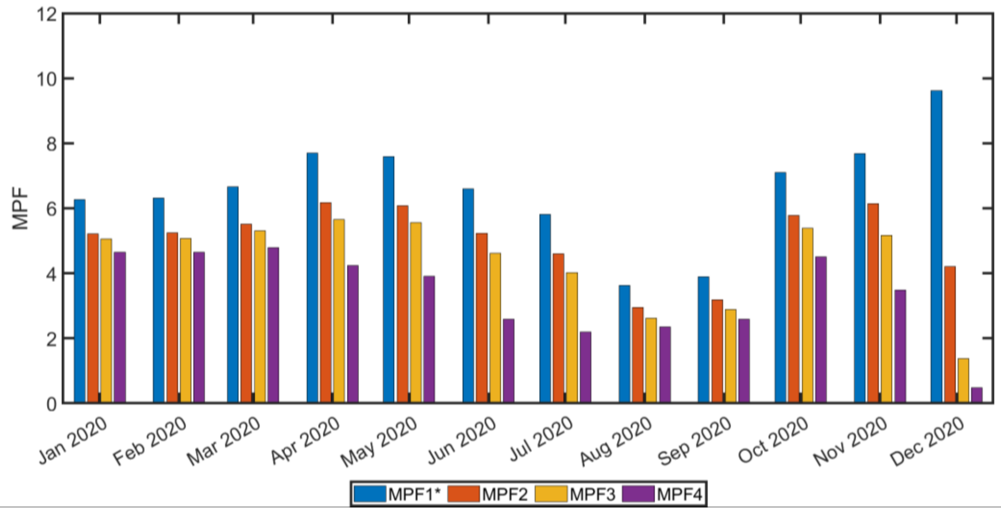


Figure 211 - MPF at Multiple Boundaries - 2020

These figures demonstrate a range of performance factors achieved by this system, reaching up to a maximum of 11.2 in February 2019 and a minimum of 3.6 in July 2016 for MPF1*.

The data during the summer months in 2016 and 2020 show the drop in performance associated with the lower loads, typically from June to September. It is also worth noting the drop in performance from boundary level 1* and boundary level 4, as boundary level 4 encapsulates all of the circulation pumps and thus ultimately determines the emissions and costs for the system as a whole.

Figure 212 to Figure 215 and Figure 216 to Figure 219 show the monthly performance factors of the system when only one heat pump is in operation: heat pump 1 or heat pump 2 respectively. Naturally, these figures are missing performance factors for a number of months, either when both heat pumps are running, the other heat pump is running in isolation, or the data is not available. Once again 2018 has been omitted from this analysis.

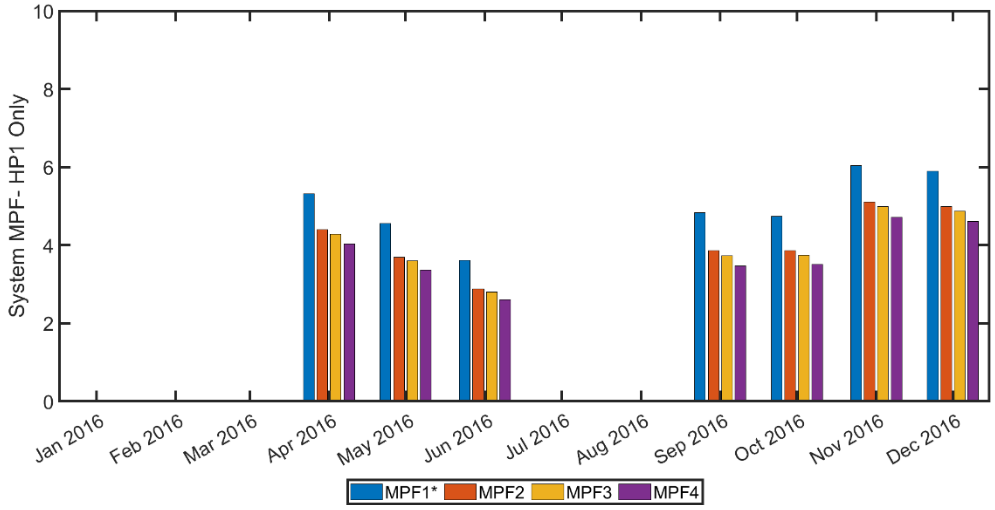


Figure 212 - HP1 MPF at Multiple Boundaries - 2016

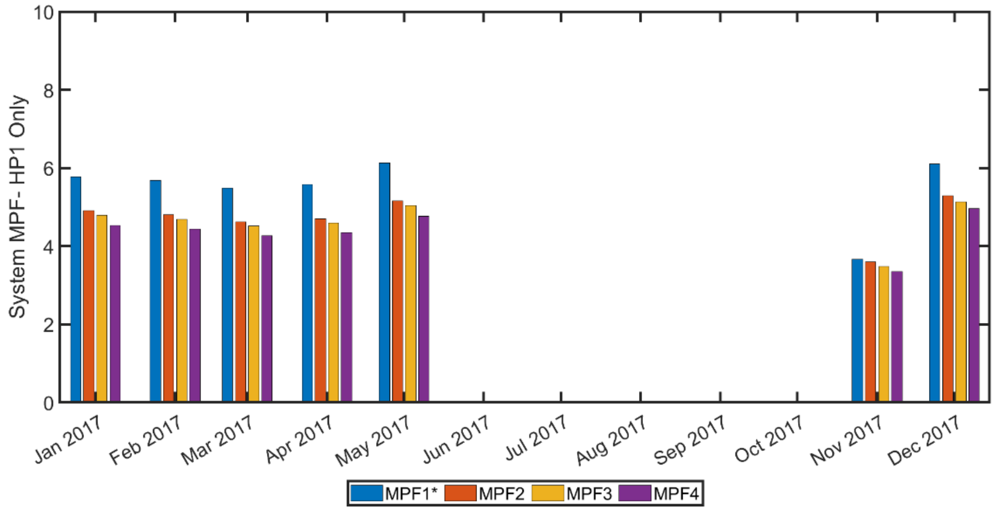


Figure 213 - HP1 MPF at Multiple Boundaries - 2017

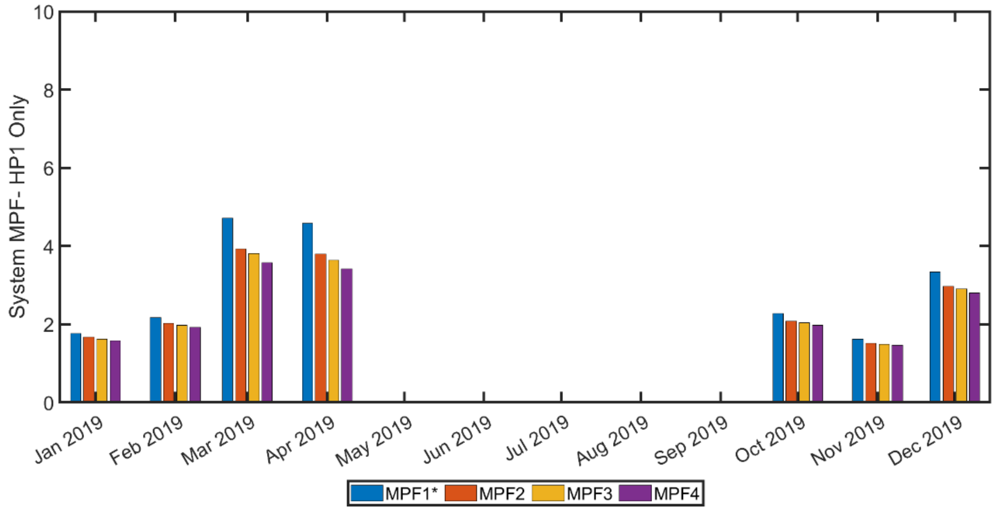


Figure 214 - HP1 MPF at Multiple Boundaries - 2019

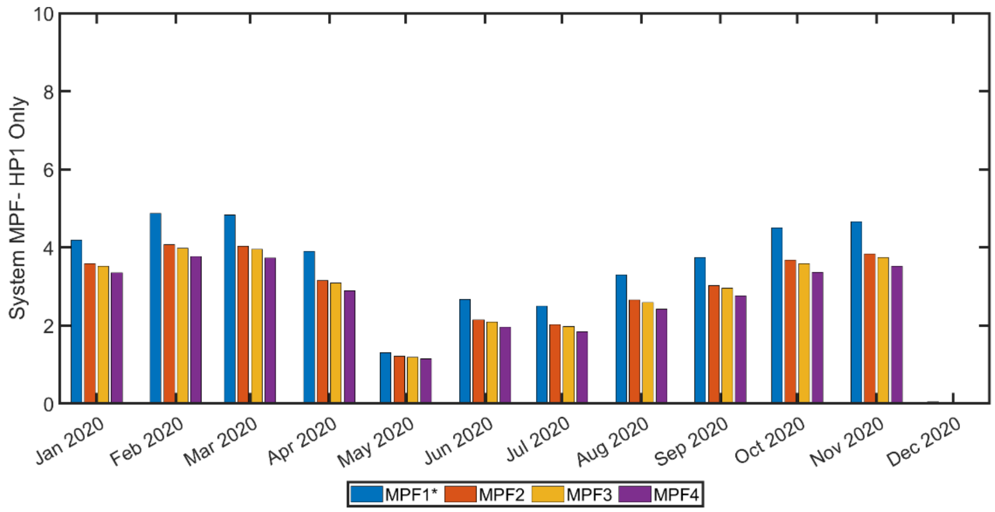


Figure 215 - HP1 MPF at Multiple Boundaries - 2020

When heat pump 1 is operation, the performance factors range from 1.3 in May 2020 to 6.1 in May 2017 at boundary level 1. This is quite a large difference for the same time of year, however the load during May 2020 was only half the load May 2017. This is potentially influenced by changes in system controls over the monitoring period, however a larger load would lead to longer cycle times and, coupled with a higher groundwater temperature due to mild weather at the time, would result in high performance factors.

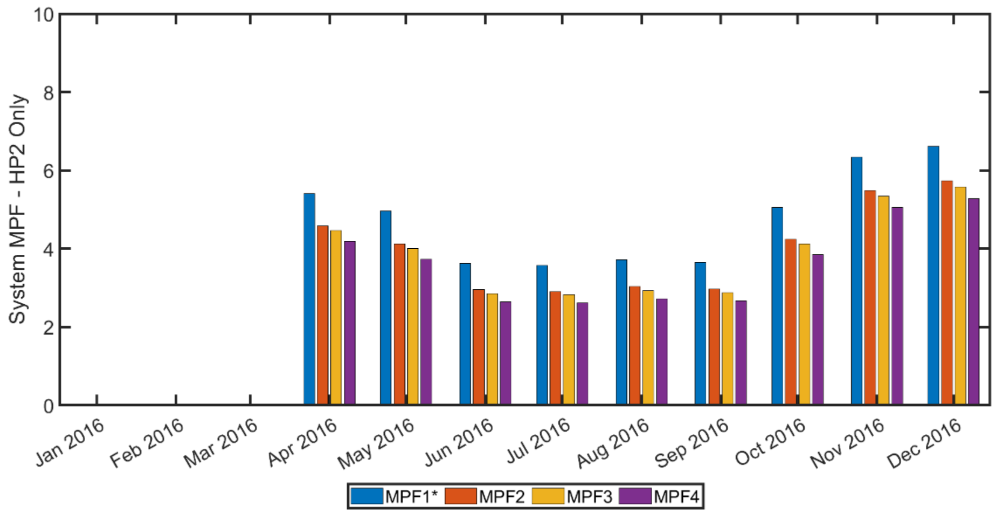


Figure 216 - HP2 MPF at Multiple Boundaries - 2016

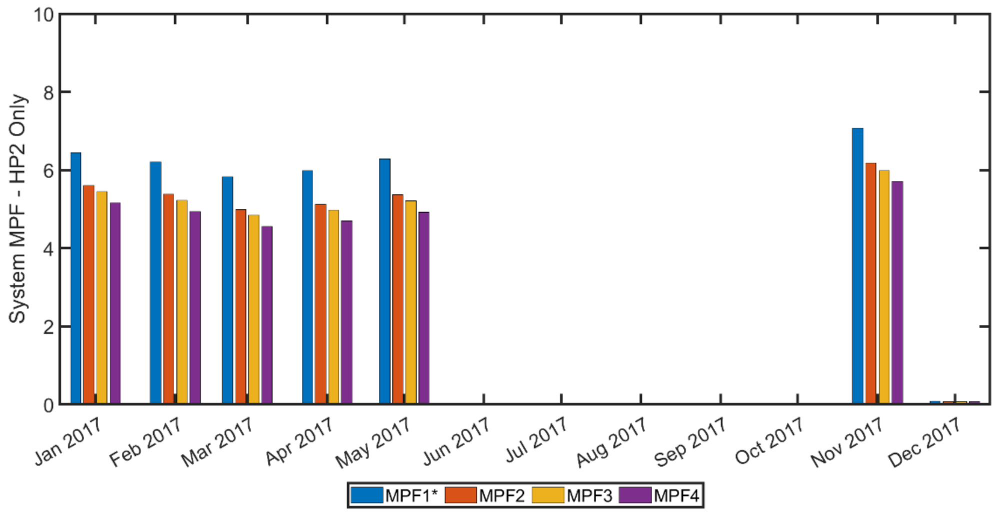


Figure 217 - HP2 MPF at Multiple Boundaries - 2017

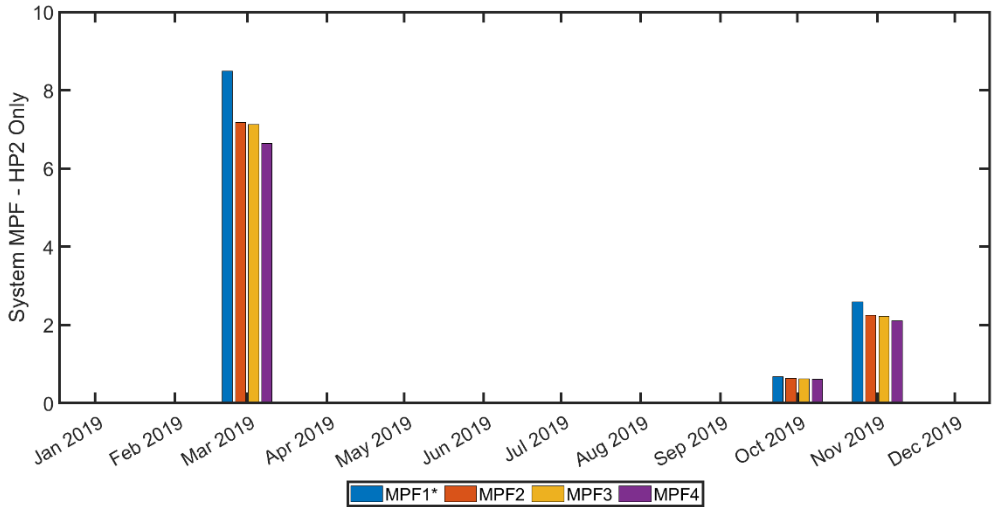


Figure 218 - HP2 MPF at Multiple Boundaries - 2019

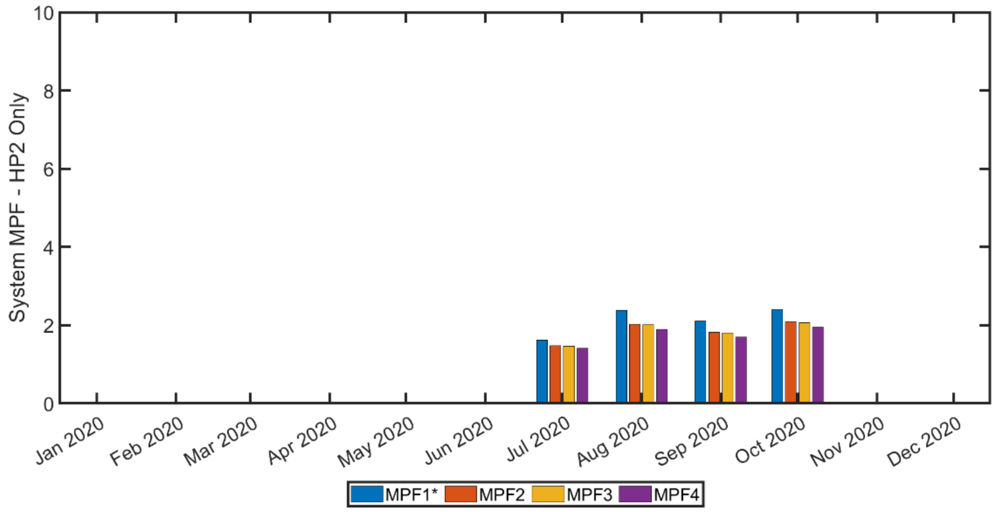


Figure 219 - HP2 MPF at Multiple Boundaries - 2020

It is immediately clear that heat pump two is utilised in isolation significantly less than heat pump one, particularly from 2019, and provides a much more variable performance factor from as low as 0.7 in October 2019 reaching up to 8.5 in March 2019. The extremely low value of 0.1 in December 2017 is the result of a limitation in how the performance factor is being calculated for this system; the heat is being calculated after the buffer tank when the main circulation pump is active. In December 2017 the main circulation pump malfunctioned and wasn't replaced until the end of the month. However, the heat pumps may still have been running and charging the water in the buffer tank even when the heat is not being circulated around the building by the main circulation pump. Unfortunately, due to the data sets available for the analysis it was not possible to calculate the heat generated before the buffer tank.

This could also be a limitation of the performance factors for the remaining monitoring period even with a functioning main circulation pump, however Figure 220 and Figure 221 show the number of hours of operation per week of the heat pumps and the main circulation pump, indicating that during typical usage the main circulation pump actually runs for longer than the heat pumps.

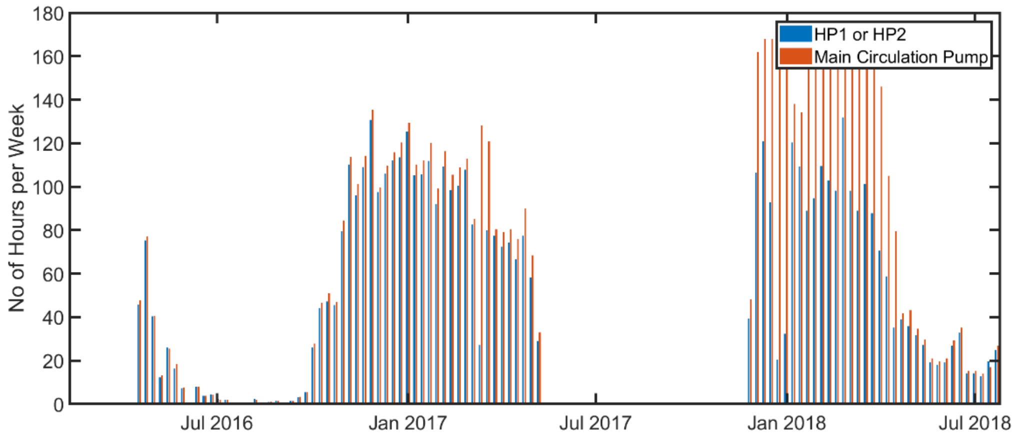


Figure 220 - Hours of Operation Per Week - HPs and Main Circ Pump Jan 2016 – July 2018

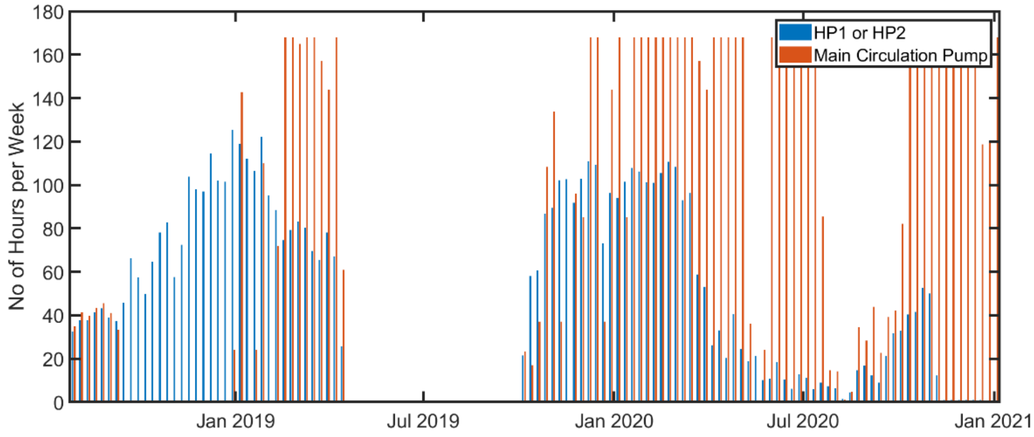


Figure 221 - Hours of Operation Per Week - HPs and Main Circ Pump July 2018 – Jan 2021

Interestingly, these figures also highlight the potentially excessive usage of the main circulation pump, particularly from 2018 onwards, with this pump running almost constantly in 2020 despite the load and operational times of the heat pumps reducing significantly during the summer months.

Figure 222 shows how the electricity usage of this pump changes over time, maintaining a higher level for longer periods towards the end of the monitoring period.

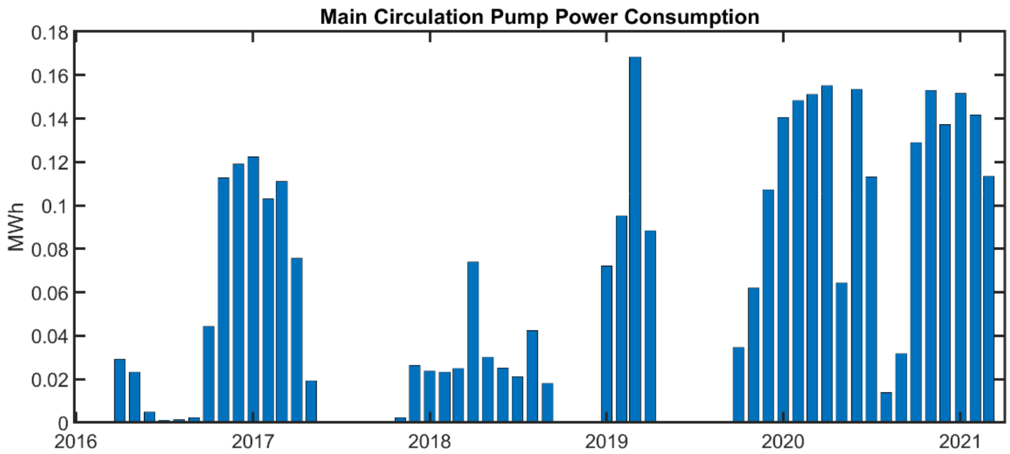


Figure 222 - Main Circulation Pump Monthly Energy Usage

Figure 223 shows the total overall electricity breakdown, again highlighting the main circulation pump to be a higher percentage than expected.

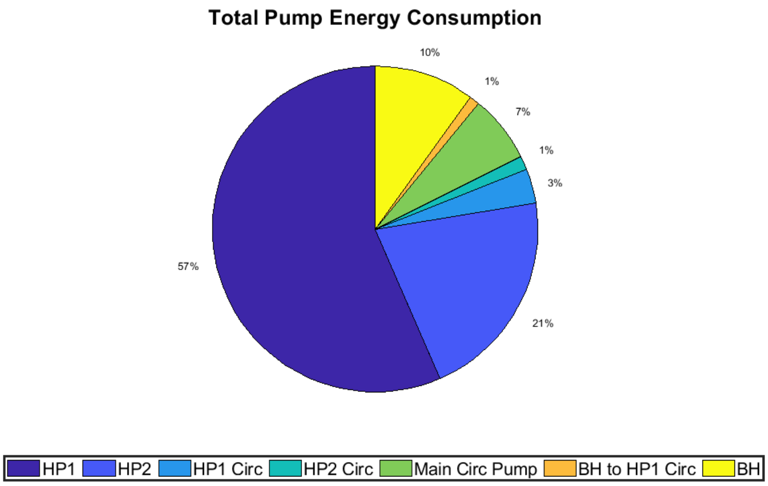


Figure 223 - System Energy Consumption Breakdown

Figure 224 and Figure 225 demonstrate how the system SPFs at each of the boundaries varies with the outdoor air temperature and groundwater temperature respectively.

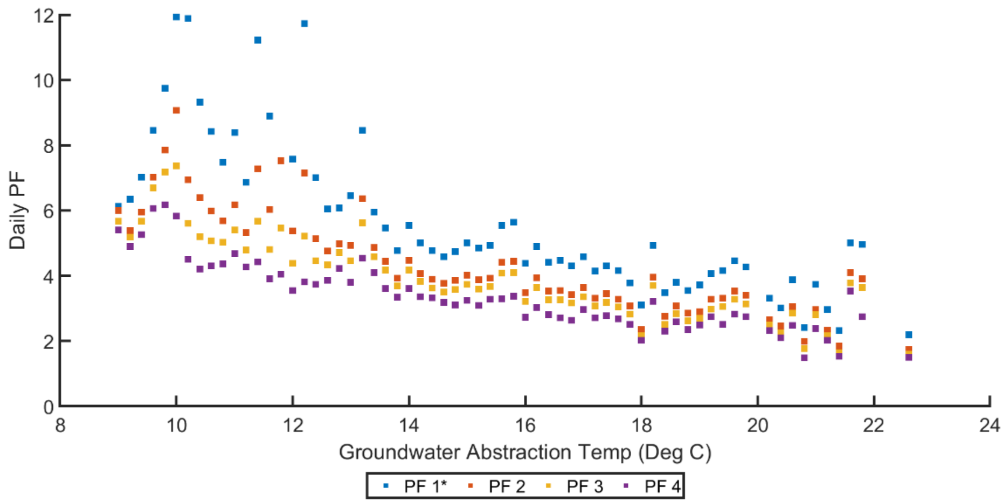


Figure 224 - Daily PF vs Groundwater Temp

Figure 224 shows a clear declining performance factor as the abstracted groundwater temperature rises, across system boundaries 1, 2, 3, and 4. This is counterintuitive, but it is likely that at these higher temperatures, the outdoor air temperature is higher, as shown by the strong correlation in Figure 192 and Figure 193, and thus there is less heat demand for the building. This in turn would cause shorter cycles and this along with no weather compensation in the controller would lead to frequent cycling and an increase in the percentage of power represented by the circulation pumps on/off times, thus degrading the performance.

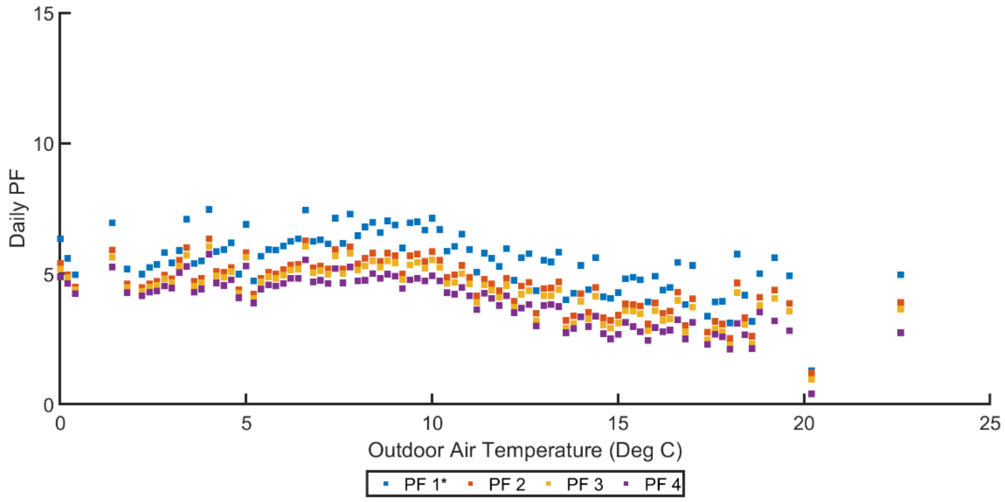


Figure 225 - Daily PF vs Outdoor Air Temp

Whilst Figure 225 still shows a decline in performance as the outdoor air temperature increases, it is not as dramatic as with the groundwater and only appears when the outdoor air increases beyond 10°C.

5.4.2.5 System Utilisation

Similarly to Figure 220 and Figure 221, Figure 226 shows the utilisation of the individual heat pumps across the whole monitoring period, this time as a percentage of time spent on per month.

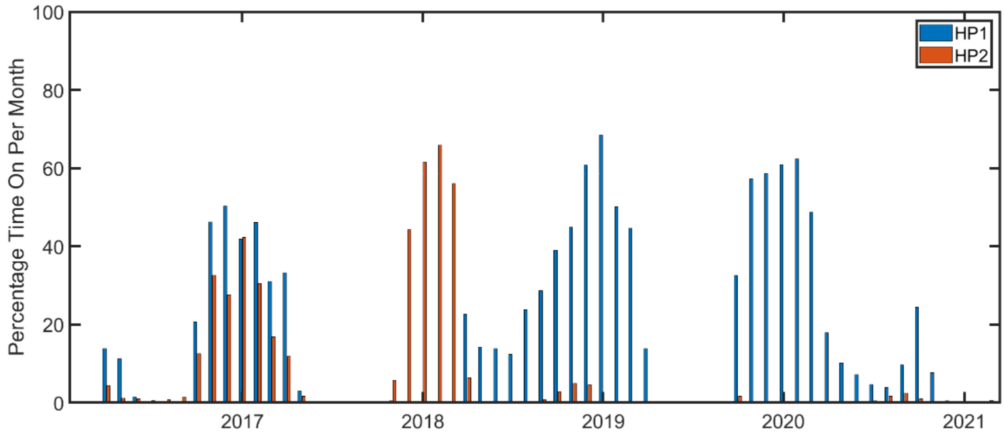


Figure 226 - Utilisation of Heat Pumps

This, again, shows the dramatic imbalance of use between the two heat pumps, particularly from 2018 onwards. The system was originally setup to operate in a duty assist manner. In this arrangement the system is usually designed to switch which heat pump is the duty heat pump every few weeks to avoid excessive wear on a single heat pump. This appears to have been the case originally, with both heat pump 1 and 2 being used to similar degrees in 2016 and 2017, but from November 2017 to April 2018, the period encompassing the main circulation pump breakdown and replacement, heat pump 2 appears to be running as the duty heat pump. This is then reversed from April 2018 to the end of the monitoring period, with heat pump 1 being the duty heat pump and heat pump 2 assisting when required. This is likely not an optimal strategy for maintaining the system.

Figure 227 shows the percentage of time that *both* heat pumps were operating simultaneously.

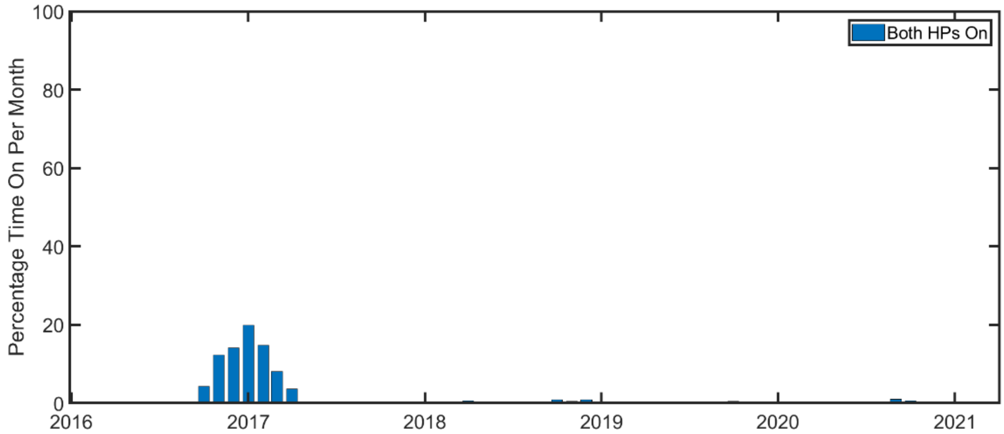


Figure 227 - Utilisation of Both Heat Pumps Simultaneously

Clearly it is rarely necessary for both heat pumps to be running together, particularly after the apparent control regime change in 2018. That does not necessarily indicate however that the system is oversized.

Figure 228 shows the instantaneous heat to the building whilst both heat pumps are in operation, in kW, and Figure 229 demonstrates how often the system is producing more than 11kW of heat for each of the three operating modes: HP1 only, HP2 only, and both HP1 and HP2 operating.

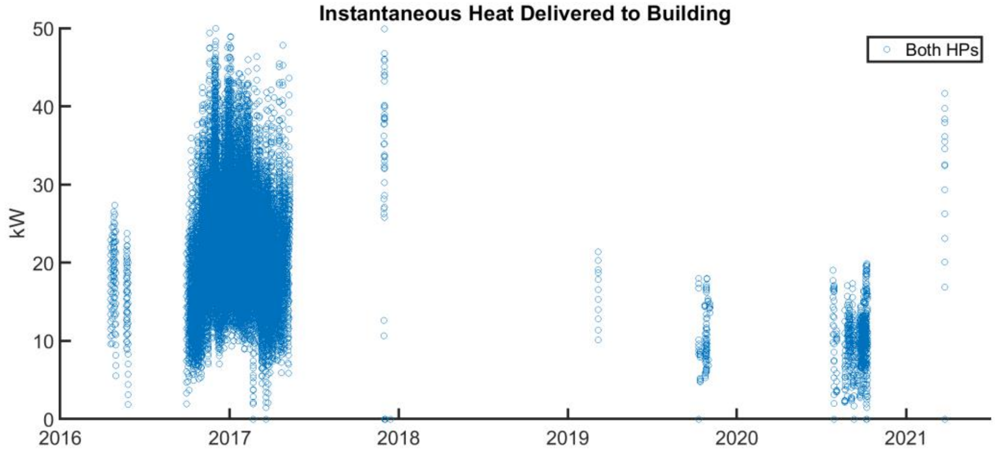


Figure 228 - Instantaneous Heat Delivered to the Building

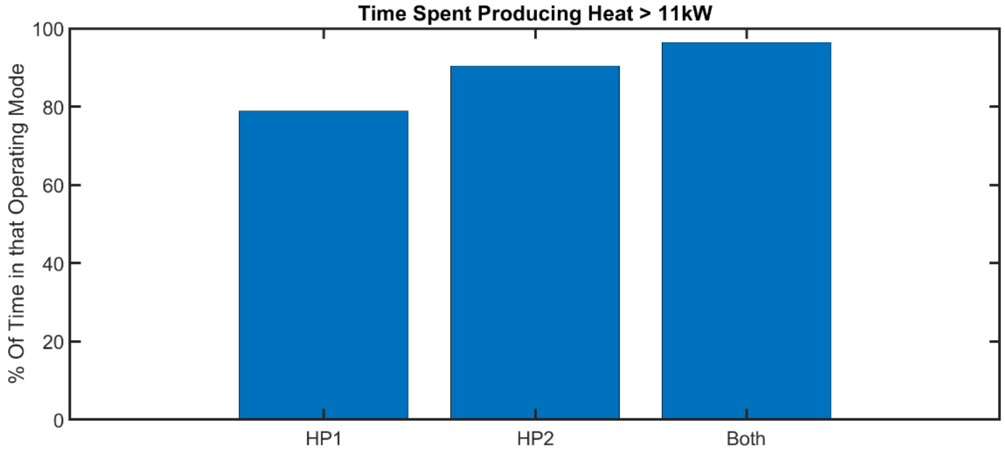


Figure 229 - Time Spent On Producing >11kW Heat

These figures show that the heat demand is greater than the 11kW each individual heat pump is rated for. The heat pumps are likely exceeding this output due to the elevated brine temperatures compared to the 0°C specified in the manufacturers data to produce the 11kW capacity. However, the extremely high values, closer to 50kW in Figure 228, seem beyond the heat pumps capabilities. These values could be being affected by how the heat has been calculated. The flow and return temperatures were used to calculate the heat whenever the main circulation pump was running, however there will be a delay in the heated fluid reaching the return temperature sensor. As such, when the pumps first start circulating the water, the flow temperature will read a high value, close to the target temperature, and the return will still read a low value, resulting in a very wide delta T. Similarly, when the main pump or the heat pump turns off, the flow temperature could read lower than the return temperature depending on how quickly it drops. Unfortunately, as the temperature data to and from the building loop is only available in 15-minute intervals, it is difficult to validate this.

Similarly to Figure 226, Figure 230 shows the amount of time the borehole pump spent switched on, according to the proxy data.

As expected, the pump runs significantly more during the winter months, but again the energy when the system was left running over the summer can be seen here. This is much lower in 2020 than in 2018 but as the building is unoccupied over the summer this is still wasted energy compared to when the system was correctly turned off in the summer of 2019.

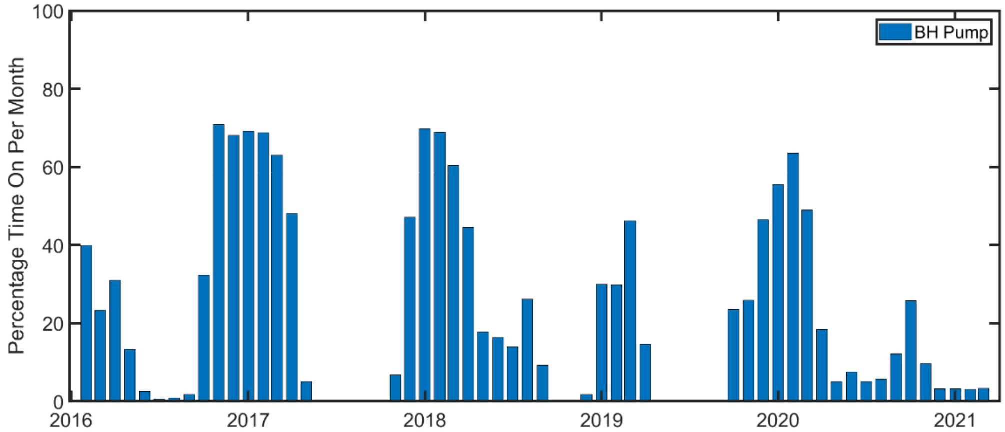


Figure 230 - Utilisation of Borehole Pump

5.4.2.6 Control – Variability

As the building is used as a nursery school it is unoccupied from the evening until early morning, unlike a residential building. Therefore, there should be little to no heat demand from the evening to mid-morning every day, and at all over the weekends.

Figure 231 shows the average heating day for each calendar month in 2020, the year with the most complete heat data available. The same figures for the other years of monitoring can be found in Appendix C2.

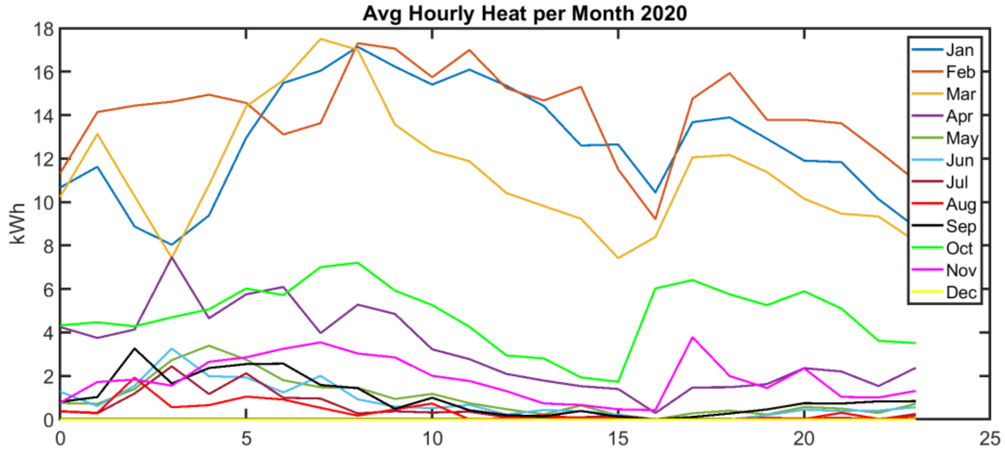


Figure 231 - Average Heating Day Per Month - 2020

These figures clearly show the difference in heat demand through the year, but they also show that the system is providing heat to the building throughout the whole day i.e. the nursery is being heated even when it is unoccupied. This is potentially wasting a lot of energy, heating an empty building during the coldest hours of the day though the decreasing demand in the later hours of the evening suggest there may be some setback control to limit this wastage.

Similarly, Figure 232 shows the typical energy usage per day for each calendar month, again in 2020.

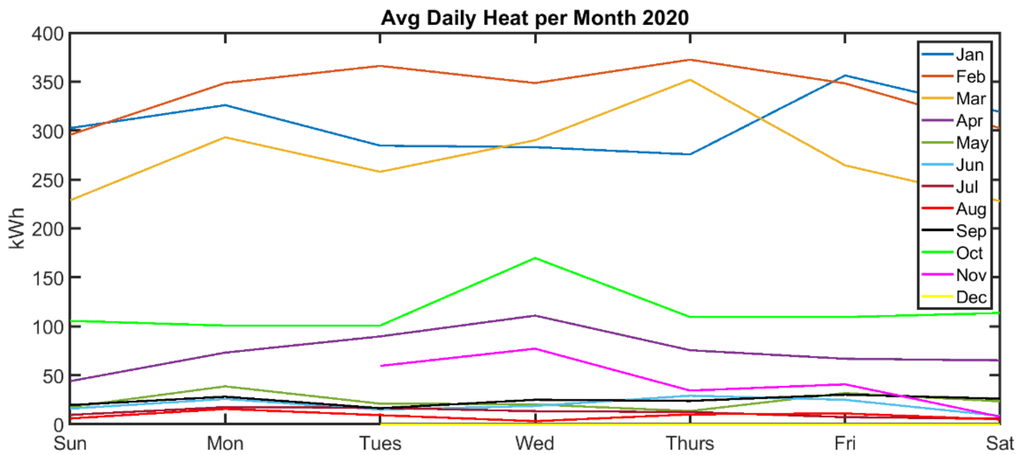


Figure 232 - Average Heating Week Per Month - 2020

These figures show that the system is not only running unnecessarily overnight, but at weekends as well. This will add to the wasted energy and mean that emissions and running costs attributed to the system are higher than necessary.

According to the instruction manual, the heat pumps were set to auto mode, which automatically turns the heat pumps up, down and off according to the programmed times. The previous figures suggest these shut down periods may not have been programmed correctly or to the extent that they could have been to further reduce costs and emissions.

5.4.2.7 Cycling

Figure 233 and Figure 234 show the average daily cycle time of heat pump 1 and heat pump 2 respectively, when operating in isolation.

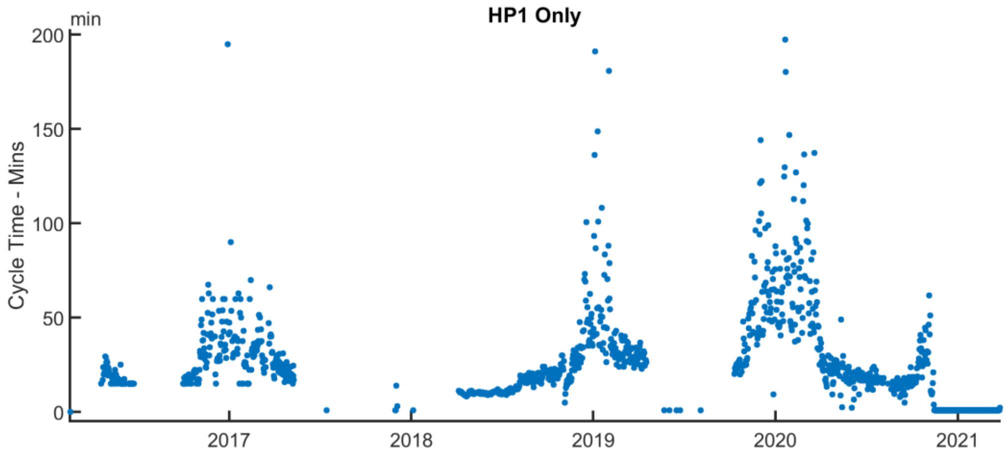


Figure 233 - Cycle Time - HP1 Operating in Isolation

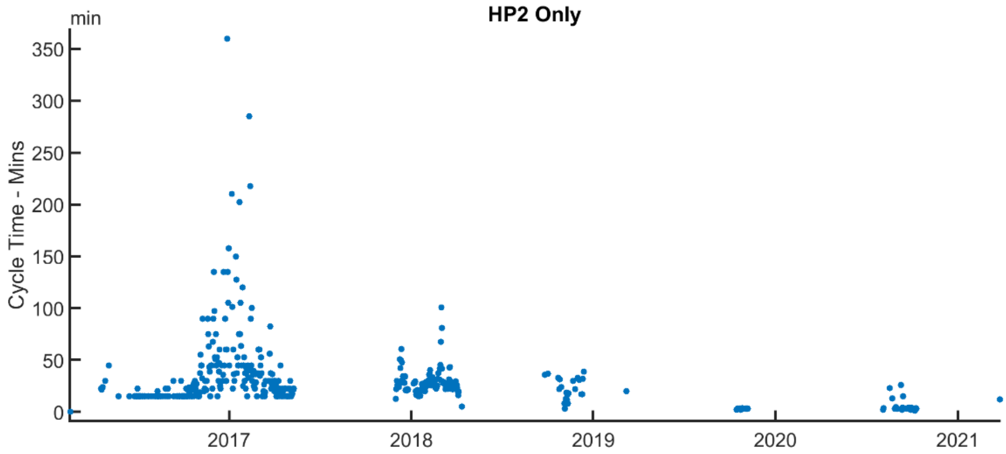


Figure 234 - Cycle Time - HP2 Operating in Isolation

Despite the reduced data available, the seasonal patterns can still be observed for both heat pumps. Heat pump 1 has significantly larger cycle times during the winter months and similarly heat pump 2 generally only appears to run in isolation over these months, albeit often at smaller cycler times than heat pump 1, particularly post 2018.

As the heat pumps are set up as duty-assist, to investigate the link between cycling times and system performance, the data had to be split and analysed when only one heat pump was in operation. This is because, for example, heat pump 1 could operate for a 60-minute cycle, but during those 60 minutes, heat pump 2 could turn on as an assist and produce heat for a 15-minute cycle. In this case, the data would produce a performance factor for heat pump 1 with a cycle time of 60-minutes with no accounting for the fact it was assisted by heat pump 2. As such the performance data was interrogated for periods when only one heat pump was operational at a time.

Figure 235 and Figure 236 show the mean system performance factor at boundary level one for each of the cycle times for heat pump 1 and 2 respectively. Only cycle times from 5 minutes and upwards have been shown here to avoid power and heat data misalignment at short time intervals from skewing the data. These figures also display the number of occurrences for each cycle length.

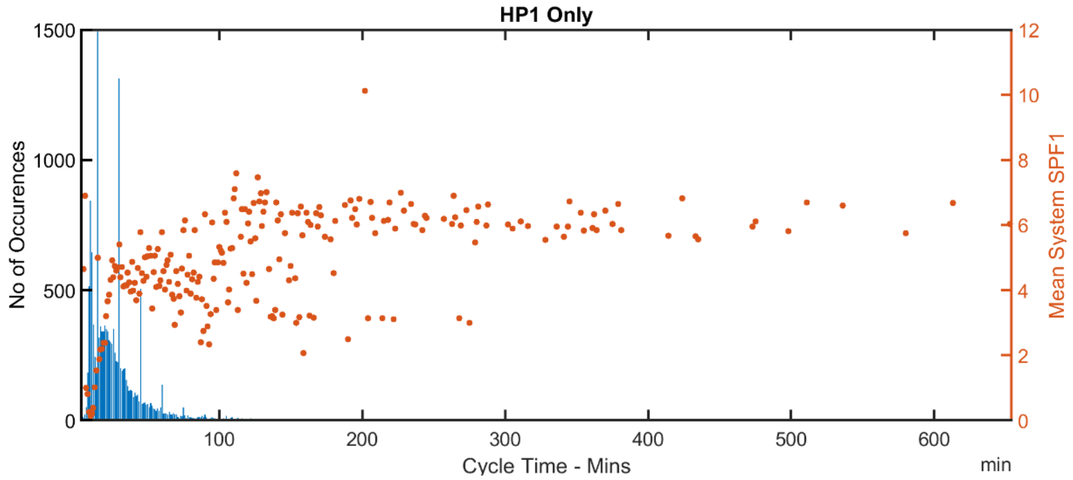


Figure 235 - HP1 PF vs Cycle Time

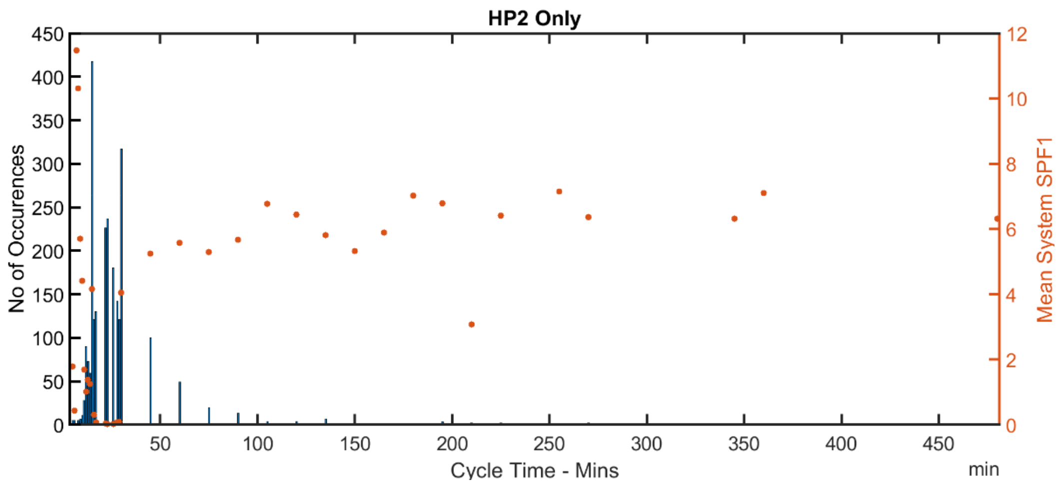


Figure 236 - HP2 PF vs Cycle Time

As would be expected, the larger cycle times have very few occurrences so Figure 237 and Figure 238 show the same data but limited to cycles lengths that occur more than five times.

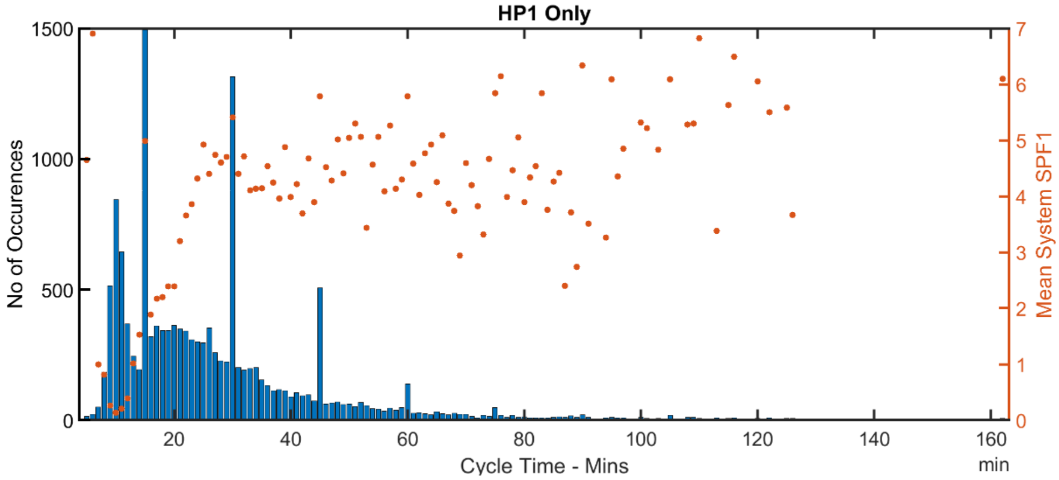


Figure 237 - HP1 PF vs Cycle Time - Adjusted

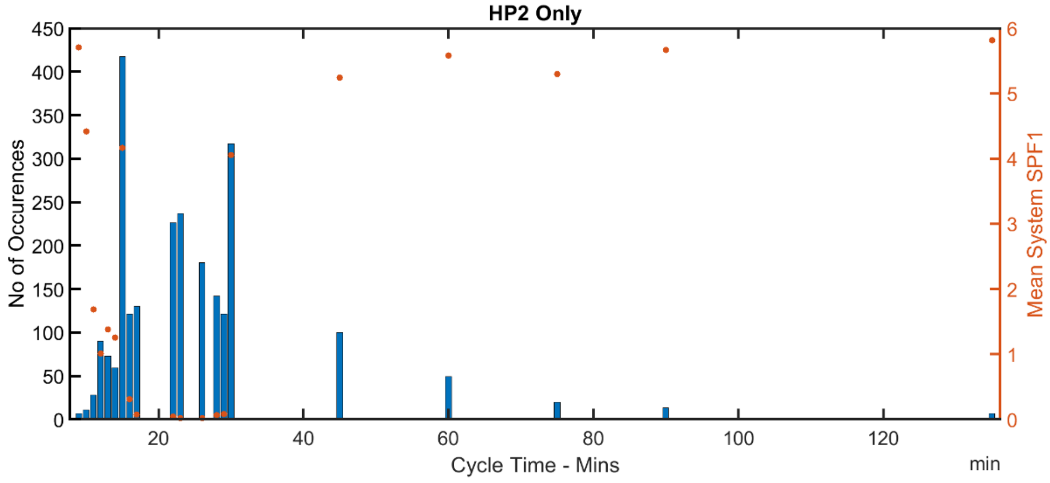


Figure 238 - HP2 PF vs Cycle Time - Adjusted

For both heat pumps, the PFs appear to stabilise as the cycle time increases beyond roughly 30 minutes. Heat pump one in particular shows a very clear trend before this point that the longer the cycle time the greater the PF, supporting some of the previously made assertions about the performance of this system.

5.5 Discussion

5.5.1 Logistical Challenges

One of the key points highlighted by this system is the need for a clearly defined monitoring strategy at the time of installation, as touched on in the literature review. It is noted that the performance of the heat pumps was not the initial focus of the monitoring for this system, rather the focus was on the effects on the underlying aquifer, and to that end the monitoring setup was appropriate. However, with a few additional pieces of equipment, a more detailed and accurate understanding of the system as a whole could have been gained. Such additional monitoring could include remote, continuous monitoring of the heat delivered to the building at smaller time scales, the heat delivered to the buffer tank, and the heat extracted from the aquifer.

That is not to say that the information available isn't useful; clearly, the significant number of issues with the various datasets made the analysis of this system challenging, however, utilising a number of different approaches and assumptions, a substantial amount of additional information has been gleaned. In fact, this study shows what can be achieved with data that is not directly set up to monitor the performance of the heat pumps. However, this was a time intensive process, and collecting the additional data points would likely have been more cost effective.

Additionally, good record keeping, monitoring, and communication about ongoing work and issues with the system would benefit all interested parties and would allow for a deeper interpretation of the data presented in this chapter. For example, detailing the parameter set for the various circulation pumps, or what maintenance has been conducted on the equipment.

A number of these records may be kept on site, but due to COVID and other challenges, a visit to site was not possible during the undertaking of this analysis. Therefore, a number of assumptions had to be made and validated to analyse this system fully, taking additional time and resources.

Finally, resource should be allocated for continual monitoring to get the most out of such a system. The large data gaps due to a drop in telemetry could likely have been addressed sooner providing better quality data, and additionally, allowing for a quicker response to any malfunctions or unusual performance such as with the main circulation pump in late 2017 to early 2018, or the fact that the system has been left running over the summer.

5.5.2 Design

The aquifer appears to be more than capable of meeting the heating requirements of the building, and the seasonal fluctuation in aquifer temperatures, likely due to the proximity to the surface water, appears to be advantageous for the system’s performance.

However, the heat “rejected” back to the ground during the summer months of 2018 should be investigated further. If, as expected, the cause is an external heat source artificially raising the return temperature post heat exchanger, this is not necessarily problematic, but it should be checked to ensure there is no issue with the sensor and that the system is not rejecting heat back to the ground unintentionally.

The fairly low utilisation rates of the heat pumps, in particular heat pump 2, suggest that the system can typically meet the load with one heat pump, however the heat output when the two heat pumps were in operation together would indicate that the second is still required at infrequent intervals to meet the peak demands. In fact, whilst the heat delivered to the building often exceeded the 11kW mark that each heat pump is rated to, the majority of the time this was delivered by one heat pump rather than both together. However, it appears that the duty heat pump is no longer switching between the two, and thus heat pump 1 is more prone to wear and damage as a result of over-use. This should be addressed to ensure minimal repair costs and heat pump down time, particularly if the system is not being continually monitored and thus any inefficiencies due to wear may go unnoticed for an extended period.

To that end, maintaining the original gas system as a back-up system has allowed the building to continue to be heated when the heat pump system has malfunctioned, but it could also be argued that this has led to delays in addressing the issues and proper running and maintenance of the heat pump system.

5.5.3 Usage patterns

It has also been found that the system is running over the weekends, and sometime during the summer months when the building is likely unoccupied. This is resulting in excessive energy usage and unnecessarily high costs as well as needless associated emissions.

The heat pumps can be set up to turn off at dedicated times via the controller and so it is suggested that this feature is investigated and adjusted to appropriately turn off the system when the building is unoccupied for prolonged periods of time.

Analysis into the average hourly heat delivered to the building suggests that the system is also being used overnight. This potentially could be at a lower setback target temperature to reduce the amount of heat, but it is still suggested that this be investigated as the energy wasted over the evening and mornings could be significantly higher than the inefficiencies that would be caused by running the system a little hotter and harder each morning. Alternatively, the system could be setup to run for a few hours before the building is likely to be occupied to pre-heat it at higher efficiencies.

These changes could provide significant savings in terms of costs and emissions.

5.5.4 Performance

Comparing the calculated performance factors to those from the manual readings in Section 5.4.1, the majority of the values align closely, though there a few discrepancies. These can likely be attributed to a combination of the filtering method used in the detailed analysis removing anomalous readings and periods of data that didn't have both electricity and heat readings, and differences between the flow rate model applied used to calculate the heat produced by the heat pump and actual flow rate.

Figure 239 to Figure 241 shows the average performance factor of the Cardiff system over the whole monitoring period, compared to some similar systems identified in the literature review. The details and references for the comparative case studies can be found in Table 56.

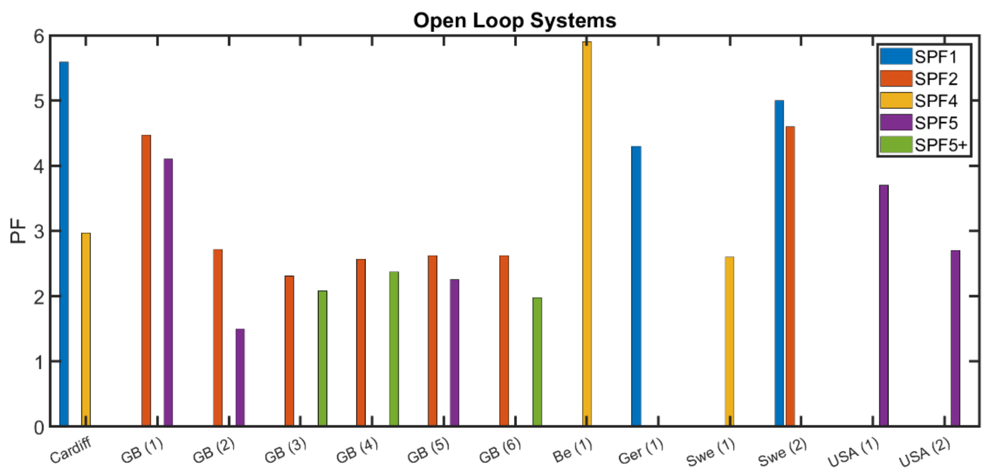


Figure 239 – Average SPF of Open Loop Systems over Monitoring Periods

Figure 239 compares the performance of open loop systems. This shows the Cardiff system to be performing relatively well, outperforming most of the other open loop systems in Great Britain, and providing comparable PFs to the European and American systems.

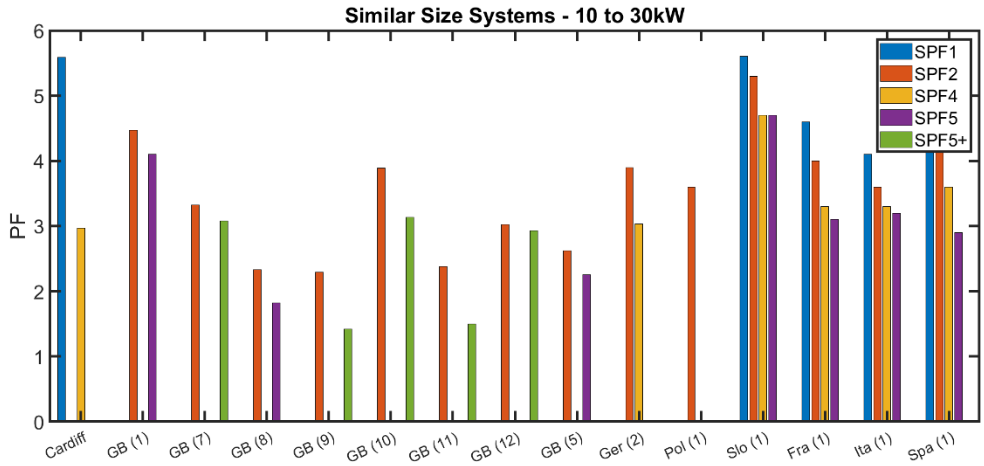


Figure 240 - SPF of 10-30 kW Systems

Similarly, Figure 240 compares the performance of systems with a rated heating capacity between 10 and 30kW. Again, this shows the Cardiff system to be performing relatively well, outperforming a number of the other systems in Great Britain, and providing comparable PFs to the European and American systems.

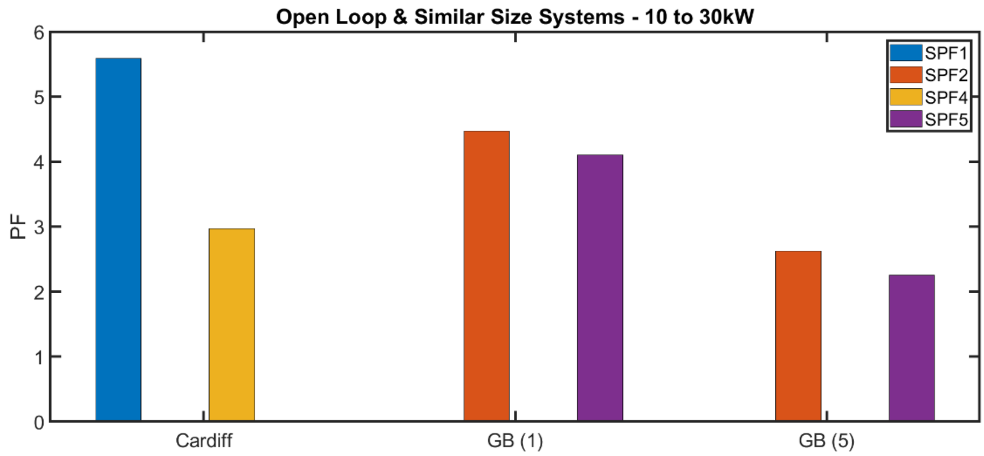


Figure 241 - SPFs of 10-30 kW Open Loop Systems

Finally, Figure 241 isolates the systems that are both open loop and between 10 and 30kW rated heating capacity. These coincidentally are all located in the UK, and whilst it is hard to directly compare due to the different boundaries applied, the Cardiff system appears to perform in line with the other two systems.

Table 56 - Cardiff Comparative Case Study References

Identifier	Country	System Capacity	Building Type	Citation
GB (1)	Great Britain	26.00	Office	(Hughes, 2018b)
GB (2)	Great Britain	96.00	Refectory & Office	(Hughes, 2018b)
GB (3)	Great Britain	60.00	Healthcare	(Hughes, 2018b)
GB (4)	Great Britain	126.00	Large House	(Hughes, 2018b)
GB (5)	Great Britain	30.00	Office & Warehouse	(Hughes, 2018b)
GB (6)	Great Britain	268.00	Large House	(Hughes, 2018b)
Be (1)	Belgium	195.00	Hospital	(Vanhoudt *et al.*, 2011)
Ger (1)	Germany	110.00	Multifamily House	(Bauer *et al.*, 2010)
Swe (1)	Sweden	300.00	Office	(Walfridson, 2021)
Swe (2)	Sweden	1835.00	Office	(Walfridson, 2021)
USA (1)	USA	754.00	Museum	(Im and Liu, 2015b)
USA (2)	USA	280.00	Warehouse	(Liu, Malhotra and Im, 2017)
GB (7)	Great Britain	21.00	Public Hall	(Hughes, 2018b)
GB (8)	Great Britain	22.00	Office	(Hughes, 2018b)
GB (9)	Great Britain	22.00	Greenhouse	(Hughes, 2018b)
GB (10)	Great Britain	14.00	Public Hall	(Hughes, 2018b)
GB (11)	Great Britain	20.00	Terrace (3 Houses)	(Hughes, 2018b)

GB (12)	Great Britain	23.00	Dwellings & Office	(Hughes, 2018b)
Ger (2)	Germany	30.00	Residential	(Bockelmann, 2021b)
Pol (1)	Poland	10.40	Office	(Pater and Ciesielczyk, 2017)
Slo (1)	Slovenia	20.00	Municipal Hall	(Karytsas and Mendrinos, 2016)
Fra (1)	France	26.00	Office	(Karytsas and Mendrinos, 2016)
Ita (1)	Italy	14.00	Factory	(Karytsas and Mendrinos, 2016)
Spa (1)	Spain	18.00	University	(Karytsas and Mendrinos, 2016)

Figures 229-231 indicate that this system is performing relatively well, and across the years monitored, the SPF4 does not drop below 3. As discussed in Section 0 this is likely primarily due to the elevated temperatures resulting from the nearby river and is therefore not typical of open loop systems in general. However, this does highlight the performance benefits available more widely if the temperature lift for the heat pump/s can be minimised.

Figure 220 and Figure 221 show the utilisation of the main circulation pump to be quite high and whilst this is common in open loop systems, with additional investigation and perhaps a change in control strategy it might be possible to reduce the associated consumption, further increasing the performance factors at this boundary level.

The cycle time of the heat pumps also appears to be a large contributor to the performance factor, as the performance for the system falls as the outdoor air temperature and groundwater temperature increase. This is counterintuitive unless the higher temperatures and thus lower loads are causing short cycling of the heat pumps and increased relative run time of the circulation pumps. It might be the case that a smaller secondary heat pump, or alternatively a larger buffer tank, would allow for longer run times even at these lower loads, increasing the efficiency whilst also still providing ample support for the higher loads during winter. Further investigation into this would be required.

5.6 Conclusions

The analysis of the long-term data sets for this system have provided the following conclusions:

- Despite the monitoring system not being set up for continuous performance evaluation, additional analyses of the available data sets have provided greater insight into the performance of the system.
- The use of the circulation pump power, to estimate the flow and allow for the calculation of heat, could be retroactively applied to other existing datasets that were not specifically designed for monitoring heat pump performance.
- Similarly, if high resolution data on the abstraction well water level is available, this can be used as a reasonable proxy for when the borehole pump is in operation
- The system is performing at high levels of efficiency despite the issues noted, highlighting the potential benefits of an open-loop system when in thermal contact with bodies of surface water, and corroborating the high performance factors initially reported (Boon *et al.*, 2019).
- The system appears to be unintentionally rejecting heat to the ground. This is particularly evident during the summer of 2018 and should be further investigated.
- The excessive usage of the main circulation pump should be investigated to potentially reduce electricity costs and associated emissions.
- The control strategy appears to have changed, with heat pump 2 being utilised significantly less more recently than in the earlier stages of the monitoring period.

- The system is running needlessly over the evenings and weekends, despite the property being unoccupied, wasting energy.
- The system would benefit from a caretaker to monitor it for faults, turn it off properly over the summer to allow the temperature to recharge, and ensure it is running smoothly.

5.7 Future Work

Further work on this system would start with a visit to the site to get an accurate understanding of the system settings and maintenance conducted throughout the monitoring period. This would allow for corroboration of the assumptions made in this analysis or allow for new analysis with modified assumptions. This would also provide some insight into the system performance in 2018 which was difficult to understand.

Additional work could also include attempting to interpolate the missing data for various data sets to allow for a more complete picture of the system.

6 Cross Comparison

Chapter 6 provides a further investigation into the three previous case studies, comparing the results of similar features of the systems, drawing out any common characteristics and highlighting differences found. Finally, the main issues and considerations will be drawn together before a recommendation for future monitoring of systems is made.

Table 57 shows a comparison of the key features of each system.

Table 57 - Comparison of Case Study Systems

	Crystal	**Heights**	**Cardiff**
Building Usage	Office & Exhibition	Multi Occupancy Residential	Nursery School
Heating &/or Cooling	Heating & Cooling	Heating Only	Heating Only
Number of Heat Pumps	2	120	2
Rated Capacity per Heat Pump	407kW (Heating) 385kW (Cooling)	3kW/6kW depending on property archetype	11kW
Total rated Capacity (kW)	814kW (Heating) 770kW (Cooling)	279kW per Building 558kW Combined	22kW
Source	Boreholes & Energy Piles	Boreholes	Shallow Aquifer
Total length of GHE	8760m	663m East 665m West	22m
Mean annual load	546 MWh Heating 465 MWh Cooling	552 MWh Estimated East 552 MWh Estimated West	33 MWh

Given only a sample of flats have been monitored for the heat loads in each of the buildings at the Heights, the total load was estimated based on the design heat loss calculations and the heating degree data for 2021.

6.1 Efficiencies

Figure 242 and Figure 243 show the distribution of the monthly and yearly performance factors of the three systems. To provide an accurate comparison, the performance factor shown for the Crystal system is for heating mode only. For the system at the Heights, the average performance across the monitored heat pumps in each building has been used. It is also worth noting that as there are no additional circulation pumps on until the distribution side, the performance figures for the Heights are the same at boundary levels 1 to 4.

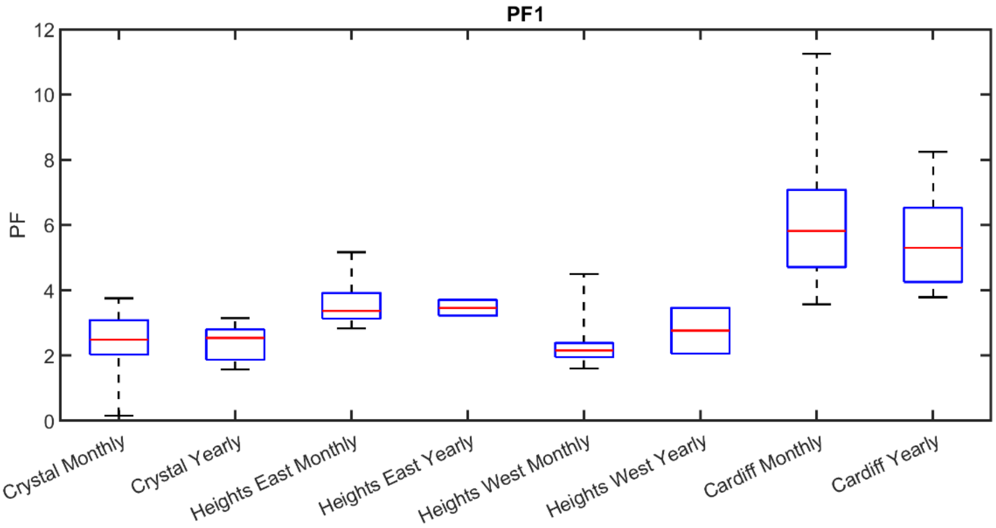


Figure 242 - Case Study MPF & SPF – Annex 52 Boundary 1

Interestingly, the open loop system installed at Cardiff is greatly outperforming the other two systems at boundary 1, likely due to the elevated temperatures of the groundwater entering the heat pump. These elevated temperatures occur due to the combination of the stable ground temperatures at depth during the winter months, giving similar benefits to a borehole heat exchanger, but also the fact that the aquifer is seemingly in hydraulic contact with the nearby river, raising the temperature beyond the ground temperature in the summer months.

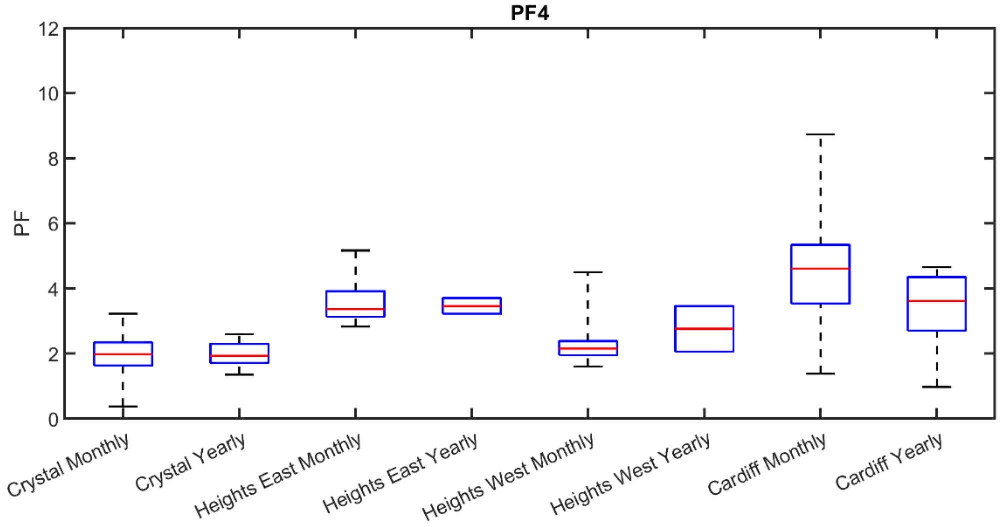


Figure 243 - Case Study MPF & SPF - Boundary 4

However, this benefit is mitigated somewhat when the additional circulation pumps are accounted for, as seen at boundary 4, with the PF's being at a much closer level to the system at the Heights in particular. The system at The Crystal performs poorly across both boundaries. The underperformance at boundary 4 could be attributed in part to the large parasitic loads, particularly in cooling mode. The unusual control strategy for the ground loop may be providing sub-optimal temperatures for the heat pumps, lowering the PF at boundary 1, however the lack of fluid temperature data makes it difficult to understand the conditions in which the heat pumps are operating and therefore why they are underperforming. Additionally, the use of a low loss header could also be introducing some thermal distortion, depending on the flow rates through the system, but again this is hard to verify without the corresponding data sets.

6.2 Emissions savings

To contextualise the performance of these systems, an estimate for the emissions savings compared to a gas boiler has been calculated for each heat pump. An additional counterfactual of electric storage heaters has been included for the Heights as this was the heating system previously installed in these residences. The emission factors for the respective fuels were taken from the UK Government's website (Department for Energy Security and Net Zero &

Department for Business Energy & Industrial Strategy, 2022) and can be seen in Figure 244.

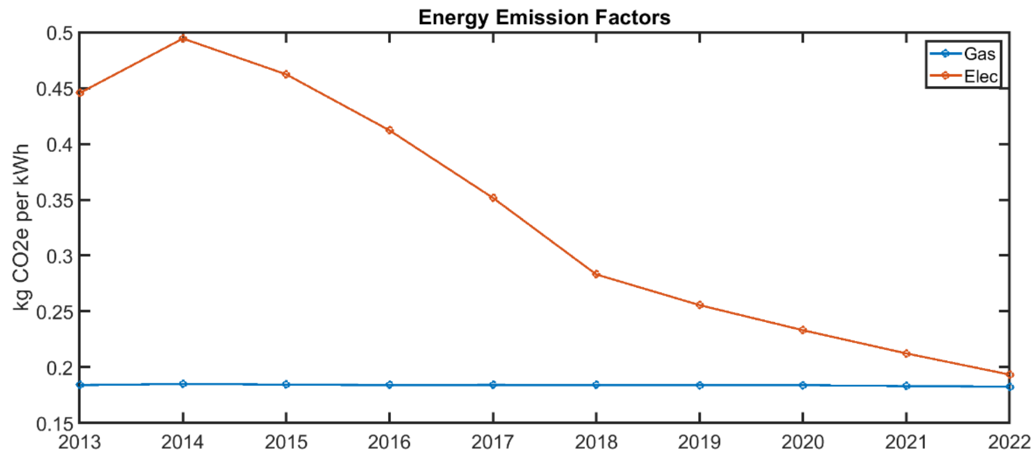


Figure 244 - Emission Factors for Energy Sources

This highlights the dramatic reduction in emissions to generate electricity over the past decade as coal has been phased out, to be replaced by gas and growing renewable generation. As renewables take a higher percentage of this generation, the electricity emission factors will continue to fall. This, combined with the efficiencies achievable by heat pumps would ensure a dramatic reduction in emissions when switching away from gas boilers in the UK.

To provide a benchmark to compare against, a gas boiler operating at an assumed efficiency of 85% has been selected. Any energy used by building side circulation pumps has been disregarded. This is because they are likely to be required in both boiler and heat pump systems, whereas the ground side circulation pumps would not be required in a gas boiler setup. As a result their associated emissions have been included in the comparison.

Figure 245 to Figure 246 show the yearly emissions for the Crystal, Heights, and Cardiff systems respectively.

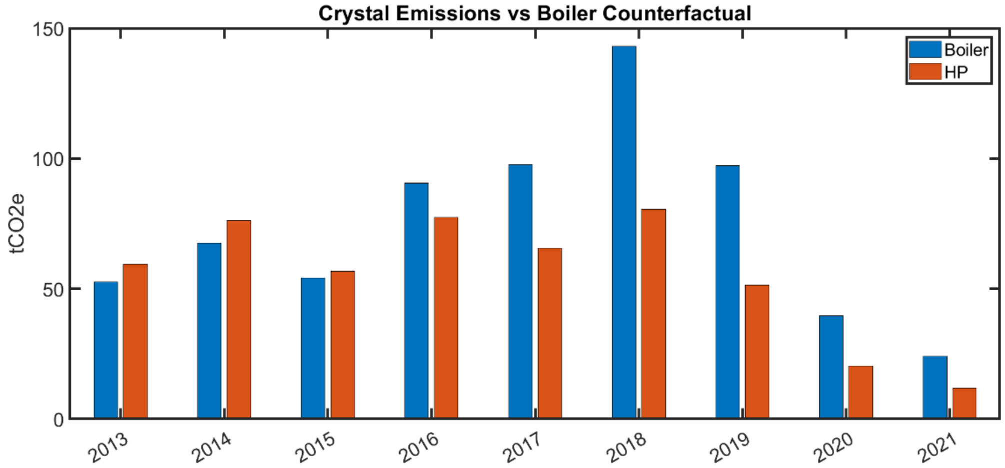


Figure 245 - The Crystal HP Emissions vs Gas Boiler

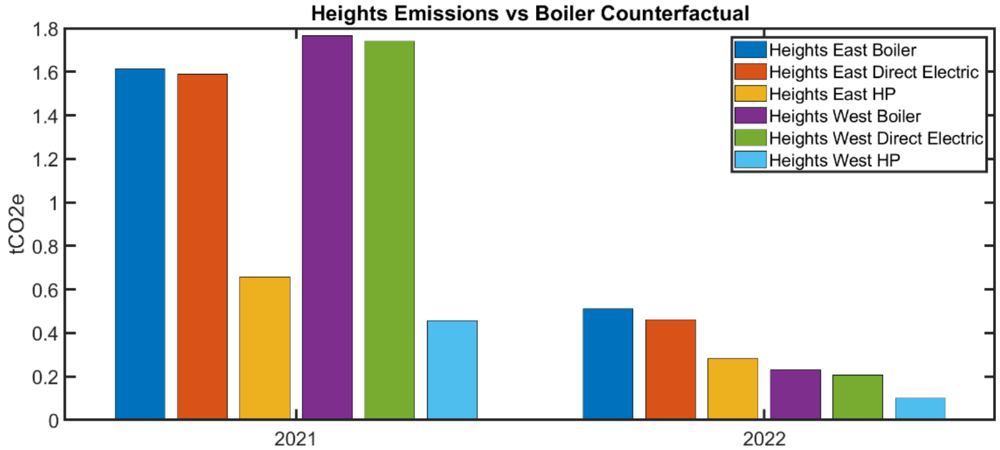


Figure 246 - The Heights HP Emissions vs Gas Boiler & Direct Electric

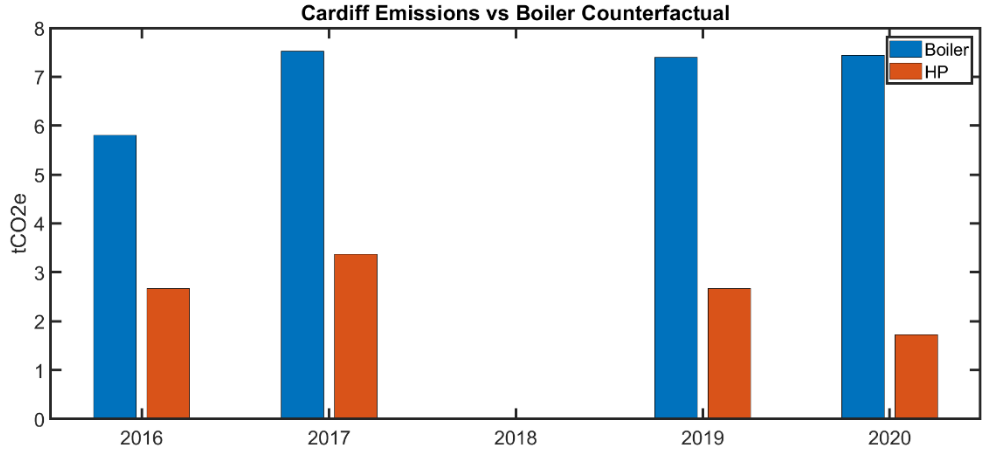


Figure 247 - Grangetown Nursery HP Emissions vs Gas Boiler

Naturally, due to the difference in sizes of these systems, the emissions savings for each are vastly different in absolute terms, though each system does show savings over the counterfactual.

Initially, from 2013 to 2015, the Crystal system shows higher emissions for the heat pump system. This is in part due to the large number of additional pumps somewhat negating the efficiency of the heat pumps themselves, but primarily this is due to the high initial emission factor associated with electricity. From 2016 onwards this system shows substantial emissions savings, and this should continue to decrease as the electricity grid continue to decarbonise.

Given the Heights utilised storage heaters prior to the heat pumps installation, a direct electric counterfactual has also been added to Figure 246. This shows similar emissions to the gas boiler counterfactual as the assumed 100% efficiency of the direct electric is offset by the higher carbon factor of the electricity over gas through the two years evaluated. As expected, the heat pump demonstrates significant emission savings over both counterfactuals.

6.3 Ground Heat Exchanger Efficiency

Figure 248 shows the ground heat extraction rate in W/m of the Crystal systems energy piles and boreholes in heating mode, compared with the boreholes at the Heights system. As the Cardiff system is an open loop system it is not shown here. The Heights East array 2 has also been omitted as the case study highlighted an unusual flow rate reading requiring further investigation.

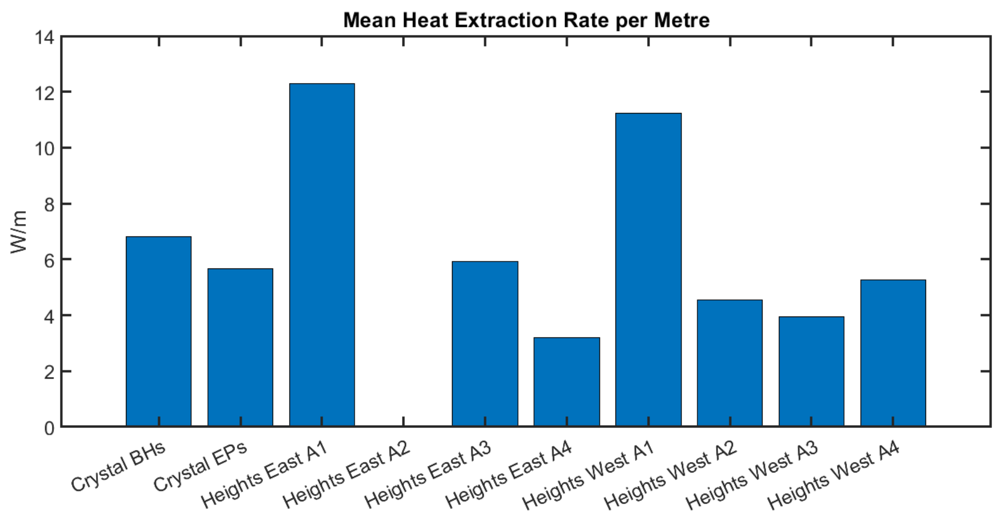


Figure 248 - Ground Specific Heat Extraction Rate

This shows similar heat extraction rates for the Crystal, which is understood to be greatly overdesigned, and the majority of the arrays at the Heights. Both systems fall below the typical bounds of 20-55 W/m as suggested by the literature (The Chartered Institution of Building Services Engineers, 2013), however Array 1 at the Heights East and Heights West, both of which have the fewest boreholes and least number of heat pumps connected, do appear to be performing at higher levels.

The low heat extraction rate in the Crystal system may have been affected by the heat recovery system that is present in the building, along with the recovered heat whilst in primarily cooling mode. These would reduce the amount of heat required to be drawn from the ground loop, resulting in a lower extraction rate. These values suggest the number of energy pile and boreholes could be drastically reduced in this system, which would in turn reduce the pumping energy required to circulate the fluid through the ground loop, and potentially increase the efficiency of the system.

The variability in the mean heat extraction rate per meter at the Heights demonstrates the difficulty in designing ground loops for a multi-occupancy system. Further monitoring to quantify the diversity in systems such as this would be useful in providing guidance on how to size the loop to meet peak loads without overdesigning and building in unnecessary cost to these projects.

Open loops do not have the same difficulties, as the abstraction flow rate achievable from the aquifer is of much more importance than the depth of the well. The Cardiff well for example was only 22m deep. However, other complexities add to the capital and ongoing costs of open loop systems, such as additional maintenance, of the abstraction pump/s, heat exchangers, and filters.

6.4 Data analysis methods & approach

Each of the three case studies had some limitations in relation to the datasets available, thus limiting what could be achieved in the analysis.

The Crystal system had a well setup BEMS, but many of the required parameters were grouped together, such as the electricity for all three ground loop circulation pumps as well as the four load side circulation pumps. This adds a layer of complexity to the analysis or simply minimised the level of detail achievable. In this case, this meant that the performance factors could not be accounted for at several system boundaries, and the individual circulation pumps performances could not be interrogated.

Additionally, the heat meters installed on the ground loop were not directional, and as a result, the ground heat exchange through the energy piles and boreholes was determined through the assumed operating mode, calculated through equations.

The Heights study was impacted by problems installing the heat meters in a number of the flats, resulting in a smaller sample of heat pumps than originally intended, and the heat meters that were installed also had issues transmitting the data back to the dataloggers.

Furthermore, the temperature probes appeared highly sensitive to knocks and changes in environment, and as such statistical change point analysis was applied to the temperature readings to determine when these changes occurred, and which data points were useable.

The Grangetown Nursery system, similarly to The Crystal, had a fairly reliable monitoring system setup, however it was not designed for monitoring the performance of the heat pump system, and therefore the analysis was less straightforward.

This led to multiple unconventional analysis techniques being developed and employed: the borehole water level was used as a proxy for when the heat pump is turned on, and the main circulation pump power was used to estimate system flow rate, and therefore calculate heat delivered.

Finally, the frequency of some of the data measurements across each of the case studies limited the analysis. The majority of the data from the Crystal system was only available at 15-minute intervals, similarly to the heat meter readings for the Heights, and the majority of the measurements in the first couple of years for the Cardiff system. Some investigations into the performance of such systems, such as how often the heat pumps or circulations pumps are cycling and how long for, may require a higher resolution of data than this. This should be considered when setting up any future monitoring of such systems, however the need for such resolution should be compared to the additional equipment costs and data storage.

The guide to effectively monitoring GSHP systems over the long term provided by Annex 52 (Gehlin *et al.*, 2022) provides welcome guidance on which parameters are required to be monitored for individual KPI's and what can be learned about the system from such measures.

Table 58 builds on this guidance, consolidating the learning from this thesis regarding the recommended datasets required for practical troubleshooting of heat pump systems and improving their performance, as well as what additional datasets would be advantageous for research purposes.

As this table is the consolidation of the learning in the previous chapters it does not cover parameters and KPIs not used in this thesis, such as system or fuel costs, or pressure drops within the system for example.

Table 58 – Monitoring System Guidance

Parameter	Primary Purpose	KPIs	Comments
Heat Pump Energy Usage	Troubleshooting /Optimising	COPs, PFs, SEIs, Cycling, Diversity in SGHE systems, Emissions	Useful for end user to understand costs Could be a simplistic way to calculate diversity in SGHE systems – i.e how many heat pumps are on at one time?
Space Heating/ Cooling Delivered by Heat Pump	Troubleshooting /Optimising	COPs, PFs, SEIs, Energy Signatures	
Domestic Hot Water Delivered by Heat Pump	Troubleshooting /Optimising	PFs, Energy Signatures, Usage Patterns	If temperature set points are known, this could provide indication into usage patterns and context for performance measures
Heat/Cool Provided by Auxiliary Sources	Troubleshooting /Optimising	PFs, Energy Signatures, Usage patterns	Significant usage could identify problems with main system
Energy Used by Auxiliary Heat/Cool Sources	Research /Inform Future Designs	PFs, Emissions	
Circulating Pump/s Energy Usage	Troubleshooting /Optimising	PFs, Flow Rates	Can be used to estimate the flow rate if flow meter data is not available
Heat Pump Flow and Return Temperatures	Troubleshooting /Optimising	Set Points, Temperature lift, Usage patterns, Delta T	Can be used, along with flow rates, to calculate heat to/from building if heat meters not installed or not producing reliable data

Heat Exchanged with Ground	Research /Inform Future Designs	Specific heat extraction rate, effectiveness of energy recycling (if applicable)	Should be directional if heating and cooling is provided
Ground Loop Flow and Return Temperatures	Troubleshooting /Optimising	PFs, SEI, Minimum flow temperatures, Temperature Lift	Can be used, along with flow rates, to calculate heat to/from ground if heat meters not installed or not producing reliable data Could indicate the sustainability/longevity of the system
Ground Loop Flow Rates	Research /Inform Future Designs	Utilisation rates/Diversity Factors in SGHE systems	Can be used, along with temperatures, to calculate heat to/from ground if heat meters not installed or not producing reliable data
Building Loop Flow Rates	Research /Inform Future Designs	Usage patterns	Can be used, along with temperatures, to calculate heat to/from building if heat meters not installed or not producing reliable data
Outdoor Air Temperature	Research /Inform Future Designs	HDD, Energy Signatures	HDD can be used to normalise year by year comparisons removing temperature as a factor This can provide useful validation for other KPIs

6.5 Logistical and Organisation Challenges for High Quality Data Sets

A common theme across the three case studies was the logistical roadblocks to accessing high quality, reliable data and information on the systems.

The changeover in ownership of The Crystal system had an adverse effect on collaboration and access to data, with permissions and explanations needing to be renewed with the new owners. It is also unclear how detailed the handover of the GSHP system was, and so any questions about the system and its original state may no longer be answerable by the owners, for example whether the control strategy has changed significantly.

Similarly in Case Study 3, Grangetown Nursery, a number of parameters that would have been useful for data analysis were not available at the time of analysis, such as pump settings and maintenance logs. This was primarily due to COVID restrictions preventing access to the plant room, but a change in ownership of the system also led to a reduced interest in monitoring its performance and challenges in communication to provide these insights.

Case study 2, The Heights, also had communication issues leading to delays and a reduction in data collected, likely driven by the fact the contractors were assisting voluntarily rather than under any contract or payment. The fact that these flats were owned by the council introduced another layer of challenges as access to the buildings and flats had to be arranged through them. This meant that any issues with equipment installations or data collection, as well as consents for data collection from the residents took additional time and were often delayed. Similarly to the previous two case studies, there was a transition of ownership of sorts for the data monitoring at The Heights. This was in the University of Leeds team taking over some of the legacy monitoring equipment, specifically the electrical meters and dataloggers, from the Leeds Beckett University team. As with any such transition additional communication was required to minimise the loss of data knowledge, such as how to effectively clean and troubleshoot the data when encountering different issues.

Moreover, the change led to a loss of familiarity for the residents with the research team, again making interactions more challenging.

Once again, COVID played a detrimental role in the setup of this system, limiting: access to flats, obtaining consent for data collection, and quickly accessing in-house expertise regarding the monitoring equipment and setup.

6.6 Summary of Performance and System Analysis Challenges

Table 59 summarises the main challenges found in the case studies, be them technical or otherwise, that either potentially caused underperformance of the system or led to difficulties in analysing them.

Table 59 - Summary of Causes for Underperformance and Challenges in Analysis Found in Case Studies

Type of Issue	Crystal	Heights	Cardiff
Design	Actual loads greater than predicted Ground loops overdesigned	Considering individual needs could have affected heat pump sizing and increased efficiencies Most ground arrays under utilised	
Control	Piles used for heat rejection and boreholes used for heat extraction – limiting the potential for using the ground as a thermal store	Controls often being overridden (see below)	Not turning system off in summers Controls potentially incorrectly re-applied after component change
Usage Patterns		Many users not operating the heat pumps in optimal way Often high usage of auxiliary heat systems	Doesn't appear to be switched off overnight or at weekends
Mechanical			Component failure and subsequent incorrect settings
Knowledge	Change in ownership causing delays and loss of knowledge		Change in ownership causing delays and loss of knowledge
Logistical		Reduced sample of heat meters installed due to logistical issues	
Monitoring	Heat meter on instrumented pile circuit never functioned	Wireless MBus transmissions limited through walls	Additional useful data not monitored
Data	Datasets grouped limiting analysis and boundaries for PFs Frequency of data limited to 15 minutes	Sensor issues causing anomalous readings	Multiple data gaps in multiple date sets Frequency of data originally limited to 15 minutes

Table 59 enables a list of transferrable recommendations to be created to enable GSHP systems in the UK to perform at higher efficiencies.

The first of these is to consider the end user in greater detail before designing the systems. Whilst assumptions will always have to be made, a simple survey to understand the end users' needs and likely usage patterns could inform changes to the load profile generation, product selection, and control strategy, which will affect the efficiencies of the system.

The next recommendation is to ensure the operators of the systems are fully informed on the systems operation, controls, and troubleshooting. This will reduce the need for changes in control strategy, and when they are required, will allow the controls to be changed in a way that is not to the detriment of the system performance.

Tied to this is the recommendation to accurately document the system details, including equipment, controls, maintenance and all associated meta data. This should be made available, online, to ensure ease of access for those investigating or monitoring the system.

To ensure the system operates to its full potential, it is suggested that a custodian should be appointed, to regularly monitor the system, not just from an operational and maintenance point of view, but from an efficiency perspective. This would reduce wasted energy, therefore reducing costs and emissions as well as allowing maintenance to be proactive rather than reactive.

This focus on efficiency should be determined up front, to allow for an appropriate monitoring strategy to be developed. The IEA Annex 52 guides along with Table 58 in this thesis, can be used in informing this strategy and what may need to be monitored.

These measures, together, should allow GSHP systems in the UK to perform above their current levels and assist in the efforts to decarbonise the UK.

7 Conclusions

This body of work investigated the long-term performance of three ground source heat pump systems in the UK. These systems differed in many areas, including the type of ground heat exchanger, load size, whether the system was centralised or distributed, and heat pump size, however each system was monitored for over a year and was either multi-occupancy or a commercial building. Investigations of GSHP systems for this length of time is typically conducted through simulations, and so the analysis of these systems provides a useful understanding of real-world performance in the UK.

The analyses presented in this thesis highlight the following key takeaways:

- Whilst a fit for purpose monitoring system would simplify analysis into the performance of GHSPs, imperfect datasets can also provide highly useful KPIs and insights.
    - Unusual analysis techniques developed in this thesis include:
        - Using change point analysis to automate data cleaning in problematic data sets.
        - Using the circulation pump power to estimate flow rate through the distribution system, and thus heat provided by the heat pumps.
        - Using the water level in an abstraction well as a proxy for pump usage to enable the calculation of the flow rate, energy usage, and heat exchanged in the well.
- The Heights was a shared ground heat exchanger system, utilising boreholes and distributed heat pumps. At the time of writing, it is thought that this is the first attempt to assess the long-term performance of heat pumps in such a system in the UK. This analysis attempted to quantify the diversity seen in a shared ground heat exchange system by looking at the flow rates through the individual arrays.

  - The majority of the arrays achieve very low utilisation rates, around a max of 50% the maximum flow, however one array reached close to 90%.
  - The array that reached close to 90% utilisation had fewer heat pumps connected to it than the other arrays for the same building. However, the same array for the second building showed a much lower utilisation rate despite having the same number of heat pumps.
  - This highlights the difficulty in accurately predicting diversity and additional analysis will be required to inform future designs of such systems.
- The system installed at Grangetown Nursery in Cardiff is the only open-loop system of the three investigated.
  - The hydraulic contact of the shallow superficial aquifer with the nearby river is likely the reason for the elevated groundwater temperatures, and thus the high performance factors for this system.
  - This could be useful when investigating locations for similar systems with similar geological properties.
- Human interactions with GSHP systems are still one of the main, if not the main, reasons for underperformance and increased bills.
  - The modified control system for the ground loop at The Crystal could be a large reason for the underperformance of this system.
  - The increased usage of the immersion heater for DHW at the Heights led to a reduced efficiency when compared to the flats only using the heat pump.
- A basic level of continual monitoring of these systems is encouraged for the end users benefit, to ensure the best performance factors are achieved. Additionally, changes of ownership of such systems should be carefully managed to ensure a consistent level of understanding, interest, and monitoring.
  - The Crystal, whilst continually providing heat and cool beyond the anticipated levels of demand, has been doing so at poor

efficiencies for multiple years, silently costing the end user money, and leading to greater associated emissions than necessary.

- This will also have longer term impacts on the longevity of the ground as an energy source, as the in the case of The Crystal where the borehole temperatures will continue to decrease due to the rejected heat primarily being returned to the energy piles.
- Similarly, the system at Cardiff has been frequently left running necessarily over evenings, weekends and holidays, resulting in higher energy usage.

These conclusions and recommendations should be considered for the case studies in this thesis, and systems in the wider UK GSHP market, to achieve and maintain the high efficiency levels that are possible from these systems. This will enable a further reduction in primary energy required for heating systems, reduce the strain on the electricity grid, and continue the push for a decarbonised UK by 2050.

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Appendix A – Publications

Throughout the development of this thesis and alongside the body of research, a number of publications have been produced. For brevity, Table 60 provides a summary of these documents and where they can be accessed.

Table 60 - Summary of Publications

Title	Document Type	Citation	Link	Relevancy to Thesis	Contribution
Energy Performance of CFA Piles Used as Heat Exchangers in a GSHP System	Conference Paper	(Turner *et al.*, 2020)	https://www.icevirtuallibrary.com/doi/abs/10.1680/pttc.65048.523	Chapter 3 – The Crystal Case Study – Thes conference paper details the preliminary findings of The Crystal case study, with a focus on the performance of the GHE	The author of this thesis conducted the analysis and wrote the paper, with guidance and reviewing from the other named authors
Case Study Report for The Crystal Building	Case Study Report	(Turner, Loveridge and Rees, 2021)	https://heatpumpingtechnologies.org/annex52/wp-content/uploads/sites/60/2022/01/turneretal2021case-study-	This report forms the basis of Chapter 3, summarising the findings from the analysis of the system at The Crystal	The author of this thesis conducted the analysis and wrote the paper, with guidance and reviewing from the other named authors

			report-the-crystal-london-ukfinal.pdf		
Subtask 3 Report – Guide for Analysis and Reporting of GSHP System Performance – System Boundaries and Key Performance Indicators	Industry Guidance Report	(Gehlin *et al.*, 2022)	https://heatpumpingtechnologies.org/annex52/wp-content/uploads/sites/60/2022/04/kpiguidesubtask-3-reportfinal.pdf	This report, similarly to the thesis, aims to provide guidance on how different KPIs can be used in the analysis of the long-term performance in GSHP systems.	The author of this thesis contributed case study specific insight from The Crystal case study on how different KPIs were used, forming a section of this publication.
Shared Ground Heat Exchange for the Decarbonisation of Heat	Policy Brief	(Bale, Barns and Turner, 2022)	Policy Brief https://eprints.whiterose.ac.uk/185509/ Rapid Evidence Assessment https://archive.researchdata.leeds.ac.uk/948/	The rapid evidence assessment conducted for this policy brief highlighted the gap in performance data available for shared ground heat exchange systems – as then explored in Chapter 4 of the thesis	The author jointly created this publication, assisting in conducting the underlying research.

The Path to Zero Carbon Heat	Report	(Net Zero Infrastructure Industry Coalition, 2020)	Report https://www.mottmac.com/download/file?id=39141&isPreview=True Pathways and Technical Annex https://www.mottmac.com/releases/race-for-heat-decarbonisation-would-spur-uks-green-economic-recovery		The author of this thesis conducted the literature review underpinning this report and its analysis. The chapter on the literature review in the technical annex was also written by the author of this thesis.

Appendix B – Heights Data Cleaning Details

This appendix contains the additional details of how the data sets used in the analysis of the system installed at The Heights were cleaned and analysed. This provides more detail to the overview provided in Section 4.3.

B1. Ground Loop Temperatures – Calibration & Change point Analysis

As summarised in Section 4.3.2, change point analysis utilises statistical measures to interrogate a signal and find the points where it changes significantly. These measures can include the mean, standard deviation, and root mean squared values of the signal among others. To find these "change points", the signal is split into two sections and an estimate of the chosen statistic is estimated for each section. The deviation for each data point from this estimate is calculated and the deviations are totalled. The section by section deviations are then totalled, giving the total residual error. The point at which the signal was split is then varied until the total residual error reaches a minimum value, as set by the user. This step by step process and the equations that govern it can be found online (MATLAB, no date).

For the change point analysis in MATLAB, either the maximum number of change points or the minimum threshold value needs to be set to constrain the number change points located in the data set.

As the change point analysis is being used to determine how many and when these changes occur, setting a maximum number of change points was not deemed appropriate and as such the minimum threshold value was chosen. The value for this parameter was set based on analysis of a data set that upon observation appeared to have no unexpected change points. For example, with the West ground loop arrays, Array 4 appears to be producing sensible readings year-round.

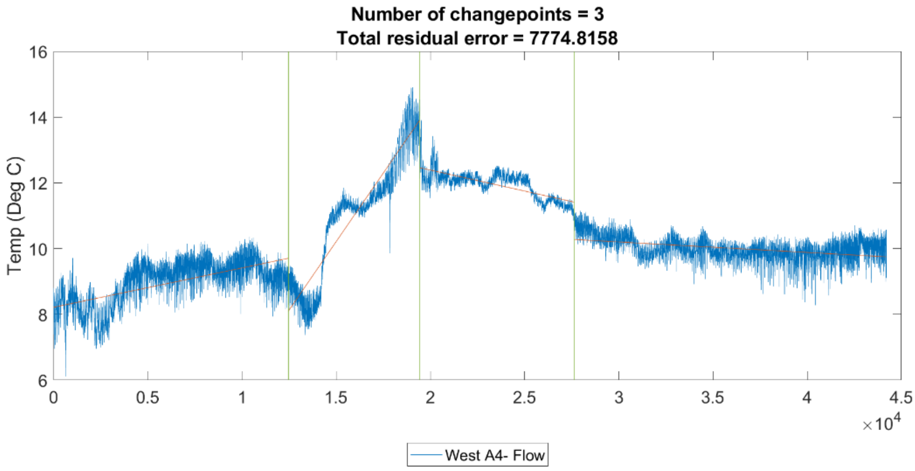

Figure 249 - West A4 Flow Temperature Change Points

It can be seen from Figure 249 that there are 4 distinct regions of varying slopes in this data: Heating season, start of cooling season, end of cooling season, heating season. Changepoint analysis was run on this data set to find the threshold values that produce the correct number of change points, in this case three. The threshold values found to produce from this data sample were between 1945 and 3982, inclusive.

Given the variance likely to occur between each of the ground loops themselves as the usage patterns change, it was decided that a value in the centre of this range would be used as the baseline. As such 3000 was used. This means that the change point analysis will iterate, splitting the signal again and again, reducing the residual error with each split, until splitting the signal again does not reduce the residual error by more than 3000.

This value was then applied to the data sets to identify where any of these 'events' occurred along with changes in the natural change points for the temperatures due to usage and weather. The results of this analyses can be seen in Figure 250 to Figure 265.

These figures show the flow and return temperatures of each array, with and without the correction factors applied, and the dates of the calibrations and change points marked. From this, it can be determined which data sets are suitable for analysis and which sections should be considered anomalous.

8.1.1.1 East Array 1

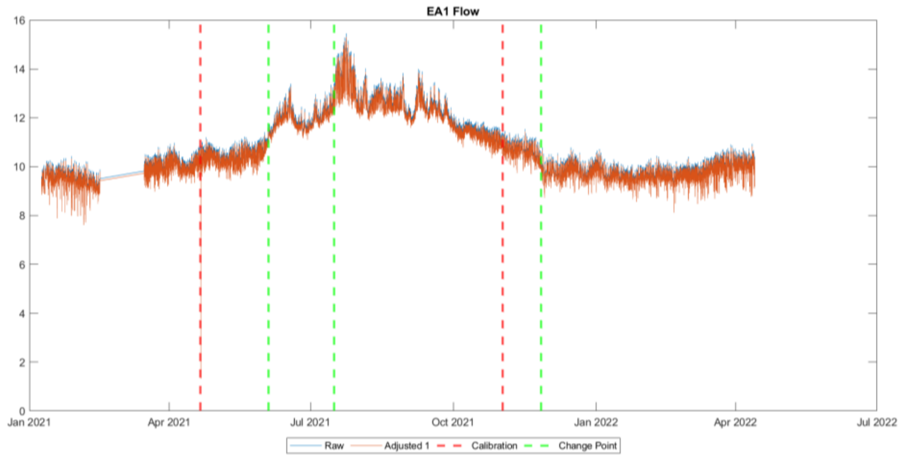

Figure 250 - East A1 Flow Temperature Calibration and Change Point Analysis

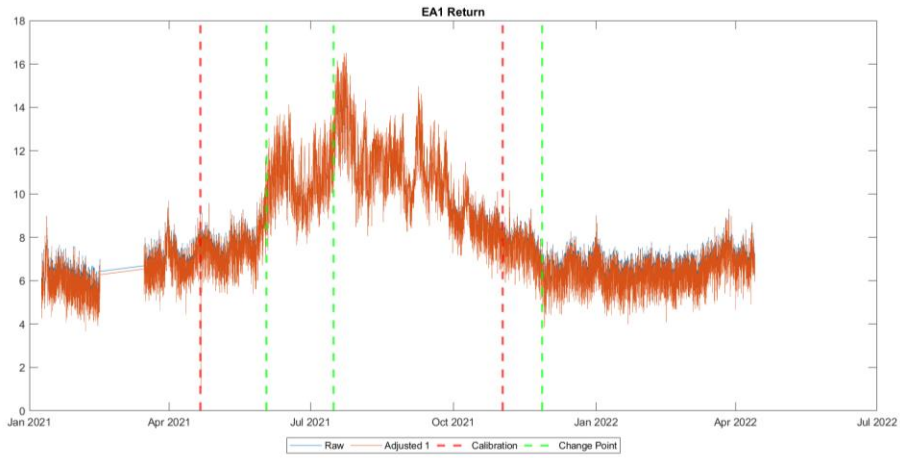

Figure 251 - East A1 Return Temperature Calibration and Change Point Analysis

As can be seen from Figure 250 and Figure 251, the calibration for East array 1 has a marginal effect on its values for both flow and return temperatures. The change point analysis also shows this data set to be relatively good, picking up 3 change points, as expected. As such the calibrated values have been used for this array.

8.1.1.2 East Array 2

Similarly, for East Array 2 the calibrated flow values are only a minor correction to the raw data and the change point analysis has found 3 similar change points, at the start point of the "heat off" period, roughly the peak of the heat of period, however the third statistical change point for this array occurs later than with Array 1. This is because there is a more marked upturn in flow temperatures at the start of 2022 and thus the change point is located roughly at the minima at the end of winter. The return temperatures, however, has multiple change points and clearly the temperature sensor has experienced a significant 'event' as the readings suddenly drop to less than minus 200°C. It is unclear what has caused this as the value appears to recover multiple times for short periods before providing the erroneous values again. As such, change point 3 onwards will be removed from the analysis.

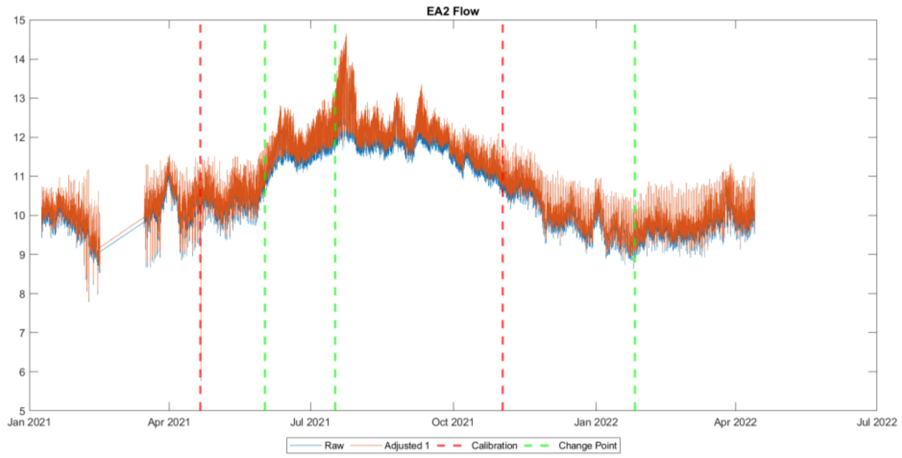

Figure 252 - East A2 Flow Temperature Calibration and Change Point Analysis

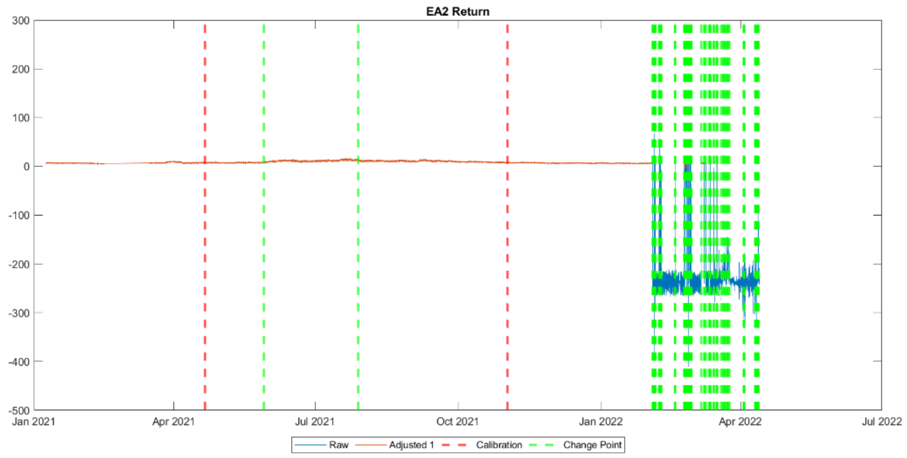

Figure 253 - East A2 Return Temperature Calibration and Change Point Analysis

8.1.1.3 East Array 3

The flow temperatures in East array 3 have some very clear change points indicating sensor 'events'. The calibration in April 2021, when applied retroactively appears to elevate the recorded temperatures to more reasonable values, however the raw data following the calibration appears much more likely to be accurate. Clearly, the cleaning and re-installation of the sensor after the calibration resolved the issue, suggesting it was perhaps a poor contact with the thermowell. As such the original flow temperatures will be used from the calibration date up until the next 'event' an April 2022, where once again a large, unexpected drop in values is identified. The return temperatures appear to have had the same initial problem, with the post-calibration reinstallation elevating the values to more realistic numbers in the raw data, which will be used for this period. Unfortunately, another 'event' occurs in Jan 2022 on the return sensor, as highlighted by the change point analysis, so data beyond this point will be removed from the analysis.

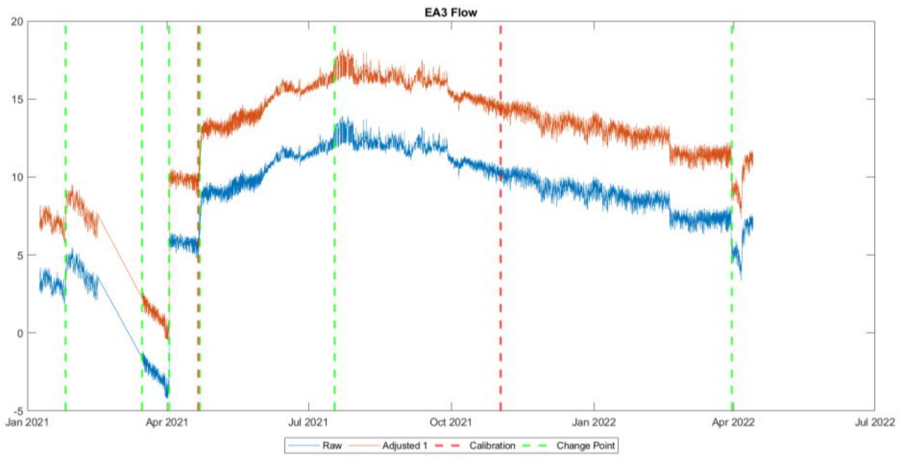

Figure 254 - East A3 Flow Temperature Calibration and Change Point Analysis

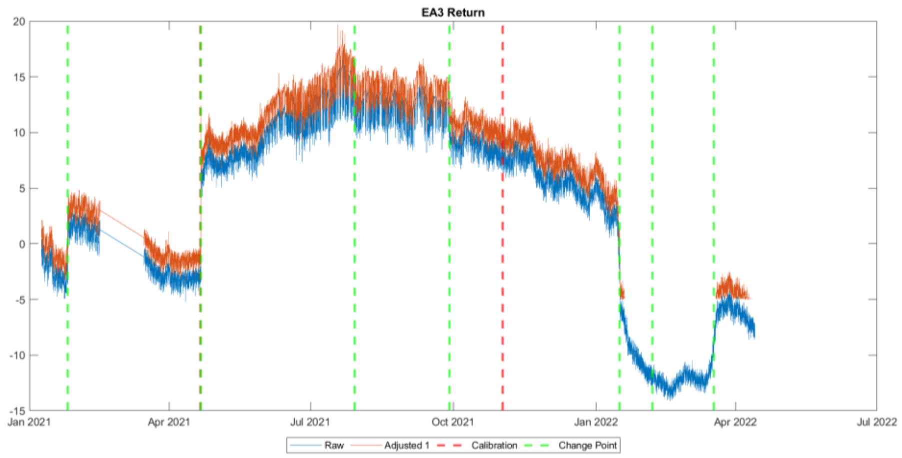

Figure 255 - East A3 Return Temperature Calibration and Change Point Analysis

8.1.1.4 East Array 4

With East Array 4, both the flow and return temperatures appear reasonable throughout the monitored period, and this is supported by the change point analysis which only finds the expected 3 change points. The calibration of these sensors show provide minor adjustments to the raw data.

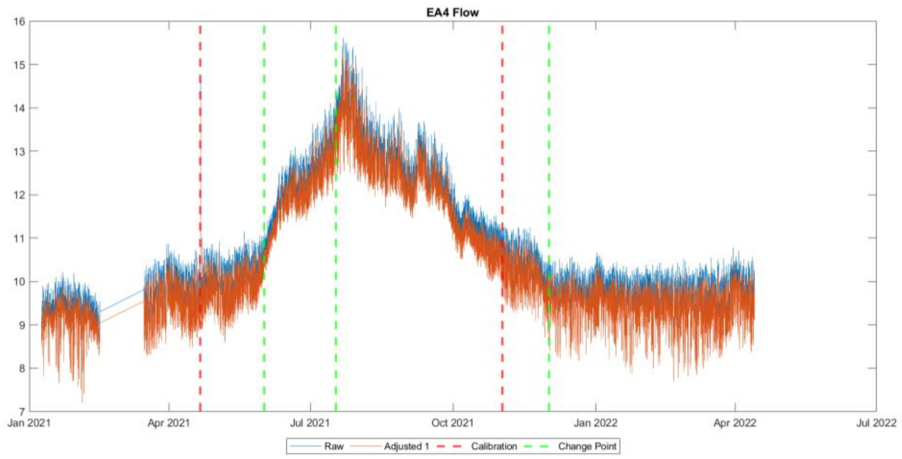

Figure 256 - East A4 Flow Temperature Calibration and Change Point Analysis

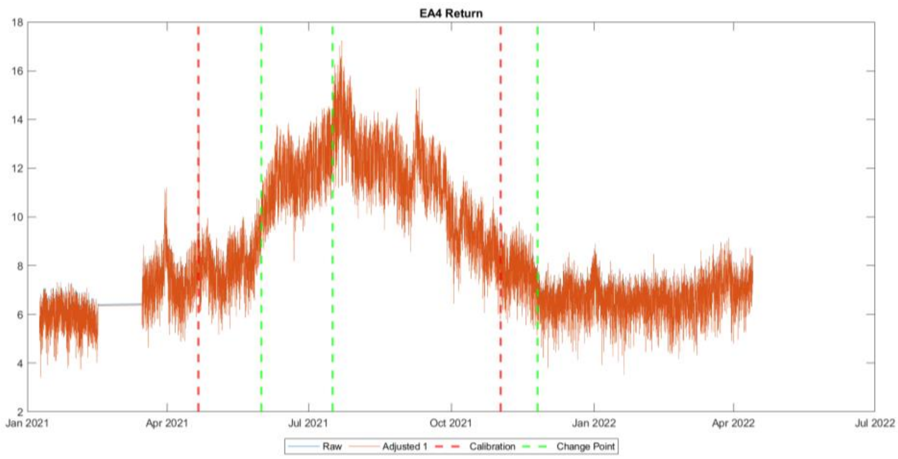

Figure 257 - East A4 Return Temperature Calibration and Change Point Analysis

8.1.1.5 West Array 1

As can clearly be seen in Figure 258, West Array 1 flow temperature sensor experienced multiple ‘events’, as well as a second attempted calibration in November 2021. Applying the first calibration factors to the data that came before it provides realistic values between the first and second change points, however it is clearly not applicable to the data before the first change point. Similarly, after the second change point the temperatures appears to fall away at a time in which the heat pumps are less likely to be running and the outdoor air temperature is increasing. This prompted the second attempted calibration however when the factors are applied to the data after the second change point it is clear that something went wrong during the calibration as the adjusted temperatures are unrealistically high. As such the period from change point 2 to change point 5 was removed from the analysis. At change point 5 the sensor appears to right itself again, producing values within the expected range, before dropping away again at change point 6. The cause of these issues may be due to a loose connection or electrical issue in the cabling underground as both the sensor itself and the connection at the datalogger were checked multiple times through the monitoring period with no issues immediately identified.

Applying the first calibration factors to the return temperatures, however, appears to produce usable values from change point 1 onwards, with few additional change points detected.

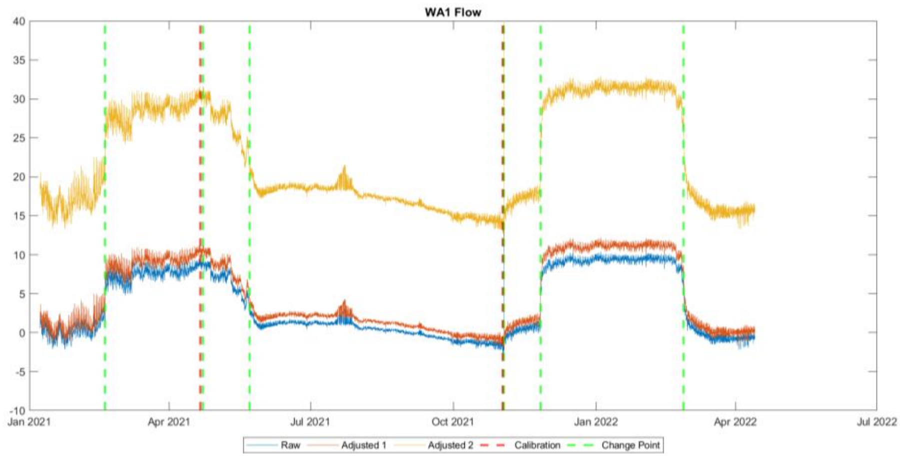

Figure 258 - West A1 Flow Temperature Calibration and Change Point Analysis

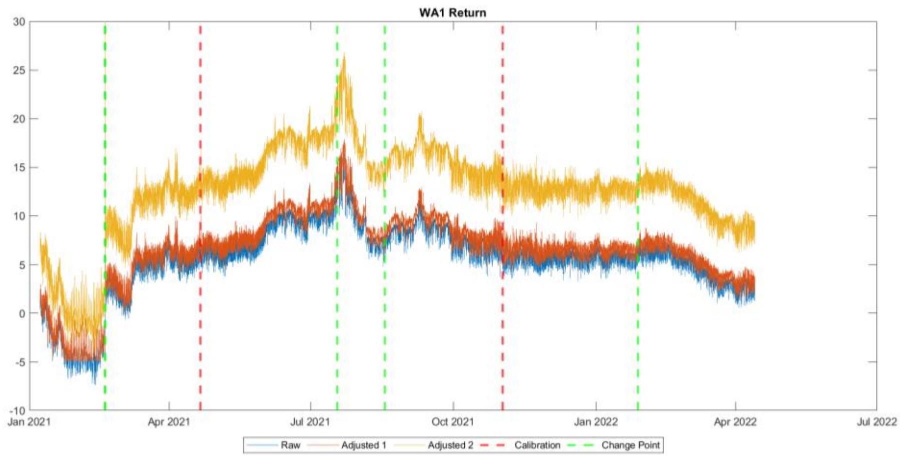

Figure 259 - West A1 Return Temperature Calibration and Change Point Analysis

8.1.1.6 West Array 2

As with the West Array 1, West Array 2 also had a second attempted calibration. It is clear that the calibrated flow temperatures after applying the factors from the first calibration, provides reasonable values from change point 1 to change point 2, and then again from change point 3 to change point 4. Before change point 1, between, 2 and 3, and after 4 however, the readings do not appear reliable. The second attempt at calibration has also produced unrealistically high values, and the cleaning and re-installation of the sensor has not in this instance fixed the issue with the raw data either. This points towards another resistance issue in the cabling underground and means the data beyond change point 4, approximately October 2021, has to be disregarded. There is an argument to be made that from the final change point onwards the values produced by applying the second calibration factors appear reasonable, however as this was not the case after the point of calibration, it is hard to understand what may have led to this being the case and as such will not be included.

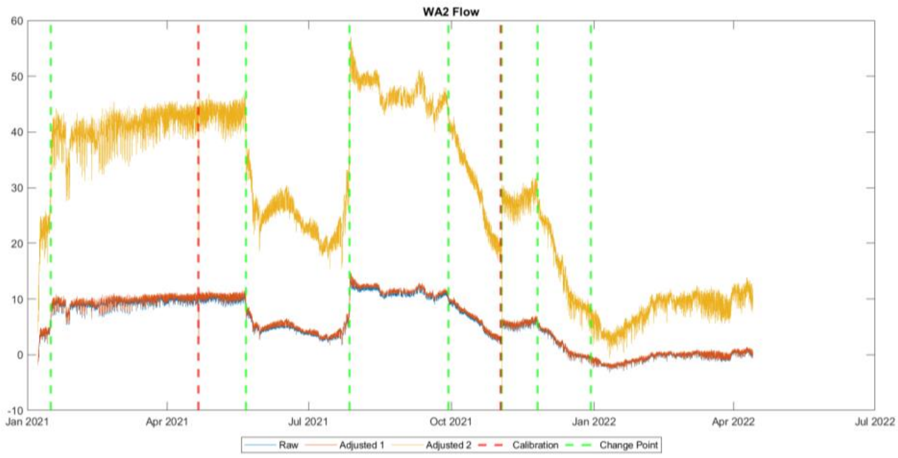

Figure 260 - West A2 Flow Temperature Calibration and Change Point Analysis

The return values are also fairly inconsistent for this array. Calibration 1 appears to be valid through to change point 2 in July 2021 and an event occurs between change point 2 and 3, requiring this data to be ignored, before producing sensible values again between change point 3 and 4. At change point 4, a significant 'event' occurs causing a dramatic drop-off of the temperature and, again, prompting the secondary calibration attempt. Whilst at first glance this appears to provide reasonable values when applied to the data after the calibration, after further inspection these values appear higher than expected. As the flow rate to the heat pumps in increasing, and the outdoor air temperature is decreasing, it is expected that the return temperatures would also decrease during this period, rather than remaining at the temperatures found in the peak of summer. As such the data after CP 4 will have to be ignored for this sensor. were removed from the analysis.

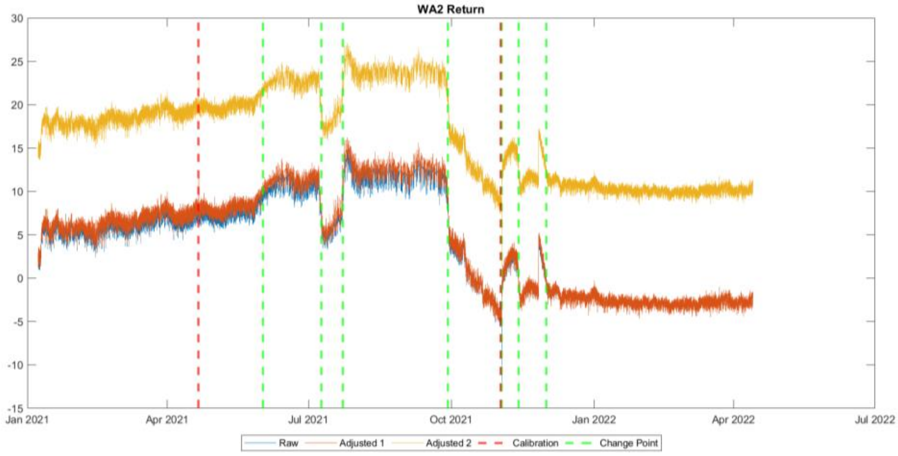

Figure 261 - West A2 Return Temperature Calibration and Change Point Analysis

8.1.1.7 West Array 3

The flow temperatures on West Array 3 also have a number of unusual readings. Applying the correction factors from the first calibration brings the temperatures to more expected values up until change point 4, with the exception of the small period between change point 1 and 2. During the small time period, the sensor seems to correct itself and the raw data fits nicely between the adjusted values. Similarly, at change point 4, the sensor seems to correct itself, producing values that closely align to the preceding calibrated values. Change point 5 however indicates the start of a decline in temperature shown in the raw data, that once again reduces the values to much lower than expected at which point the calibrated values look reasonable again. However, given that it is difficult to understand why this would be the case, and it is not justifiable to say that the initial calibration would be valid after the sensor ‘corrects’ itself, the data from change point 5 will be negated.

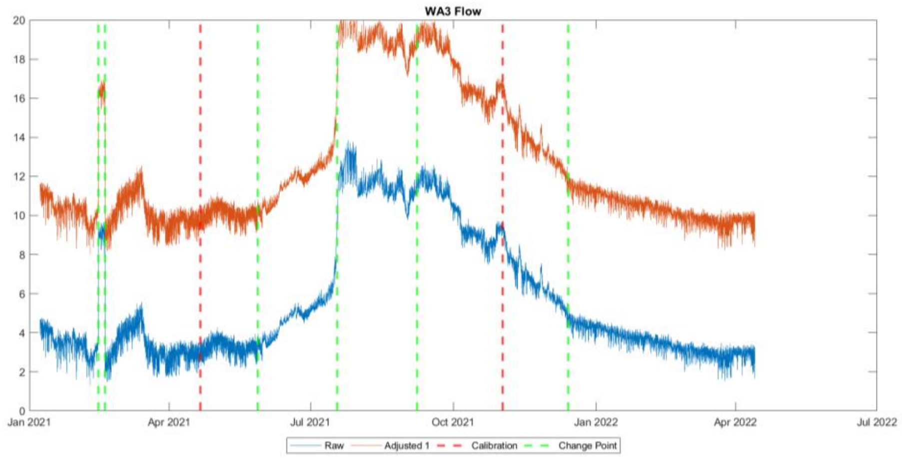

Figure 262 - West A3 Flow Temperature Calibration and Change Point Analysis

With the return temperatures, the calibrated and uncalibrated data tells the same story as one another, meaning in order to clean the data it is not about whether to use the calibrated values or the raw values, as with the flow temperatures, but instead about which periods these readings are valid. Comparison with the expected values seen across the other arrays suggest that the calibrated values from change point 2 to 3, 4 to 5, and 6 to 7 are to be used and all other sections will be ignored. From change point 7, the temperature is again lower than expected.

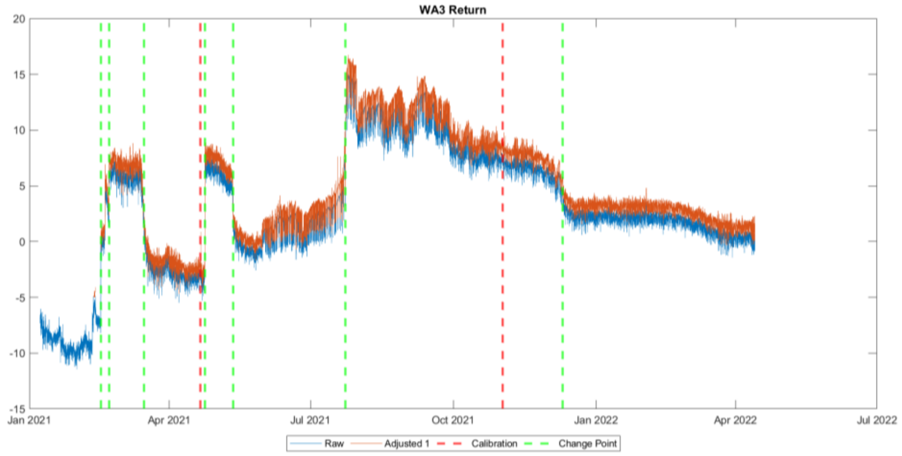

Figure 263 - West A3 Return Temperature Calibration and Change Point Analysis

8.1.1.8 West Array 4

Looking at the flow temperatures of West Array 4 it may initially seme that a sensor 'event' has occurred, as in previous graphs, however this is partially down to the scale of the axis, and with the daily mean temperature overlayed, it can be seen that this coincides with a large increase in outdoor air temperature. Additionally, the change point analysis produces the expected 3 change points at the end of the heating period, the peak of the "heat off" period, and the start of the heating period. As such the calibrated values will be used for this array.

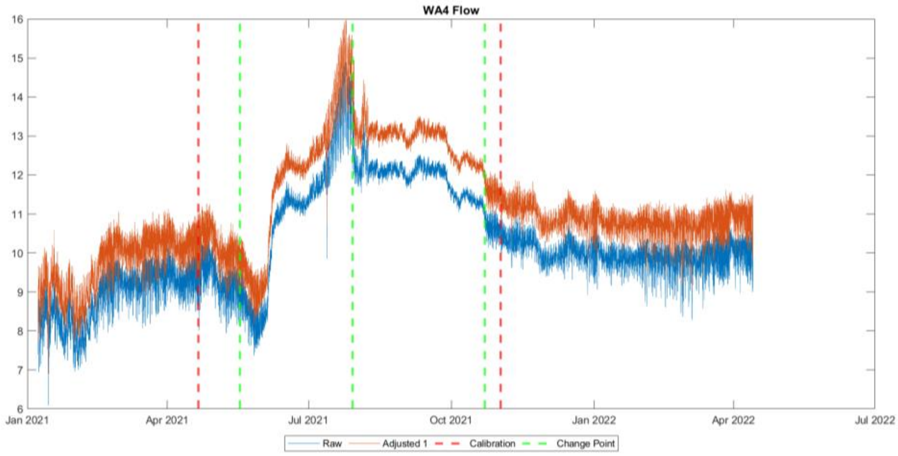

Figure 264 - West A4 Flow Temperature Calibration and Change Point Analysis

The calibrated values align very closely to the raw values for the return temperatures, and both the overall pattern, and change point analysis support use of the values provided.

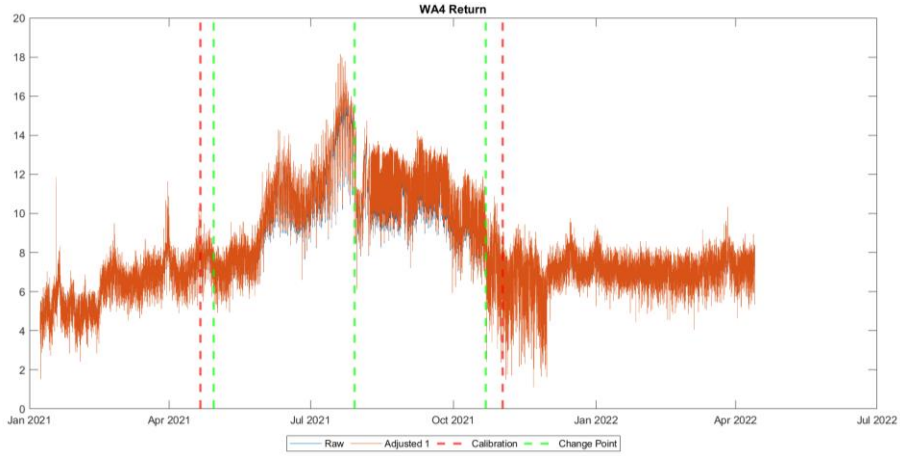

Figure 265 - West A4 Return Temperature Calibration and Change Point Analysis

B2. Backfilling Heat Meter Data

As discussed in Section 4.3.4, the accumulative flow parameter recorded by the heat meters allows the opportunity to fill backfill between the intermittent heat meter readings received. Where electricity data was also available for the heat pump, this assisted in the backfilling. The following section details the different backfilling methods attempted depending on the available data, including some that were not ultimately used.

In cases with both electricity and heat meter data, the power readings from the heat pump indicate when the additional flow through the heat meter likely occurred. Three methods of backfilling were attempted in this case:

1) Originally the total volumetric flow was distributed as a percentage of time for each cycle over the total time for all cycles, however this produced unrealistic COPs, as if a long cycle using low power levels would be attributed unrealistically large portions of flow.
2) Then, a simple percentage of the additional flow has been attributed to the periods of electrical energy usage, based on the percentage power over the whole period. However, this produced flow rates beyond the capability of the heat pump and so was also unused.
3) As such, it was decided to use the manufacturer’s data along with the power data and ground loop temperature data to estimate the heat outputs at each of the electricity meter readings. These values were then totalled and compared to the total volumetric flow difference in the heat readings. The heat per cycle (as a percentage of the total heat between the two heat meter readings) was then calculated, and these percentages were used to redistribute the total volumetric flow between heat meter readings. This also produced flow rates beyond the feasibility of the heat pump, and in these instances, the flow was distributed in the ways detailed below.

In the cases of heat meter data only, either where the flat has no electricity data at all or there was no data for the period of missing heat meter readings, the heat meter readings were interpolated by one of the follwoing methods.

1) If the latest reading had occurred whilst the heat pump was operational, it would include a flow rate value. It was then calculated how long the heat pump would need to operate at that flow rate to reach the total volumetric flow change between the current and the previous reading. If this closely matched the time gap between the two readings, it was assumed that the heat pump was operating for the whole time period at this flow rate.
2) If the time gap between the two readings was deemed too large for the heat pump to be operating continuously (> 1 hour), the average flow rate required over the whole time period to constitute the total additional volumetric flow was calculated. This allowed for the heat data to be captured for use in longer term KPIs such as daily performance factors, despite not being of as much use for KPIs such as COP
3) If the time gap is less than an hour but the flow rate is too large for the heat pump to have been on for the whole period, one of three things happens:
    a. If the current reading has an instantaneous flow rate, it is assumed that the 'on' period for the heat pump immediately preceded this reading
    b. If the current reading doesn't have an instantaneous flow rate, but the previous reading does, it is assumed the 'on' period immediately follows the previous reading
    c. If neither have an instantaneous flow rate, the average flow rate required over the whole period is calculated and applied, as in the case of large time gaps (see method 1)).
4) If the time gap between the two readings is less than an hour but is much shorter than is required at the recorded flow rate:
    a. If the time gap is only slightly off what is required (+/- 5 minutes) then it is assumed that the flow rate is only slightly off at the moment of recording. Thus, the flow rate is adjusted to a value that would account for the total overall flow change in the time between the two readings

b. If the time gap is off by more than +/- 5 mins, then it is assumed the reading was taken as the heat pump was ramping up/down and as such the flow rate is not representative. In this case the flow rate is replaced by a more suitable measurement from surrounding readings and applied as per method 2) above.

It was also the case that the heat meter readings would sometimes display a delta T that was deemed unrealistic. This could be:

1) The delta T was too small, as would be the case if the heat pump had just been turned off, i.e., the flow temperature would drop away faster than the return.

2) The delta T being too large, as would be the case if the operation of the heat pump had just been switched on, or perhaps switched from space heating to the heat battery, i.e., the return temperature is much lower than the flow temperature.

In both cases, surrounding heat meter readings with reasonable temperature differences were collated and averaged, providing surrogate temperature with which to calculate the heat.

B3. Electricity Meter Data

Section 4.3.5 summarises the methods used to backfill the electricity data for this case study. The electricity data was recorded by two separate dataloggers per building for redundancy and the data recorded by each datalogger is cumulative, meaning that after a large period of missing data the next recorded value is the electricity over that whole period. This means however, that combining the datasets is not as straightforward as filling any missing values with those recorded by the other datalogger. This could lead to the filling of one missing timestep in data from datalogger A, with a cumulative value at that same timestep from datalogger B.

The simplest method of cleaning this dataset would be to combine the two datasets as mentioned above and then removing any values deemed to be too large, as set out by the heat pump and thermal battery documentation. This would, however, leave a number of gaps in the data, potentially affecting the performance figures for the system.

Instead, in the cases where datalogger B has an cumulative value for a missing timestep in datalogger A, and vice versa, a more accurate value for that timestep was calculated. This was done by subtracting all of the recorded values from datalogger A that were missing in datalogger B in the accumulation period, from the accumulative value recorded by datalogger B.

This process was only implemented when at least 90% of the missing data in datalogger B was available in datalogger A. Where this wasn’t the case, the two tables were simply combined, and any accumulative values were removed by a simple filter as previously discussed.

Appendix C - Cardiff Data Limitations & Analysis Details

C1. Heating Degree Days

In Section 5.3.1.3 of this thesis, heating degree days were used to validate the assumptions made to calculate the provided by the heat pumps. The following section aims to provide a more detailed description of heating degree days, how they are calculated, and how they are often used.

Broadly speaking, heating degree days (HDD) provide a value for how long the outdoor air temperature was below a certain specified level, and by how much. This is often used in calculations of energy consumption in buildings, as the energy required to heat a building will vary depending on the outdoor air temperature.

To calculate heating degree days, a base temperature is required, and this is generally the outdoor air temperature below which heating is required to maintain a comfortable internal temperature. This will vary depending on the building, its occupation levels, the equipment used etc due to the heat gains from these factors.

The HDD can then be calculated. As an example, if the outdoor air temperature was 1 degree below the base temperature for 12 hours, this would be 0.5 HDD (1 degree * 0.5 days).

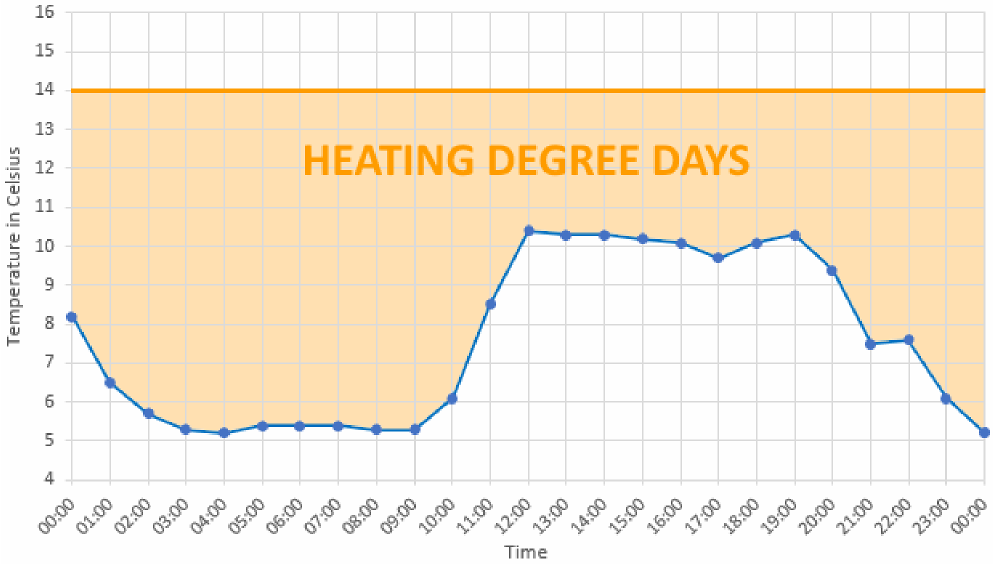

Figure 266 - Example of HDD with a 14-degree base temperature

The HDD values can then be used to normalise the energy consumption data, allowing for comparisons between years of different temperatures and conditions. To do this the total energy consumption would be divided by the total HDD to provide the kWh per HDD used.

Bromley (no date) provides additional information on heating degree days and their uses.

C2. Average Daily Heating Loads Per Month

Section 5.4.2.6 shows the average daily heat profile, per month, for 2020 as well as the average weekly heat profile, per month. The following figures provide the same values for the remaining years in the monitoring period.

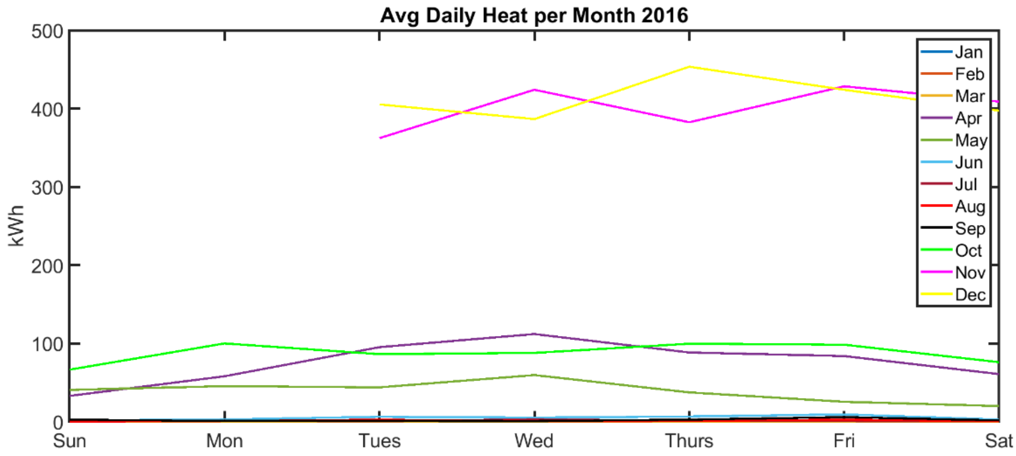

Figure 267 - Average Heating Week Per Month - 2016

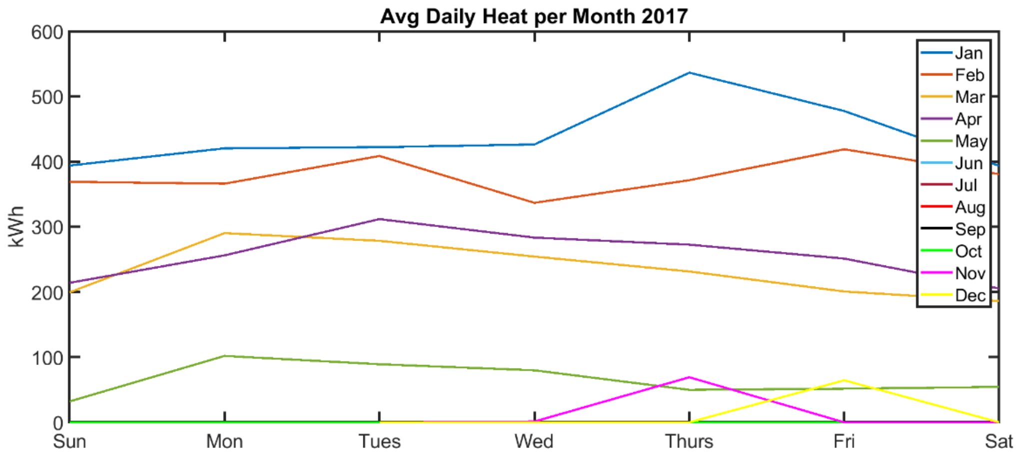

Figure 268 - Average Heating Week Per Month - 2017

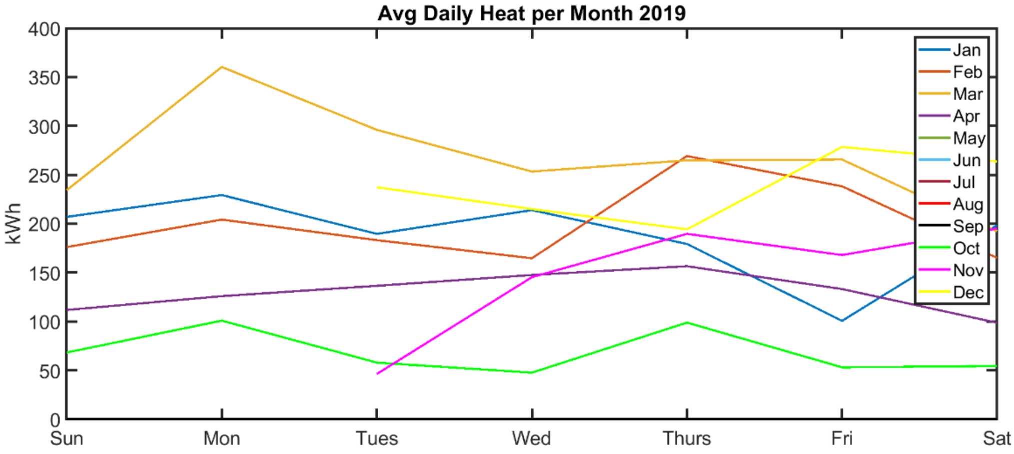

Figure 269 - Average Heating Week Per Month - 2019

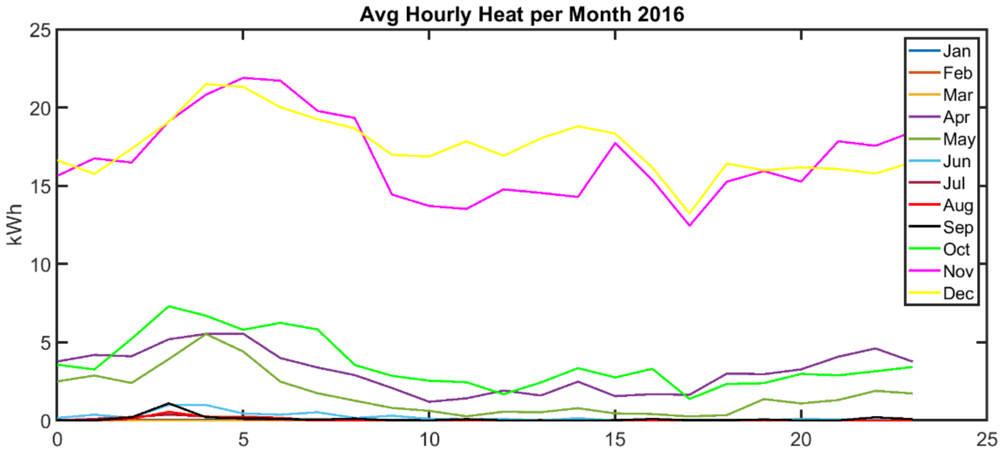

Figure 270 - Average Heating Day Per Month - 2016

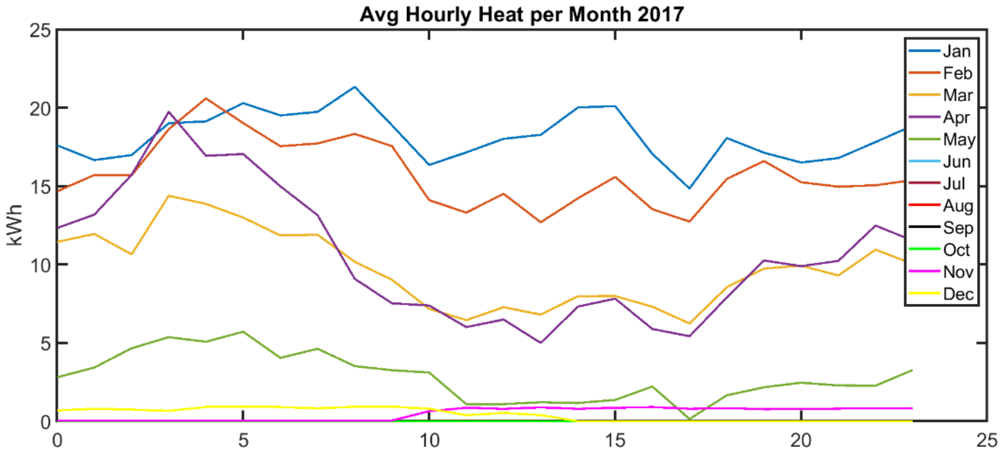

Figure 271 - Average Heating Day Per Month - 2017

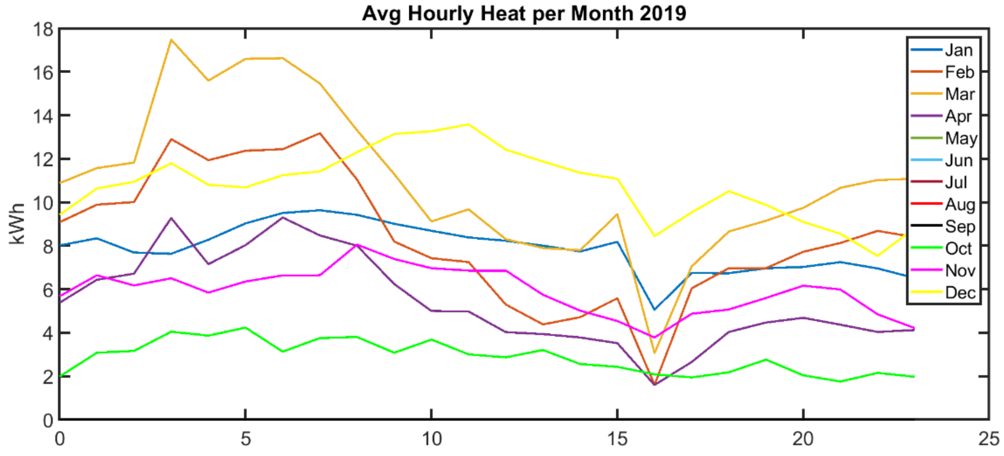

Figure 272 - Average Heating Day Per Month - 2019

Appendix D – Heights Data Collection Ethical Approvals

In order to collect and analyse the data from the individual flats at The Heights, permission was required from the occupants. An ethical review was also undertaken internally at the University of Leeds. The documents in this appendix include the information sheets provided to the users, a copy of permission form each of them signed, the application form for the ethical review, and the email confirming approval of the review.

D1. Ethical Review Application

UNIVERSITY OF LEEDS RESEARCH ETHICS COMMITTEE APPLICATION FORM [1]

UNIVERSITY OF LEEDS

Please read each question carefully, taking note of instructions and completing all parts. If a question is not applicable please indicate so. The superscripted numbers (eg[8]) refer to sections of the guidance notes, available at http://ris.leeds.ac.uk/UoLEthicsApplication. Where a question asks for information which you have previously provided in answer to another question, please just refer to your earlier answer rather than repeating information.
Information about research ethics training courses: http://ris.leeds.ac.uk/EthicsTraining.

To help us process your application enter the following reference numbers, if known and if applicable:

Ethics reference number:	**MEEC 20-005**
Student number and/ or grant reference:	**N/A**

PART A: Summary

A.1 Which Faculty Research Ethics Committee would you like to consider this application?[2]

- ○ Arts, Humanities and Cultures (AHC)
- ○ Biological Sciences (BIOSCI)
- ○ Business, Environment and Social Sciences (AREA)
- ◉ FS&N, Engineering and Physical Sciences (EPS)
- ○ Medicine and Health (Please specify a subcommittee):
  - ○ School of Dentistry (DREC)
  - ○ School of Healthcare (SHREC)
  - ○ School of Medicine (SoMREC)
  - ○ School of Psychology (SoPREC)

A.2 Title of the research[3]

Long term performance of ground source heat pump systems

A.3 Principal investigator's contact details[4]	
Name *(Title, first name, surname)*	Dr Fleur Loveridge
Position	Associate Professor
Department/ School/ Institute	Civil Engineering
Faculty	EPS
Work address *(including postcode)*	Civil Engineering 4.10 (but working from home) University of Leeds, Leeds, LS2 9JT
Telephone number	07773346203 (working from home)
University of Leeds email address	f.a.loveridge@leeds.ac.uk

A.4 Purpose of the research:[5] (Tick as appropriate)

- [x] Research
- [ ] Educational qualification: ***Please specify:*** ______________________
- [ ] Educational Research & Evaluation[6]
- [ ] Medical Audit or Health Service Evaluation[7]
- [ ] Other

A.5 Select from the list below to describe your research: (You may select more than one)

- [ ] Research on or with human participants
- [ ] Research which has potential adverse environmental impact.[8] ***If yes, please give details:*** ______________________
- [x] Research working with data of human participants
  - [ ] New data collected by qualitative methods
  - [x] New data collected by quantitative methods
  - [ ] New data collected from observing individuals or populations
  - [ ] Routinely collected data or secondary data
  - [ ] Research working with aggregated or population data
  - [ ] Research using already published data or data in the public domain
- [ ] Research working with human tissue samples (*Please inform the relevant Persons Designate if the research will involve human tissue*)[9]

A.6 Will the research involve NHS staff recruited as potential research participants (by virtue of their professional role) or NHS premises/ facilities?

- [ ] Yes
- [x] No

If yes, ethical approval must be sought from the University of Leeds. Note that approval from the NHS Health Research Authority may also be needed, please contact FMHUniEthics@leeds.ac.uk for advice.

A.7 Will the research involve any of the following:[10] (You may select more than one)

*If your project is classified as research rather than service evaluation or audit and involves any of the following an application must be made to the NHS Health Research Authority via IRAS www.myresearchproject.org.uk as NHS ethics approval will be required. **There is no need to complete any more of this form**. Further information is available at http://ris.leeds.ac.uk/NHSethicalreview and at http://ris.leeds.ac.uk/HRAapproval.*
*You may also contact **governance-ethics@leeds.ac.uk** for advice.*

- [ ] Patients and users of the NHS (including NHS patients treated in the private sector)[11]
- [ ] Individuals identified as potential participants because of their status as relatives or carers of patients and users of the NHS
- [ ] Research involving adults in Scotland, Wales or England who lack the capacity to consent for themselves[12]
- [ ] A prison or a young offender institution in England and Wales (and is health related)[14]
- [ ] Clinical trial of a medicinal product or medical device[15]
- [ ] Access to data, organs or other bodily material of past and present NHS patients[9]
- [ ] Use of human tissue (including non-NHS sources) where the collection is not covered by a Human

Tissue Authority licence[9]

☐ Foetal material and IVF involving NHS patients

☐ The recently deceased under NHS care

☑ None of the above

You must inform the Research Ethics Administrator of your NHS REC reference and approval date once approval has been obtained.

The HRA decision tool to help determine the type of approval required is available at http://www.hra-decisiontools.org.uk/ethics. If the University of Leeds is not the Lead Institution, or approval has been granted elsewhere (e.g. NHS) then you should contact the local Research Ethics Committee for guidance. The UoL Ethics Committee needs to be assured that any relevant local ethical issues have been addressed.

A.8 Will the participants be from any of the following groups? (Tick as appropriate)

☐ Children under 16[16] ***Specify age group:*** ______________________________

☐ Adults with learning disabilities[12]

☐ Adults with other forms of mental incapacity or mental illness

☐ Adults in emergency situations

☐ Prisoners or young offenders[14]

☐ Those who could be considered to have a particularly dependent relationship with the investigator, eg members of staff, students[17]

☐ Other vulnerable groups

☑ No participants from any of the above groups

Please justify the inclusion of the above groups, explaining why the research cannot be conducted on non-vulnerable groups.

It is the researcher's responsibility to check whether a DBS check (or equivalent) is required and to obtain one if it is needed. See also http://ris.leeds.ac.uk/healthandsafetyadvice and http://www.homeoffice.gov.uk/agencies-public-bodies/dbs.

A.9 Give a short summary of the research[18]

This section must be completed in ***language comprehensible to the lay person****. Do not simply reproduce or refer to the protocol, although the protocol can also be submitted to provide any technical information that you think the ethics committee may require. This section should cover the main parts of the proposal.*

Together Leeds City Council (LCC), Leeds Beckett University (LBU) and the University of Leeds (UoL) are conducting research on the efficiency and energy savings from improving the heating systems of social housing by retrofitting low carbon technologies.

LCC are retrofitting two blocks of flats with ground source heat pump systems. This includes upgrading the heating systems within each individual flat. LCC have contracted LBU to monitor the electrical energy consumption used for heating in a sub-set of 20 flats before and after the retrofit and change of heating system. This will allow them to test the effectiveness of the retrofit before rolling out to other LCC social housing.

UoL will additionally monitor the quantity of heat used use in the flats, both for space heating and domestic hot water.

UoL will additionally monitor the heat extracted from the ground, but this is outside of the individual flats and does not comprise any information specific to any individual flat and hence has no ethical issues.

Together the data gathered by LBU and UoL will allow us to assess the efficiency of the ground source heat pump system and permit recommendation to be made to LCC and the wider community about best practice in future schemes. This sort of work is essential to help demonstrate ground source heat technologies which are required to reduce carbon emissions from buildings.

The above describes the entire research project by the full research team. This ethics application pertains only to the work of UoL which is as follows:
(i) working with the commercial retrofit contractor who will install heat meters for us, direct receipt of the heat data from dataloggers,
(ii) initial indirect receipt of the electricity data from LBU, followed by direct download of data from the logging system installed by LBU.
(iii) storage and analysis of these data sets.

Consent for the research has already been obtained by LBU, who have undergone their own ethics assessment procedure. This ethics application pertains to data collection and storage by UoL and data sharing between the two parties. We are additionally seeking consent to extent the time period of data collection and therefore new participant consent is required for this aspect.

A.10 What are the main ethical issues with the research and how will these be addressed?[19]
Indicate any issues on which you would welcome advice from the ethics committee.

Use and storage of energy data from the 20 flats, including
- the pseudonymisation of the data during analysis;
- further anonymization of the data for publication;
- secure storage of the data (in confidential form) during the project;
- suitable archiving of the pseudonymised and anonymised data.

Participant information sheet and consent forms for extending the duration of data collection.

PART B: About the research team

B.1 To be completed by students only[20]
Please note: whilst some of the data from this study while appear in the PhD of Josh Turner (along with the necessary ethics documents), this is a collaborative project that will continue beyond the completion of his PhD and hence he is not name as the principal investigator in Part A.

Qualification working towards (eg Masters, PhD)	Josh Turner, working towards PhD
Supervisor's name (Title, first name, surname)	Dr Fleur Loveridge
Department/ School/ Institute	Civil Engineering
Faculty	EPS
Work address (including postcode)	University of Leeds, Leeds, LS2 9JT (but working from home)
Supervisor's telephone number	07773346230
Supervisor's email address	f.a.loveridge@leeds.ac.uk
Module name and number (if applicable)	

B.2 Other members of the research team (eg co-investigators, co-supervisors) [21]

Name *(Title, first name, surname)*	Dr Fleur Loveridge
Position	Associate Professor
Department/ School/ Institute	Civil Engineering
Faculty	EPS
Work address *(including postcode)*	University of Leeds, Leeds, LS2 9JT (but working from home)

Telephone number	07773346203
Email address	f.a.loveridge@leeds.ac.uk

Name (Title, first name, surname)	Prof Simon Rees
Position	Professor
Department/ School/ Institute	Civil Engineering
Faculty	EPS
Work address (including postcode)	University of Leeds, Leeds, LS2 9JT (working from home)
Telephone number	07952757097
Email address	S.J.Rees@leeds.ac.uk

Part C: The research

C.1 What are the aims of the study?[22] (Must be in language comprehensible to a lay person.)

To understand the energy efficiency of ground source heat pump systems used to heat multiple family domestic accommodation, such as large blocks of flats.

To make recommendations about how such systems should be monitoring on a routine basis, so that maximum benefit can be derived for the householders.

To make recommendations about design and construction of future schemes for economic and energy efficiency.

C.2 Describe the design of the research. Qualitative methods as well as quantitative methods should be included. (Must be in language comprehensible to a lay person.)

It is important that the study can provide information about the aims that it intends to address. If a study cannot answer the questions/ add to the knowledge base that it intends to, due to the way that it is designed, then wasting participants' time could be an ethical issue.

The research involves working with the retrofit contractor to install sensors in the ground source heat pump heating system as follows:

- a heat meter in each of the 20 flats

- a sensor to determine whether the heat pump is delivering space heat or hot water in each of the 20 flats

- flow meters and temperature sensors on the pipes that exit the ground (in the drying room, and caretakers office)

All sensors in the flats will be installed by the contractors carrying out the heating system retrofit.

The sensors will all be monitored remotely. Data will be analysed by researchers at the UoL to determine the efficiency of the heating system.

C.3 What will participants be asked to do in the study?[23] *(e.g. number of visits, time, travel required, interviews)*

The participants do not need to do anything for our research. The sensors will be installed as part of the contractor's programme of works and will be monitored remotely.

C.4 Does the research involve an international collaborator or research conducted overseas?[24]

☐ Yes ☑ No

If yes, describe any ethical review procedures that you will need to comply with in that country:

Describe the measures you have taken to comply with these:

Include copies of any ethical approval letters/ certificates with your application.

C.5 Proposed study dates and duration

Research start date (DD/MM/YY): 01/06/2020 Research end date (DD/MM/YY): 01/06/2023

Fieldwork start date (DD/MM/YY): Late September 2020 Fieldwork end date (DD/MM/YY): Spring 2021

C.6. Where will the research be undertaken? (i.e. in the street, on UoL premises, in schools)[25]

The Heights East, Leeds, LS12 3TT
The Heights West, Leeds, LS12 3TY

RECRUITMENT & CONSENT PROCESSES

C.7 How will potential participants in the study be identified, approached and recruited?[26]
How will you ensure an appropriately convened sample group in order to meet the aims of the research? Give details for subgroups separately, if appropriate. How will any potential pitfalls, for example dual roles or potential for coercion, be addressed?

Participants have already been recruited by LCC and LBU and consent obtained for an initial period of data collection. We are now seeking to extend the data collection period and will provide new participant information and consent forms.

C.8 Will you be excluding any groups of people, and if so what is the rationale for that?[27]
Excluding certain groups of people, intentionally or unintentionally may be unethical in some circumstances. It may be wholly appropriate to exclude groups of people in other cases

Not applicable.

C.9 How many participants will be recruited and how was the number decided upon?[28]
It is important to ensure that enough participants are recruited to be able to answer the aims of the research.

20 participants have been recruit by LCC and LBU. This is not within UoL scope.

If you have a formal power calculation please replicate it here.

Remember to include all advertising material (posters, emails etc) as part of your application

C10 Will the research involve any element of deception?[29]
If yes, please describe why this is necessary and whether participants will be informed at the end of the study.

No.

C.11 Will informed consent be obtained from the research participants?[30]

☑ Yes ☐ No

If yes, give details of how it will be done. Give details of any particular steps to provide information (in addition to a written information sheet) e.g. videos, interactive material. If you are not going to be obtaining informed consent you will need to justify this.

Informed consent has already been obtained by LCC and LBU. LBU have already completed their own ethics assessment for this process.

We will now seek additional informed consent to extend the data collection period to maximise the benefits from the study.

If participants are to be recruited from any of potentially vulnerable groups, give details of extra steps taken to assure their protection. Describe any arrangements to be made for obtaining consent from a legal representative.

Not applicable

Will research participants be provided with a copy of the Privacy Notice for Research? If not, explain why not.
Guidance is available at https://dataprotection.leeds.ac.uk/information-for-researchers.

☑ Yes ☐ No

***Copies of any written consent form, written information and all other explanatory material should accompany this application**. The information sheet should make explicit that participants can withdraw from the research at any time, if the research design permits. Remember to use meaningful file names and version control to make it easier to keep track of your documents.*
Sample information sheets and consent forms are available from the University ethical review webpage at http://ris.leeds.ac.uk/InvolvingResearchParticipants.

C.12 Describe whether participants will be able to withdraw from the study, and up to what point (eg if data is to be anonymised). If withdrawal is not possible, explain why not.
Any limits to withdrawal, eg once the results have been written up or published, should be made clear to participants in advance, preferably by specifying a date after which withdrawal would not be possible. Make sure that the information provided to participants (eg information sheets, consent forms) is consistent with the answer to C12.

Participants will be able to withdraw from the study at any point by contacting the applicant.

C.13 How long will the participant have to decide whether to take part in the research?[31]
It may be appropriate to recruit participants on the spot for low risk research; however consideration is usually necessary for riskier projects.

They have already decided to take part in the research. When LBU return for their second set of participant interviews, they will be asked if they will be willing to remain in the study for a further two years.

C.14 What arrangements have been made for participants who might have difficulties understanding verbal explanations or written information, or who have particular communication needs that should be taken into account to facilitate their involvement in the research?[32] *Different populations will have different information needs, different communication abilities and different levels of understanding of the research topic. Reasonable efforts should be made to include potential participants who could otherwise be prevented from participating due to disabilities or language barriers.*

From liaison with LBU this will not be applicable.

C.15 Will individual or group interviews/ questionnaires discuss any topics or issues that might be sensitive, embarrassing or upsetting, or is it possible that criminal or other disclosures requiring action could take place during the study (e.g. during interviews or group discussions)?[33] *The information sheet should explain under what circumstances action may be taken.*

☐ Yes ☑ No *If yes, give details of procedures in place to deal with these issues.*

Not applicable.

C.16 Will individual research participants receive any payments, fees, reimbursement of expenses or any other incentives or benefits for taking part in this research?[34]

☑ Yes ☐ No

If Yes, please describe the amount, number and size of incentives and on what basis this was decided.

When recruiting the participants, LBU provided incentives (vouchers). To be consistent with this earlier approach we will offer a small value voucher (£10) to compensate the participants for their time in discussing and agreeing to the extension of the data collection period.

RISKS OF THE STUDY

C.17 What are the potential benefits and/ or risks for research participants in both the short and medium-term?[35]

Benefits: recommendations to LCC (the participants' landlords) about improving the energy efficiency of the heating systems, hence potentially saving the tenants money.

There are no risks to the participants.

C.18 Does the research involve any risks to the researchers themselves, or people not directly involved in the research? *Eg lone working*[36]

☑ Yes ☐ No

If yes, please describe:
(i) There are risks are related to visits to the heating system retrofitting, which is effectively a live construction live. This are dealt with via a separate risk assessment. An example for the initial site visit is attached. Updates were made for subsequent different tasks.
(ii) The principal investigator will visit to participants to obtain consent for the data collection extension. This will be done at the same time as the second LBU interviews in April or May 2021. There will therefore be no lone working. UoL and LBU staff will also be accompanied by a LCC representative.

Is a risk assessment necessary for this research?
If you are unsure whether a risk assessment is required visit http://ris.leeds.ac.uk/HealthAndSafetyAdvice or contact your Faculty Health and Safety Manager for advice.

☑ Yes ☐ No If yes, please include a copy of your risk assessment form with your application.

RESEARCH DATA

C.19 Explain what measures will be put in place to protect personal data. E.g. anonymisation procedures, secure storage and coding of data. Any potential for re-identification should be made clear to participants in advance.[37] *Please note that research data which appears in reports or other publications is not confidential, even if it is fully anonymised. For a fuller explanation see http://ris.leeds.ac.uk/ConfidentialityAnonymisation. Further guidance is available at http://ris.leeds.ac.uk/ResearchDataManagement.*

Raw data will be of two sorts. Heat data received directly from dataloggers, and electricity data supplied by LBU or received directly from dataloggers.

Raw data will be linked to individual flat locations (numbers) to enable engineering interpretations to be made. This is because the flat locations (e.g. north or south facing) may effect energy performance. This data will be kept confidential. It will be password protected with the password stored within a separate file and folder on the secure university cloud storage. Access to the data folders will be limited to the research team members identified in this application only.

No participant names will be held by UoL in associated with the above data, only flat numbers. Participant names will only be stored on the consent forms, which will be kept in paper copy in a locked cabinet or drawer on the UoL campus.

The raw heat and electricity data will then be pseudonymised, whereby each flat will be given a code, rather than its original number. The key to the pseudonymisation will be password protected with the password stored within a separate file and folder on the secure university cloud storage. Access to the data folders will be limited to the research team members identified in this application only. Routine analysis during the research project will happen with the pseudonymised data. It will be kept confidential.

Publication of findings from the research will be carried out only with anonymised data. In these cases no information will be provided about the location of the flats, or the flat codes or numbers.

Archiving of data (in accordance with UKRI policy) will only be carried out with anonymised data.

The above process will be formalised in a data management plan based in DMPOnline.

C.20 How will you make your research data available to others in line with: the University's, funding bodies' and publishers' policies on making the results of publically funded research publically available. Explain the extent to which anonymity will be maintained. *(max 200 words)* Refer to http://ris.leeds.ac.uk/ConfidentialityAnonymisation and http://ris.leeds.ac.uk/ResearchDataManagement for guidance.

Research publications will be open access. Data contained within the publications will be anonymous (see above) so that the precise locations, and the respective flats at those locations will not be disclosed.

Limited anonymised data will be made publically available (in accordance with UKRI procedures).

C.21 Will the research involve any of the following activities at any stage (including identification of potential research participants)? (Tick as appropriate)

- ☐ Examination of personal records by those who would not normally have access
- ☐ Access to research data on individuals by people from outside the research team
- ☐ Electronic surveys, please specify survey tool: ______________________________ (further guidance)
- ☐ Other electronic transfer of data
- ☐ Use of personal addresses, postcodes, faxes, e-mails or telephone numbers
- ☐ Use of audio/ visual recording devices (NB this should usually be mentioned in the information for participants)
- ☐ FLASH memory or other portable storage devices

Storage of personal data on, or including, any of the following:

- ☑ University approved cloud computing services
- ☐ Other cloud computing services
- ☑ Manual files (paper consent forms only – see above for details)
- ☐ Private company computers
- ☐ Laptop computers
- ☐ Home or other personal computers (not recommended; data should be stored on a University of

Leeds server such as your M: or N: drive where it is secure and backed up regularly: http://ris.leeds.ac.uk/ResearchDataManagement.)

Unclassified and Confidential University data must be kept on the University servers or in approved cloud services such as Office 365 (SharePoint or OneDrive). The N: Drive or Office 365 should be used for the storage of data that needs to be shared. If Highly Confidential information is kept in these shared storage areas it must be encrypted. Highly Confidential data that is not to be shared should be kept on the M: Drive. The use of non-University approved cloud services for the storage of any University data, including that which is unclassified, is forbidden without formal approval from IT. Further guidance is available via http://ris.leeds.ac.uk/ResearchDataManagement.

C.22 How do you intend to share the research data? (Indicate with an 'X) *Refer to http://library.leeds.ac.uk/research-data-deposit for guidance.*

- [ ] Exporting data outside the European Union
- [ ] Sharing data with other organisations
- [ ] Publication of direct quotations from respondents
- [ ] Publication of data that might allow identification of individuals to be identified
- [x] Submitting to a journal to support a publication
- [x] Depositing in a self-archiving system or an institutional repository
- [ ] Dissemination via a project or institutional website
- [ ] Informal peer-to-peer exchange
- [ ] Depositing in a specialist data centre or archive
- [ ] Other, please state: ____.
- [ ] No plans to report or disseminate the data

C.23 How do you intend to report and disseminate the results of the study? (Indicate with an 'X) Refer to http://ris.leeds.ac.uk/ResearchDissemination and http://ris.leeds.ac.uk/Publication for guidance.

- [x] Conference presentation
- [x] Peer reviewed journals
- [x] Publication as an eThesis in the Institutional repository
- [ ] Publication on website
- [ ] Other publication or report, please state: ______________________________
- [ ] Submission to regulatory authorities
- [ ] Other, please state: ____.
- [ ] No plans to report or disseminate the results

C.24 For how long will data from the study be stored? Please explain why this length of time has been chosen.[38] Refer to the RCUK Common Principles on Data Policy and http://ris.leeds.ac.uk/info/71/good_research_practice/106/research_data_guidance/5.
Students*: It would be reasonable to retain data for at least 2 years after publication or three years after the end of data collection, whichever is longer.*

_10____ years, ___0___ months (as per RCUK guidance)

CONFLICTS OF INTEREST

C.25 Will any of the researchers or their institutions receive any other benefits or incentives for taking part in this research over and above normal salary or the costs of undertaking the research?[39]

☐ **Yes** ☑ **No**

If yes, indicate how much and on what basis this has been decided

____

C.26 Is there scope for any other conflict of interest?[40] *For example, could the research findings affect the any ongoing relationship between any of the individuals or organisations involved and the researcher(s)? Will the research funder have control of publication of research findings? Refer to http://ris.leeds.ac.uk/ConflictsOfInterest.*

☐ Yes ☑ No

If so, please describe this potential conflict of interest, and outline what measures will be taken to address any ethical issues that might arise from the research.

C.27 Does the research involve external funding? (Tick as appropriate)

☑ Yes ☐ No ***If yes, what is the source of this funding?*** _

Royal Academy of Engineering Research Fellowship, EPSRC PhD funding

NB: If this research will be financially supported by the US Department of Health and Human Services or any of its divisions, agencies or programmes please ensure the additional funder requirements are complied with. Further guidance is available at http://ris.leeds.ac.uk/FWAcompliance and you may also contact your FRIO for advice.

PART D: Declarations

Declaration by Principal Investigators

1. The information in this form is accurate to the best of my knowledge and belief and I take full responsibility for it.
2. I undertake to abide by the University's ethical and health & safety guidelines, and the ethical principles underlying good practice guidelines appropriate to my/ discipline.
3. If the research is approved I undertake to adhere to the study protocol, the terms of this application and any conditions set out by the Research Ethics Committee (REC).
4. I undertake to seek an ethical opinion from the REC before implementing substantial amendments to the protocol.
5. I undertake to submit progress reports if required.
6. I am aware of my responsibility to be up to date and comply with the requirements of the law and relevant guidelines relating to security and confidentiality of patient or other personal data, including the need to register when necessary with the University's Data Protection Controller (further information available via http://ris.leeds.ac.uk/ResearchDataManagement).
7. I understand that research records/ data may be subject to inspection for audit purposes if required in future.
8. I understand that personal data about me as a researcher in this application will be held by the relevant RECs and that this will be managed according to the principles established in the Data Protection Act.
9. I understand that the REC may choose to audit this project at any point after approval.

Sharing information for training purposes: *Optional – please tick as appropriate:*

☐ I would be content for members of other Research Ethics Committees to have access to the information in the application in confidence for training purposes. All personal identifiers and references to researchers, funders and research units would be removed.

Principal Investigator:

Signature of Principal Investigator: ……… ………………………………………………
(This needs to be an actual signature rather than just typed. Electronic signatures are acceptable)

Print name: …Dr.Fleur Loveridge.. Date: (dd/mm/yyyy): ….31/03/2021..

Supervisor of student research:

I have read, edited and agree with the form above.

Supervisor's signature: ……………………………………………………….
(This needs to be an actual signature rather than just typed. Electronic signatures are acceptable)

Print name: ………………………………………………. Date:(dd/mm/yyyy): ……………………………………………….

Please submit your form by email to the FREC or School REC's mailbox.

Remember to include any supporting material such as your participant information sheet, consent form, interview questions and recruitment material with your application.

To help speed up the review of your application:

- ❑ Answer the questions in plain English, avoid using overly technical terms and acronyms not in common use.
- ❑ Answer all the questions on the form, including those with several parts (refer to the guidance if you're not sure how to answer a question or how much detail is required).
- ❑ Include any relevant supplementary materials such as
  - ❑ Recruitment material (posters, emails etc)
  - ❑ Sample participant information sheet
  - ❑ Sample consent form. Include different versions for different groups of participants eg for children and adults, clearly indicating which is which.
  - ❑ Signed risk assessment (If you are unsure whether a risk assessment is required visit http://ris.leeds.ac.uk/HealthAndSafetyAdvice or contact your Faculty Health and Safety Manager for advice).

  Remember to include use version control and meaningful file names for the documents.
- ❑ If you are not going to be using participant information sheets or consent forms explain why not and how informed consent will be otherwise obtained.
- ❑ If you are a student it is essential that you discuss your application with your supervisor.
- ❑ Submit a signed copy of the application, preferably electronically. Students' applications need to be signed by their supervisors as well.

D2. Ethical Review Approval Email

Fwd: MEEC 20-005 - Ethics Application - APPROVAL

Fleur Loveridge <F.A.Loveridge@leeds.ac.uk>
Wed 02/06/2021 11:33
To: Joshua Turner [mn11jlt] <mn11jlt@leeds.ac.uk>

---------- Forwarded message ----------
From: EPSResearchEthics <EPSResearchEthics@leeds.ac.uk>
Date: 2 Jun 2021 09:52
Subject: MEEC 20-005 - Ethics Application - APPROVAL
To: Fleur Loveridge <F.A.Loveridge@leeds.ac.uk>
Cc: EPSResearchEthics <EPSResearchEthics@leeds.ac.uk>

Dear Fleur

MEEC 20-005 - Long term performance of ground source heat pump systems

NB: All approvals/comments are subject to compliance with current University of Leeds and UK Government advice regarding the Covid-19 pandemic.

I am pleased to inform you that the above research ethics application has been reviewed by the Engineering and Physical Sciences Committee and on behalf of the Chair, I can confirm a favourable ethical opinion based on the documentation received at date of this email.

Please retain this email as evidence of approval in your study file.

Please notify the committee if you intend to make any amendments to the original research as submitted and approved to date. This includes recruitment methodology; all changes must receive ethical approval prior to implementation. Please see https://ris.leeds.ac.uk/research-ethics-and-integrity/applying-for-an-amendment/ or contact the Research Ethics Administrator for further information epsresearchethics@leds.ac.uk if required.

Ethics approval does not infer you have the right of access to any member of staff or student or documents and the premises of the University of Leeds. Nor does it imply any right of access to the premises of any other organisation, including clinical areas. The committee takes no responsibility for you gaining access to staff, students and/or premises prior to, during or following your research activities.

Please note: You are expected to keep a record of all your approved documentation, as well as documents such as sample consent forms, risk assessments and other documents relating to the study. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited.

It is our policy to remind everyone that it is your responsibility to comply with Health and Safety, Data Protection and any other legal and/or professional guidelines there may be.

I hope the study goes well.

Best wishes

Kaye Beaumont

On behalf of James Young, CHAIR, MEEC

From: Fleur Loveridge <F.A.Loveridge@leeds.ac.uk>
Sent: 01 September 2020 17:26
To: EPSResearchEthics <EPSResearchEthics@leeds.ac.uk>
Subject: Ethical Review Form Submission

Hello,

Please find attached my application for ethics approval. It is the first time I have used this process, please let me know if I have missed anything.

With best wishes, Fleur.

D3. Participant Information Sheet

Leeds City Council High Rise Pilot

Participant Information Guide

About the project

The University of Leeds are carrying our research into the performance of heating and hot water systems, like the ones recently installed at your home, to help understand how we can maximise energy efficiency and reduce costs to residents in the future. We are working with Leeds City Council and Leeds Beckett University to extend the study they started to achieve greater impact and improvement potential for residents here and at other blocks of flats throughout Leeds and beyond.

Who we are

Dr Fleur Loveridge is an Associate Professor and Josh Turner is a PhD student. We both work in the Faculty of Engineering and Physical Science at the University of Leeds.

What am I being asked to do?

You don't need to do anything. If you agree, sensors already installed within your homes by the building contractor Cenergist and by Leeds Beckett University, will continue to be read remotely for a further two years. No further access to your home will required.

As before, only information on energy use, temperature and air quality will be collected. The sensors don't record what you say or do or any other information. The sensors will remain in place for up to two years, and will continue to be located near to your electricity meter and in your Lounge, Bedroom, Kitchen and Bathroom.

Will anybody find out about the energy I use?

No. We will store all the information we collect in a secure format. Only the people directly involved in the research (at the University of Leeds and Leeds Beckett University) will see the energy readings. When we look at the energy data, it will be disconnected from your flat number so that no one can connect the information to your personal energy use. We may later publish reports or scientific articles about what we have learnt about the performance of your heating and hot water system, but all information will be anonymous and will not be able to be connected to your household in any way.

Will you share my contact details with anybody?

No, we won't pass your contact details on to anybody else.

UNIVERSITY OF LEEDS

Do I have to take part?

No. We hope that you will take part so that we can learn about the performance of your heating and hot water system and potentially help you and other residents save money in the future. But you are not under any pressure to take part, and you may choose to leave the study at any time by contacting us.

Who can I contact if I have any questions or concerns or I have changed my mind?

If you have any questions or concerns, you can contact Fleur Loveridge by telephone (0113 343 2248) or email (f.a.loveridge@leeds.ac.uk).

D4. Participant Permission Form

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Do you consent to take part in the study?

Please read each of the following points and tick the box if you agree. Just ask if there is anything you don't understand or you are unsure about.

1. I have read and understood the information sheet for the study and I understand what is expected of me. ☐

2. I understand that taking part in the research is voluntary and that I can change my mind about taking part. ☐

3. I understand that I can contact the researchers at any time to tell them that I don't want to be involved in the study. ☐

4. I have been given the opportunity to ask questions about the study and if I asked, my questions were answered fully. ☐

Your name (print) ....

Your signature .... **Date** …………...

Researcher's signature …………………………………… **Date** ……………

Thank you for this information.

Contact details: Fleur Loveridge, f.a.loveridge@leeds.ac.uk
School of Civil Engineering, Faculty of Engineering and Physical Science, University of Leeds.