Department for Energy Security & Net Zero

Electrification of Heat Demonstration Project

Interim Heat Pump Performance Data Analysis Report

Written by Energy Systems Catapult

This report has been funded by DESNZ and is issued on their behalf

Catapult Energy Systems
LCPDelta
Oxford Computer Consultants

Contents

Glossary

ASHP	Air Source Heat Pump
BEIS	Department for Business, Energy and Industrial Strategy
CI	Confidence Interval (typically 95%)
COP	Coefficient of Performance
$COP_{(HX)}$	COP using the specific SPF calculation boundaries (X = 2, 3 or 4)
COP_{SH}	COP in space heating mode only (used for Hybrid system calculations)
DB	Database
DC	Delivery Contractor
DESNZ	Department for Energy Security and Net Zero
EoH	Electrification of Heat
EPC	Energy Performance Certificate
ESC	Energy Systems Catapult Ltd.
FNC	Frazer Nash Consultancy
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential (where CO_2 has a GWP of 1)
HP	Heat Pump
HPR	Heat Pump Return (temperature)
HPHF	Heat Pump Heating Flow (temperature)
HT	High Temperature
HWF	Hot Water Flow (temperature)
Hybrid	Hybrid system containing a gas boiler and an electric heat pump.
ID	Identification (number)
IQR	Interquartile Range
ITT	Invitation to Tender
LT	Low Temperature
MC	Management Contractor
MCS	Microgeneration Certification Scheme
n	Number / Sample size
NUTS	Nomenclature of Territorial Units for Statistics

Q1, Q3	Quartile 1, Quartile 3
QA	Quality Assurance
R290, R32, R410a	Refrigerant fluids / gases used within heat pumps
RHI	Renewable Heat Incentive
RHPP	Renewable Heat Premium Payment scheme
SAP	Standard Assessment Procedure (UK building energy assessment)
SCOP	Seasonal Coefficient of Performance
SEPEMO	**SE**asonal **PE**rformance factor and **MO**nitoring for heat pump systems in the building sector project.
SGL	Shared Ground Loop (GSHP)
SPF	Seasonal Performance Factor
SPF_{HX}	SPF Calculated using the specific boundaries in Section 7
TTPS	Technical Third Party Support

1. Executive summary

1.1 Project background

The Electrification of Heat (EoH) demonstration project is funded by the Department for Energy Security and Net Zero (DESNZ)[1] and seeks to better understand the feasibility of a large-scale rollout of heat pumps across the UK. It aims to demonstrate that heat pumps can be installed in a wide variety of homes and deliver high customer satisfaction across a range of customer groups.

The project team consists of a Management Contractor (MC) consortium (including LCP Delta[2] and Oxford Computer Consultants) led by Energy Systems Catapult Ltd. and three Delivery Contractors (DCs). The DCs were responsible for the participant recruitment, home survey, design, and installation of the heat pumps. They also maintain the heat pump monitoring systems to ensure continuous performance data is collected. The MC is responsible for management of the project and collation of the data as well as associated analysis and dissemination of project findings.

The three DCs are: E.ON (operating in North-East England); OVO Energy (operating in South-East England, excluding London); and Warmworks (operating in South-East Scotland).

In total the EoH project has installed 742 heat pump systems in a range of different housing types and ages. Installation statistics are provided in Table 1.1.

Table 1.1: Heat pump installation statistics.

Criteria	Group	Installations (%)	Installations (No.)
Heat Pump Type	LT ASHP	41.2%	306
	HT ASHP	32.7%	243
	GSHP	5.1%	38
	Hybrid	20.9%	155
Property Form	Detached	40.6%	301
	Semi-detached	42.8%	261
	End-terrace		57
	Mid-terrace	11.1%	82
	Flats	5.5%	41
Property Age	Pre-1919	7.8%	58
	1919 to 1944	14.2%	105
	1945 to 1964	24.0%	178
	1965 to 1980	22.2%	165
	1981 to 1990	9.2%	68
	1991 to 2000	9.6%	71
	2001+	13.1%	97

Each of the heat pump installations includes equipment which monitors the heat pump performance over time. This equipment monitors the energy used and output by each component of the system and various system temperatures. The data collected by this

[1] Prior to the formation of the Department for Energy Security and Net Zero (DESNZ) on 7th February 2023; the project was funded by the Department for Business, Energy and Industrial Strategy (BEIS).
[2] Formerly Delta-EE.

equipment is used to analyse the heat pump performance throughout this report. Most of the heat pumps will continue to be monitored until September 2023.

1.2 About this report

This report provides interim analysis of the heat pump performance data collected by the monitoring systems. The analysis will be refreshed, and additional analysis will be undertaken after the completion of the projects monitoring period in September 2023.

As well as the analysis, the report provides all details relating to how the heat pumps were monitored, data was collected and interpreted. This includes:

- Detail on the physical monitoring system,
- Detail on the performance data cleansing,
- Detail on the data quality checks conducted, and how the results were interpreted,
- Detail on calculation assumptions made,
- Detail on known data quality issues and known data biases.

1.3 Data Cleansing, Quality Checks, and Analysis

To ensure the data was of sufficient standard to form analysis conclusions, an iterative process of cleansing and quality checking was conducted. The cleansing activity is the process of taking "raw" data and making slight adjustments to prepare the data for analysis. These adjustments included:

- Timestamp realignment to exact 2-minute periods.
- Adjustments if meter was reversed (negative daily difference between readings).
- Anomalous single point removal from cumulative meter data.
- Removal of anomalous data from start of monitoring period (data indicating faulty monitoring equipment installation).
- Relevelling data following a meter reset.
- Removal of out-of-range temperatures.
- Reassigning non-cumulative (temperature) data to the correct columns.
- Supplementary data cleansing – amending spelling or grammar variations.
- Supplementary data cleansing – aligning property age ranges.

Following the data cleansing, quality checks were performed to ensure the best analysis windows were selected and the data was of sufficient standard to be included within the analysis. These quality checks scored each quality issue and a threshold score was applied over which, data was insufficient to be included in the analysis.

In addition to the quality scoring, data was rejected from the analysis for erroneous Seasonal Performance Factor (outside of the range of 1.5 to 4.5) and, if less than 50% of the expected heat pump data was available.

Seasonal Performance Factors and Coefficients of Performance were calculated using the performance data. These calculations used the system boundaries defined in the SEPEMO project [1] and the results of all calculations were used to form the analysis findings.

1.4 Key findings

1.4.1 Seasonal Performance Factor values

The median Seasonal Performance Factors (SPFs) observed in Air Source Heat Pumps (ASHPs) have increased significantly since RHPP (Renewable Heat Premium Payment scheme) [2]. A comparison of the EoH and RHPP SPFs can been seen in Table 1.2.

Table 1.2: EoH and RHPP observed Air Source Heat Pump SPFs.

SPF Value	Interim EoH ASHP Sample	EoH Median ASHP SPF [IQR]	RHPP ASHP Sample	RHPP Median ASHP SPF [IQR]
SPF_{H2}	291	2.94 [2.66, 3.20]	292	2.65 [2.33, 2.95]
SPF_{H4}	291	2.80 [2.53, 3.09]	292	2.44 [2.15, 2.67]

As seen above, ASHP SPFs have improved by around 0.3 to 0.4 compared with installations completed under RHPP. Note that when reviewing the EoH figures against the RHPP figures, no adjustment has been made for weather variations within the analysis windows.

The improvement in performance is likely due to industry innovation and the heat pump units themselves becoming more efficient over the period between the two projects. As noted above, relative weather conditions may also account for some of the performance improvement. This performance improvement may also be partially a result of improvements in the design (and installation) of heat pump systems. However, the EoH project has also found that variation in performance between heat pumps remains high (see Section 1.4.2).

The median SPF values observed for heat pumps within hybrid systems (i.e. excluding boiler efficiency) are provided within Table 1.3.

Table 1.3: EoH observed SPF for heat pumps within hybrid systems (excluding boiler efficiency).

SPF Value	Interim EoH Hybrid Sample	EoH Median Hybrid SPF [IQR]
SPF_{H2}	58	2.54 [2.25, 2.93]
SPF_{H4}	58	2.37 [2.01, 2.81]

It should be noted that these SPF values do not account for the heat generated by the boiler and the efficiency of the boilers within the hybrid systems was not monitored as part of this project. Section 9.2 provides an indication of the whole hybrid system efficiency with assumed average boiler efficiencies.

Figure 1.1 shows the observed SPF values for ASHPs and heat pumps in hybrid systems in a box plot.

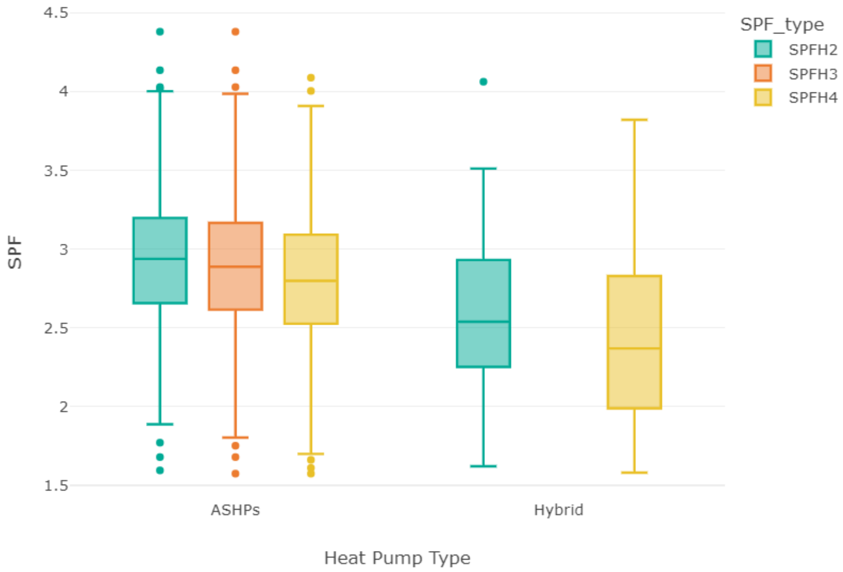

Figure 1.1: Box plot of SPF values for ASHPs and heat pumps within hybrid systems.

1.4.2 Seasonal Performance Factor variations

When comparing the EoH and RHPP ASHP SPFs, the variation in SPF between installations remains high with similar Interquartile Range (IQR). The variation in system efficiencies suggests that progress is still required on improving the quality and consistency of heat pump designs and installations to support a large-scale rollout of heat pumps in existing homes and deliver positive energy, carbon, and consumer outcomes. These findings should be factored into modelling and policy decisions.

One of the reasons for this variation is the efficiency of the heat pump models. This is partially demonstrated by comparing the heat pump performance by the refrigerant used. This comparison is shown in Table 1.4 below. Despite this comparison inidicating one reason for the variation, the overall performance variation is not explained by the data analysis completed to date.

Table 1.4: Median SPF_{H4} values observed in ASHPs, broken down by refrigerant type.

Refrigerant	Sample	Median SPF_{H4} [IQR]
R32	82 (76 LT, 6 HT)	2.94 [2.57, 3.25]
R290	98 (all HT)	2.89 [2.68, 3.08]
R410a	111 (all LT)	2.66 [2.40, 2.84]

The above table indicates that the heat pumps using the R410a refrigerant have been observed to operate with lower efficiency than those using R290 and R32. It should be noted that this is unlikely to be exclusively a result of the efficiency of the refrigerant. The R410a refrigerant is being phased out and therefore models of heat pump using R410a are likely to be older than those using R290 and R32. These older units may have less efficient mechanical components and control strategies.

Another reason for the performance variation is control strategy and flow temperature of the heat pumps. The observed SPF is higher for installations that have a lower mean operating flow temperature.

Despite this, ASHPs capable of operating at high temperatures (>65°C flow) are observed to operate at a similar SPF to low temperature ASHPs. This is likely due to a combination of higher performing refrigerants and weather compensation controls meaning that they operate at lower temperatures most of the time.

Heat pumps installed in detached houses have been observed to have a statistically significantly higher SPF compared to semi-detached houses The cause of this result may be because detached houses have the lowest proportion of heat pumps using the refrigerant R410a installed.

From the installations in the EoH project, home age did not have a statistically significant impact on the observed SPF. It should however be noted that all houses which received installations through the project were deemed suitable for a heat pump installation by trained designers and installers, so this result may not be representative of the UK housing stock.

1.4.3 Hybrid System Operation

A hybrid heat pump system is a system which utilises a gas boiler alongside a heat pump. In this project, the hybrid system control was cost-optimised and, as a result the system performance results are varied across the range of properties. The median heat pump energy output as a proportion of total space heating energy output observed in hybrid systems was 39%. As the heat pump energy output decreased as proportion of total space heating energy output, the observed SPF also decreased.

1.4.4 Coldest Day Performance

The observed heat pump efficiency ($COP_{(H4)}$) decreased as the external temperature decreased. The median $COP_{(H4)}$ on the coldest day (mean temperature -0.4°C) was:

- Median coldest day $COP_{(H4)}$ = 2.44; IQR = [2.20, 2.70]; n=484

2. Introduction

This report provides interim analysis of the data from the monitoring of domestic heat pump systems installed as part of the Electrification of Heat (EoH) demonstration project.

EoH is funded by the Department for Energy Security and Net Zero (DESNZ). The project seeks to better understand the feasibility of a large-scale rollout of heat pumps into existing homes across the UK. To support this, the project aims to:

- Develop, test and evaluate products and services that increase the appeal of heat pumps and identify optimal solutions for a wide range of homes.
- Demonstrate that heat pumps, including gas-electric hybrids, can deliver high consumer satisfaction across a wide range of consumers in Great Britain.
- Demonstrate the practical and technical feasibility of heat pumps, including gas-electric hybrids, across Great Britain's diverse housing stock, as well as identifying the costs.
- Capture learning from the project to help improve awareness across the renewable heating supply chain, raise acceptance and support wider deployment of heat pumps in Great Britain.

2.1 Aims

The aim of this report is to provide:

- Detailed heat pump performance and monitoring insights from the EoH project to date.
    - Noting that the heat pump monitoring is ongoing until September 2023, so all insights and analysis will be updated after this point.
- Technical details of the system used to monitor the operation of the heat pumps installed as part of the EoH project.
    - Including an overview of the data recorded by the system and any issues faced during the monitoring window.
- A detailed description of the quality checks and data cleansing conducted to ensure the heat pump monitoring data was of sufficient standard for analysis.
- A detailed description of all analysis conducted on the heat pump monitoring data, including all calculation methodologies and assumptions.
- Basic statistics on the heat pump systems installed.
    - For detailed statistics see the Heat Pump Installation Statistics Report [3].
- Basic overview of the supplementary house and participant information used as part of the analysis.
    - For a more detailed overview of this information, see the Home Surveys and Install Report [4].

The main insights from the heat pump monitoring to date, as detailed in this report, are summarised in a separate Insights Paper [5].

2.2 Sources of data used for this report

The data and information provided in this report is derived from the following sources:

- **Heat Pump Performance Monitoring Systems** as described in Section 4 of this report. These collect the operational heat pump data and store it in its raw form.
    - This data has then been downloaded, cleansed and analysed to form all insights.
    - The raw and cleansed monitoring datasets are accessible to the public through the UK Data Archive. [6]
    - Summary datasets showing the analysis outcomes are accessible to the public via the UK Data Archive or USmart. [7] [8]
- **The Electrification of Heat project Database** (currently USmart): this is the central database used for the project where all participant, survey, design and installation data are held. [9]
- **Qualitative Insights from the Project Team** from meetings with the Delivery Contractors and quality assurance visits for items such as known ongoing monitoring issues and known data biases.

2.3 Project Stakeholder Overview

The EoH project was funded by BEIS (now DESNZ) and made up of a number of key contracts as illustrated below:

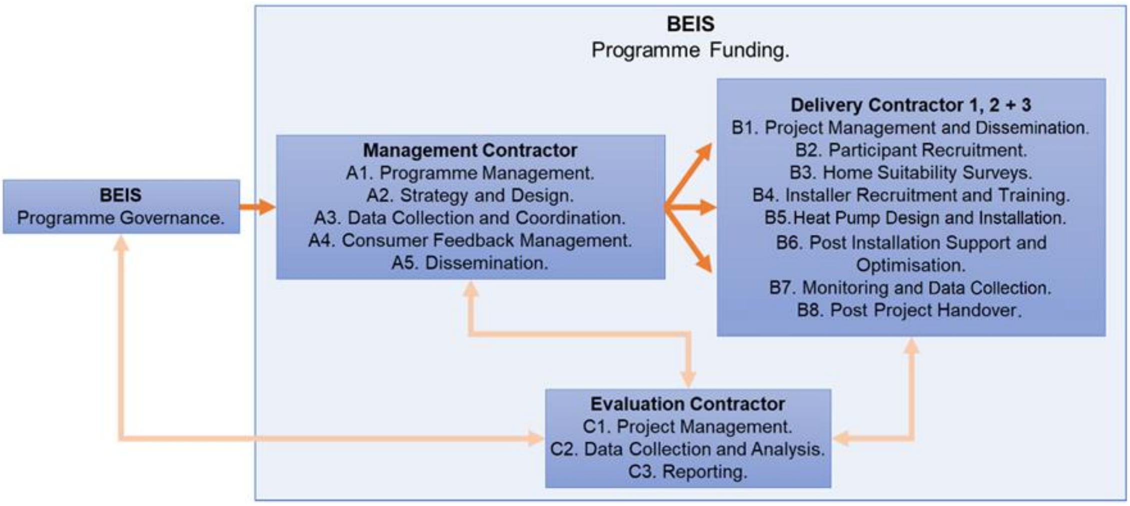

Figure 2.1: EoH project structure.

Following an open tender process, the following lead organisations were appointed to each role:

Table 2.1: Lead organisations appointed to the EoH project.

Role	Organisation Name
Management Contractor	Energy Systems Catapult (ESC) with LCP Delta and Oxford Computer Consultants
Delivery Contractor 1	E.ON
Delivery Contractor 2	Warmworks Scotland
Delivery Contractor 3	OVO Energy

Evaluation Contractor	ICF

As shown in Figure 2.1, the Delivery Contractors (DCs) were responsible for the installing and monitoring of the heat pumps, all three DCs employed sub-contractors to assist with the installation and maintenance of equipment. The Management Contractor was responsible for the collection of data and associated analysis and dissemination of project findings.

2.4 Project stages

Figure 2.2 below shows the key stages of the EoH demonstration project and Figure 2.3 presents a high level project timeline. Participants were initially recruited by the DCs, then technical surveys were undertaken and designs were produced for eligible properties. Following successful design, the heat pump system was installed along with monitoring equipment so that the system performance may be monitored.

See [4] and [10] for more details on the recruitment, survey, design and installation phases.

Figure 2.2: Flow chart of key project stages.

The monitoring period for each property began immediately after successful installation of the heat pump and monitoring equipment. Therefore, the monitoring of some properties began in Autumn 2020, whilst for others monitoring did not begin until late 2021. The initial monitoring period was due to run through until March 2022 however, to increase the quality of the monitoring dataset, all participants were offered the opportunity to sign up to a monitoring extension until September 2023. Some of the participants opted out of this monitoring extension and therefore, monitoring of some of the heat pump systems have ceased prior to the writing of this report.

Figure 2.3: Project timeline.[3]

As the heat pump monitoring is ongoing, **the analysis and insights discussed throughout this report are only interim findings** from the project and will be revised after September 2023. The data analysed to form this report is the monitoring data from the beginning of the project up to and including August 24th 2022.

For some of the analysis, such as finding the Seasonal Performance Factor (SPF), 12 months of data is required. As a result, several properties have been excluded from these aspects of the analysis because their monitoring period began less than 12 months ago. Notably, at this

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[3] Contractors had the opportunity to complete installations beyond this deadline on a case-by-case basis, if they could guarantee completion within a short timeframe of the deadline.

interim stage, there is an insufficient sample of Ground Source Heat Pumps (GSHP) with 12 months of data to draw conclusions on the average SPF, as such, the GSHP SPF results are provided for individual homes only.

2.5 Caveats and Known Biases

- All homes with heat pumps installed through this project were deemed suitable for an installation by trained designers and installers. The decisions were made based on project targets, timescales and budgets, and many properties were triaged out of the project at the early stage for a variety of reasons. More details on this can be found in the Home Surveys and Installation report [4]. Therefore, when reviewing the heat pump performance across different property types and ages, the results may not be representative of the whole UK housing stock.
- The sample of heat pumps installed through this project is not representative of all heat pumps available in the UK. The full sample is provided in the Property, Design and Installation dataset [11]. As a result of this, the average results may not be representative of all heat pumps available in the UK.
- All of the heat pumps installed through this project were in three different Nomenclature of Territorial Units for Statistics level 1 (NUTS1) regions. Therefore, a geographical bias may exist in the results.
- For most properties, the analysis presented in this report utilises only one year worth of collected data. The heat pump monitoring is ongoing and the analysis presented at the end of the project will utilise all data across the whole monitoring period and therefore may present better rounded results.
- Some of the circulation pumps electricity meters did not provide readings, as a result of this and due to the metering strategy (see Section 4.1), the impact of this is that the SPF_{H2} and SPF_{H3} results are skewed lower than their true value. More details on the impact are provided in Section 6.6.3.
- The hybrid heat pump SPFs calculated do not include for the boiler efficiency and all hybrid system results only account for space heating (i.e. they exclude hot water production).

3. Heat Pump Installations

3.1 In-Scope Heat Pump Types

As part of the project it was required that a range of heat pump systems were installed. This range covered system type, heat pump size and necessary system components such as controls and thermal storage. The heat pump system types included within the scope of the project are given below, alongside some comments regarding the specific systems which were installed.

Table 3.1: In-scope heat pump types.

System Type	Definition and comments
Low Temperature Air to Water (LT ASHP)	An Air Source Heat Pump (ASHP) capable of providing water at an outlet temperature of no more than 65°C.
High Temperature Air to Water (HT ASHP)	An ASHP capable of providing water at an outlet temperature of >65°C.
Ground to Water (GSHP)	Both boreholes and ground loops for the circulation of the heat transfer fluid (brine) were in scope for the project however, only borehole installations were installed. Both individual property and shared systems were in scope and installed as part of the project.
Gas-Electric Hybrids (Hybrid)	Both hybrid systems with a heat pump and boiler in separate units and integrated systems (which contain the heat pump and boiler in the same unit). The systems can be further broken down by those properties which installed heat pumps alongside existing boilers and those which had new boilers and heat pumps installed.

3.2 Installation Statistics

In total the EoH project has installed 742 heat pump systems. The project was limited to heat pump installations in domestic buildings within Great Britain and it was required that each of the three DCs installed their heat pumps within different Nomenclature of Territorial Units for Statistics level 1 (NUTS1) region. The regions covered by each DC are shown in Table 3.2. In addition, the number of heat pumps installed for each heat pump type and the number of successful installations in each property type and age are shown in Table 3.3:

Table 3.2: Delivery Contractor regions.

Delivery Contractor	Region	Additional Information
E.ON	North-East England	Focused on Newcastle and the surrounding area. Initially this was a largely urban area, but throughout the project recruitment expanded in to semi-urban and semi-rural areas within surrounding Northumberland, Gateshead and North Tyneside.
OVO Energy	South-East England	Worked across the region covering both rural and urban areas but excluding London.
Warmworks	Scotland	Focussed on the south-east of Scotland in the area spanning five local authority areas (Fife, Edinburgh City, Midlothian, East Lothian, and the Scottish Borders). Encompasses a broad range of urban and rural areas.

Table 3.3: Heat pump installation statistics.

Criteria	Group	Installations (%)	Installations (No.)
Heat Pump Type	LT ASHP	41.2%	306
	HT ASHP	32.7%	243
	GSHP	5.1%	38
	Hybrid	20.9%	155
Property Form	Detached	40.6%	301
	Semi-detached	42.8%	261
	End-terrace		57
	Mid-terrace	11.1%	82
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Property Age	Pre-1919	7.8%	58
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	1945 to 1964	24.0%	178
	1965 to 1980	22.2%	165
	1981 to 1990	9.2%	68
	1991 to 2000	9.6%	71
	2001+	13.1%	97

The majority of the 38 GSHPs were not installed early enough to provide 12 months of monitoring data. As a result, the GSHP sample size has not been deemed large enough provide a reliable average GSHP SPF at this stage in the project.

The GSHP installations can be further broken down as follows:

- 16 GSHP units in a block of 16 flats served by a shared system comprising four boreholes.
- 12 GSHP units in a block of 12 flats served by a shared system comprising three boreholes.
- 10 individual property installations.

The heat pump installation statistics, including number of types of heat pump installed by property type and age are covered in more detail in the Installation Statistics Report [3] and the installation data can be found on the EoH Project Database [12] [13].

3.3 Installation Quality

As described in Table 2.1, ESC were appointed as the lead of the MC consortium and were contracted to provide Quality Assurance (QA) on 20% of the heat pump installations. The QA site visits were conducted by GTEC Ltd after the installers had commissioned and handed over the systems to the householder.

The purpose of the installation reviews was to assess the heat pump system installations against criteria based on the The Microgeneration Certification Scheme (MCS) requirements. Whilst it did not form part of the core scope, in many cases, the QA assessor also conducted a high level review of the installation of the monitoring system. Whilst not all installations were reviewed, those installations which were reviewed covered a range of heat pump makes and models installed by different companies to give a representative view of all installations across the project.

The QA assessors provided photographs of all systems reviewed. These were submitted to the ESC for future reference and reviewed to form assumptions regarding the installation standard and location of the monitoring equipment described in Section 4.

Aside from issues highlighted in Section 4.3.2, the heat pump monitoring systems are judged to be installed to a good enough standard to analyse the data and form conclusions. The majority of the issues highlighted in Section 4.3.2 would cause erroneous data which will have been removed from the analysis during the data quality checks (discussed in Section 6), or will have had minimal impact on the results of the analysis when drawing conclusions from a large quantity of installations.

3.4 System Optimisation

The inclusion of heat pump monitoring within the installed heat pump systems has enabled the project delivery team to track heat pump performance and where necessary to optimise the heat pump systems. Some of this optimisation activity has been contractor led, where the delivery team has noticed low performance and contractors have visited the property to try to improve system efficiency. Other activity may have been participant led, where participants have followed guidance provided by the contractors to improve efficiency.

One example of system optimisation which has been performed is that in spring 2022, a large proportion of the Hybrid systems installed through the EoH project had their controls optimised during a heat pump service visit. This is because they were not performing as expected.

The optimisation performed throughout the project is envisaged to alter system performance but is no extraordinary changes have been made to system operation so, the analysis results still provide a valid representation of heat pump performance. An overview of the heat pump optimisation will be reported on by the project team prior to the end of the project.

4. Monitoring Data Collection

4.1 Monitoring System Design Configurations

Following review of several monitoring system proposals, all three DCs selected a PassivSystems system which is described herein.

As required by the DC Invitation to Tender (ITT) [14] PassivSystems metering equipment collects all data points in 2 minute intervals; enabling the calculation of the Coefficient of Performance (COP), Seasonal Performance Factor (SPF_{H2} and SPF_{H4}, as defined by the SEPEMO Build Project [1] and clarified for Energy Saving Trust's heat pump field trial [15] [16]) and heating demand for any period.

The equipment is equivalent to the Metering and Monitoring Service Package (MMSP) available under the Domestic Renewable Incentive (RHI) [17] [18] and complies with the technical specification set out in the MCS Domestic RHI Metering Guidance Document [19].

The exact monitoring solution and configuration varies slightly with each heat pump type however, the measurement principles are the same in each case. The below subsections give the general configuration which may be present in an ASHP, GSHP and Hybrid Heat Pump system installation.

Each home has a data collection hub (Passiv Hub) which collects all of the monitoring readings from the sensors described in the below subsections. The internal temperature sensor provides measurements to the hub via a Z-Wave link, all other sensors are physically connected (wired) to the hub. Once collected, the hub uploads all readings to an online data collection database (DB) where they can be forwarded onto the project stakeholders for storage and analysis purposes. In most cases the data is uploaded from the hub via a home broadband connection however, where home broadband is not available, a 3G/4G sim card may be used to transmit the data.

The key components of this process are shown in Figure 4.1

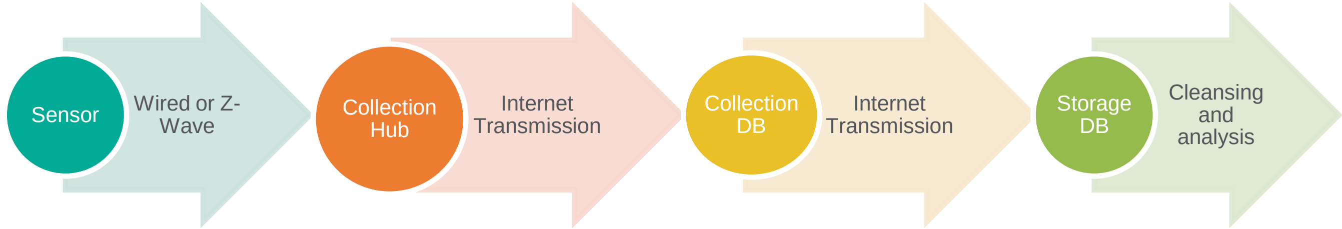

Figure 4.1: Key components of the monitoring data collection system and how they transmit data.

Note that for all installations, the external temperature data is collected from the local Met Office weather station, rather than the property itself. All installations include an internal temperature sensor which is located centrally within the property.

The specific meters used and which datapoints they record is discussed further in Section 4.2.

4.1.1 ASHP Configuration

Whilst the configuration of each heat pump model varies slightly, Figure 4.2 shows the typical monitoring system configuration for an (LT or HT) ASHP installation.

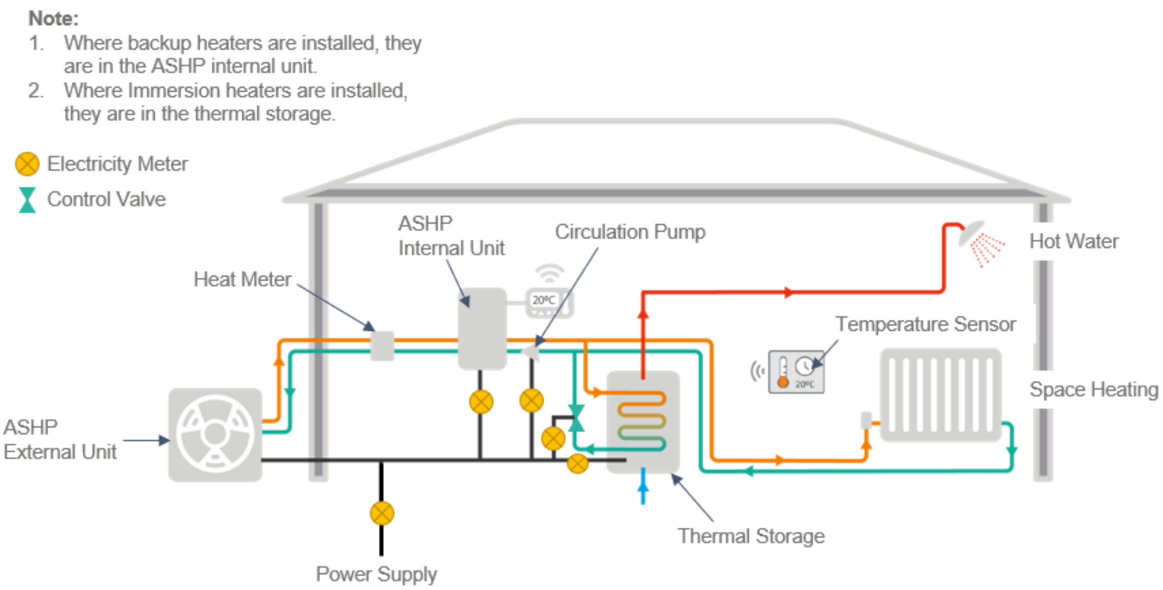

Figure 4.2: Typical arrangement of sensors in ASHP monitoring solution.

The ASHP monitoring system includes a maximum of five electricity meters, all of which are shown in Figure 4.2. Working from left to right, the electricity meters record the following:

- The whole heat pump system energy consumed.
- Back-up heater energy consumed.
- Circulation pump energy consumed.
- Position of the control (diverter) valve, to inform whether the heat pump is in space heating or hot water mode.
- Immersion heater energy consumed.

In many of the installations, the back-up heaters were not metered independently. In these situations, it is assumed that the back-up heater energy consumed is recorded alongside the immersion heater energy consumed by a single electricity meter.

It should be noted that the heat pump unit energy consumed is not metered independently. Therefore, to obtain the heat pump energy input, it is necessary to take the whole heat pump system energy consumed value and subtract all energy consumed by the non-heat pump components.

As well as the electricity meters, the other metering equipment installed for ASHP units is a single heat meter. The heat meter records the flowrate, flow temperature and, return temperature to derive heat pump energy output. The heat meter is installed inside the home, as close to the external heat pump unit as possible, prior to any additional heating equipment. As such, the heat meter will generally only record the heat produced by the heat pump unit and not that which is be produced by a back-up or immersion heater.

Where monobloc ASHPs are installed (i.e. an ASHP without an internal unit), the heat meter is still installed in a similar position in relation to the outdoor unit and the rest of the system however, the back-up heater may be inside the external heat pump unit. In this case, the heat meter may record heat generated by the back up heater, this is discussed further within Section 6.6.

The electricity meter connected to the diverter valve does not send an energy use reading to the dataset. It only monitors the position of the valve to assign whether the flow temperature measurement is for heating or hot water.

4.1.2 GSHP Configuration

The EoH project has deployed GSHP in two main configurations:

- Shared ground loop (SGL) systems using one or more boreholes to feed multiple properties.
- Individual property systems.

In each case the monitoring system configuration is mostly the same as the ASHP system discussed in Section 4.1.1, but with the addition of flow and return temperature sensors on the brine side of the heat pump. For SGL systems, there are brine temperature sensors for each individual property.

This system arrangement is illustrated by Figure 4.3 below.

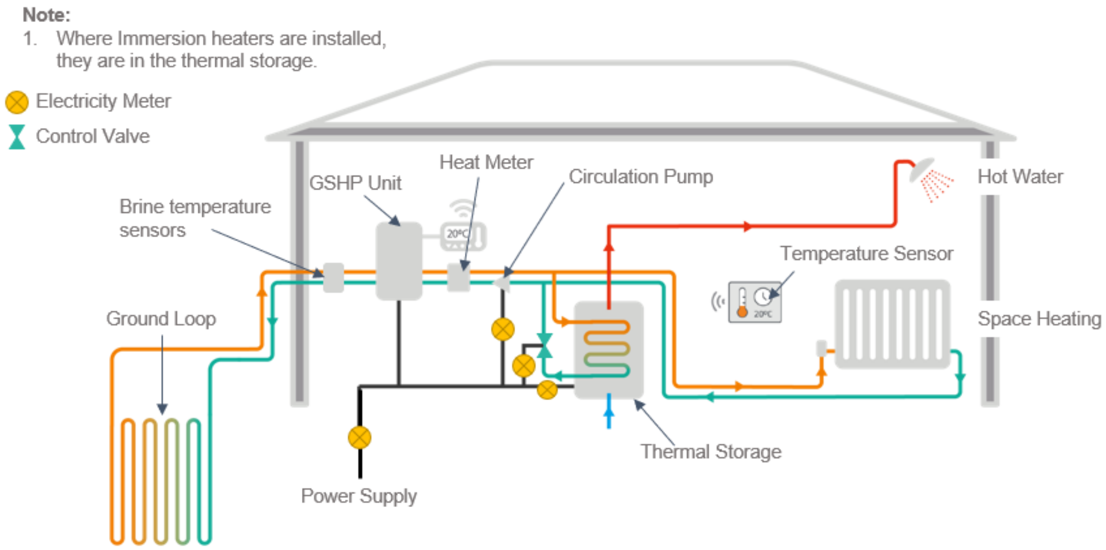

Figure 4.3: Typical arrangement of sensors in GSHP monitoring solution.

None of the GSHP systems installed through this project include a back-up heater so only a maximum of four electricity meters are present. These record the following:

- The whole heat pump system energy consumed.
- Circulation pump energy consumed.
- Position of the control (diverter) valve, to inform whether the heat pump is in space heating or hot water mode.
- Immersion heater energy consumed.

As well as the electricity meters and brine temperature sensors, the monitoring system also includes a heat meter which should be situated as close to the heat pump as possible, prior to any additional heating elements, to record only the heat pump energy output.

4.1.3 Hybrid Heat Pump Configuration

As noted in Section 3.1, the EoH project deployed hybrid heat pumps in both separate and integrated configurations using either standard or combi boilers. Where a standard boiler is used, the system also includes a thermal store for the provision of hot water.

In all hybrid heat pump system configurations, the monitoring system is configured similarly to the ASHP configuration discussed in Section 4.1.1, but with the inclusion of a second heat meter to monitor the space heating provision from the gas boiler.

Note that for all of the hybrid systems installed through this project, the hot water is generated by the gas boiler alone, and hot water provision from the boiler has not been metered. As such, only the space heating provision from the hybrid systems is monitored.

Figure 4.4 illustrates the typical monitoring system configuration for a hybrid system (combi boiler version shown). Note that whilst this system shows the typical configuration, both the heating and monitoring system configurations may differ for different heat pump models.

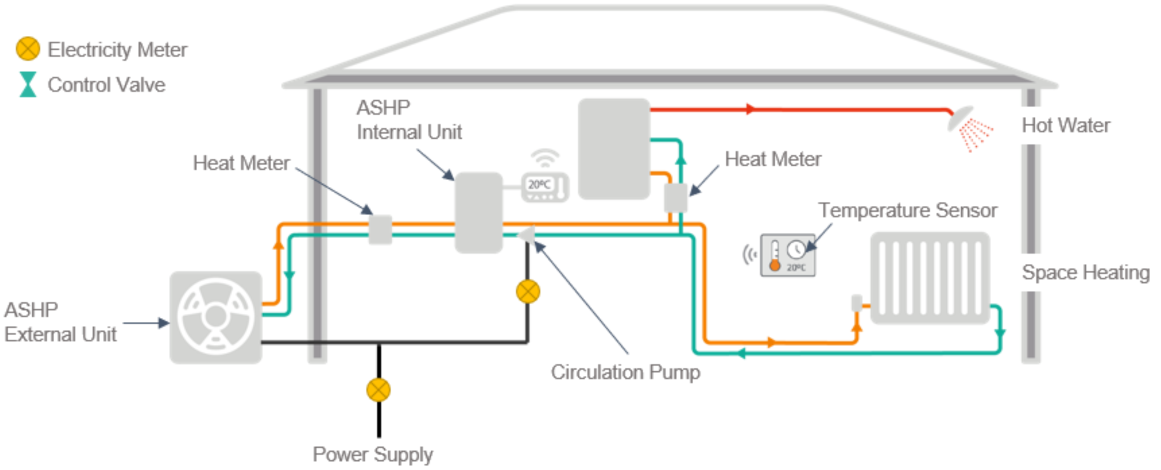

Figure 4.4: Typical arrangement of sensors in hybrid heat pump system monitoring solution.

None of the hybrid systems installed through this project include a backup heater or an immersion heater and, as previously discussed, all hot water provision is by the gas boiler alone. As such, there are only two electricity meters in the hybrid heat pump monitoring system. These record the following:

1. The whole heat pump system energy consumed.
2. Circulation pump energy consumed.

As noted above, the hybrid monitoring system also includes two heat meters, these record the heat output from the heat pump and boiler for space heating provision. As with the ASHP and GSHP configurations, the heat meters should be located near to the components which they are monitoring in the system such that, they do not monitor heating output from any other components.

4.1.4 Alternative Configurations

As noted in all sections, the configurations shown in Figure 4.2, Figure 4.3 and, Figure 4.4 are that of a typical installation and they vary dependent upon the heat pump models. One case where the configuration varies significantly is that of the SIME hybrid heat pumps.

Five SIME hybrid heat pumps were deployed by E.ON as an innovation measure aimed at overcoming specific project barriers. These units comprise a heat pump and gas boiler connected in series within a single internal unit. Compared to the other hybrid heat pumps, the SIME heat pumps operate slightly differently as the heat pump and gas boiler run simultaneously. The SIME system configuration is also different to that of a standard hybrid installation.

Because of the above factors, the heat metering strategy for the SIME unit differs somewhat. A single heat meter is installed downstream of the unit to measure overall heat output, however this measurement must be split and allocated to the heat pump and boiler. The heat pump contains three temperature probes – one each side of the heat pump heat exchanger and a third after the boiler.

As the heating components are in series, the flowrate through the heat pump heat exchanger and boiler will be identical. In the event of simultaneous heat pump and boiler operation, the water in the heating system flows through the heat pump heat exchanger where it is heated to an intermediate temperature. The water then flows through the boiler where it is heated to the desired flow temperature. The monitoring system accesses the three temperature probes via the SIME OpenTherm module and then splits the total heat recorded by the heat meter in proportion to the differences between these sensors. The system configuration is demonstrated in Figure 4.5.

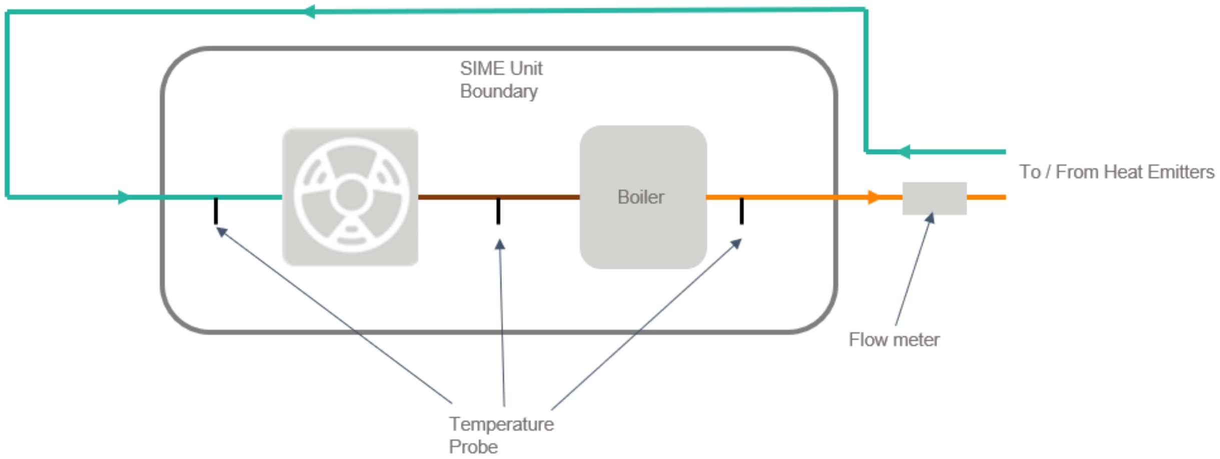

Figure 4.5: A simplistic representation of the internal components of a SIME hybrid heat pump solution. Indicating how the heat meter components are distributed to split the heat output between the boiler and heat pump.

In the event of the heat pump or boiler operating on their own, the entire heat is allocated to one or the other as required.

4.2 Meters Installed and Data Recorded

Table 4.1 provides a list of the data recorded by the heat pump monitoring systems as well as the sensors and meters used as part of the monitoring system.

Table 4.1: The heat pump monitoring system data recorded and sensors used.

Data Label	Data source	Sensor or Meter Installed	Description
Heat Pump Energy Output	Heat pump heat meter	Sontex SuperStatic 440 *calibrated for DTX glycol where required*	Cumulative meter (measuring kWh). Contains temperature sensors and a flow meter and automatically calculates kWh output using these. Located as close as possible to the heat pump on the primary flow and return pipework such that it measures only the heat pump energy output.
Boiler Energy Output	Gas boiler heat meter	Sontex SuperStatic 440 *adjusted for 1Wh energy reporting*	Hybrid only. Cumulative meter (measuring kWh). Similar to heat pump energy output but for the gas boiler. Should measure only the gas boiler output.
Whole System Energy Consumed	Whole system electricity meter	Eastron SDM630Modbus	Cumulative meter (measuring kWh). Located on the primary wiring for the whole heat pump system. Measures all of the electrical energy consumed by the system. Heat Pump Energy Consumed derived by taking this and subtracting all other electricity meter readings.
Back-Up Heater Energy Consumed	Back-up heater electricity meter	Eastron SDM120	Cumulative meter (measuring kWh). Where it forms part of the system, the back-up heater should be located within the internal heat pump unit or be directly plumbed into the primary heating system flow pipework.

Data Label	Data source	Sensor or Meter Installed	Description
Immersion Heater Energy Consumed	Immersion electricity meter	Eastron SDM120	Cumulative meter (measuring kWh). Where it forms part of the system, the immersion heater should be located in the primary thermal storage.
Circulation Pump Energy Consumed	Circulation pump electricity meter	Eastron SDM630Modbus	Cumulative meter (measuring kWh). Where systems have multiple circulation pumps the meter should capture the energy used by all of them.
Heat Pump Heating Flow Temperature	Heat pump heat meter	Sontex SuperStatic 440	Non-cumulative sensor. Reading is measured by a temperature sensor which forms part of the heat meter only when in heating mode (mode is detected by monitoring the diverter valve).
Hot Water Flow Temperature	Heat pump heat meter	Sontex SuperStatic 440	Non-cumulative sensor. Reading is measured by a temperature sensor which forms part of the heat meter only when in hot water mode (mode is detected by monitoring the diverter valve).
Internal air temperature	Zone air temperature sensor	DH-SES-302	Non-cumulative sensor. Sensor installed somewhere within the home. Only one per home, should be centrally located and away from direct sunlight.
External air temperature	Local weather station	-	Record sent from local weather station readings.
Brine flow temperature	Heat pump brine side temperature measurement	Sontex SuperCal 531	GSHP only. Non-cumulative sensor. Sensor located on the flow pipework of the brine loop before it enters the heat pump system. Brine is pumped around the ground loop and is pumped through the borehole to extract geothermal heat.
Brine Return Temperature	Heat pump brine side temperature measurement	Sontex SuperCal 531	GSHP only. Non-cumulative sensor. Sensor located on the return pipework of the brine loop after it leaves the heat pump system.

Data Label	Data source	Sensor or Meter Installed	Description
Heat Pump Return Temperature	Heat pump heat meter	Sontex SuperStatic 440	Non-cumulative sensor. Reading is measured by a temperature sensor which forms part of the heat meter in both heating and hot water mode.

Both the heat and electricity meters are cumulative (i.e. the measurements provided are the total consumption or generation since the equipment started recording). The consumption over a 2 minute period can therefore be deduced by subtracting one measurement from the one preceding it.

The temperature measurements are instantaneous, reflecting the measured value at the point of transmission.

4.3 Monitoring Issues

Whilst there have not been issues with the majority of the data collected through this project, there are situations where issues have occurred in the monitoring systems of some of the properties. Generally, these are minor however, in some cases they render the monitored heat pump data unusable for all or some of the analysis.

4.3.1 Transmission Issues

One common issue experienced when monitoring the heat pumps was the loss of transmission of the monitored heat pump data to the database. This issue is evidenced by gaps in one or more of the data readings.

A gap in a single data reading where the data prior to and after the gap is as expected may indicate an issue with the transmission lines between the specific sensor taking that reading and the data collection hub. An example of the cause of this type of issue may be a disconnected wire or an issue with the Z-Wave link. In this situation, the data from the specific sensor or meter is unrecoverable as the data is not stored locally.

A gap in all of the data recordings for one property (aside from external temperature) may indicate an issue transmitting data from the hub to the collection database. Some examples of the cause of this issue are disconnection of the hub from the internet or the powering down of the hub entirely. In the situation when there is an internet connection error, up to 10 days worth of data from all sensors may be stored on the local hub. When the internet connection resumes, the most recent 10 days of data is then sent to the collection database and is forwarded onto storage database so not all data is lost.

A gap in all data recordings for all properties including external temperature indicates an issue sending data from the collection database to the storage database. An example of a cause of this issue could be a breakdown in software of either the data collection database or the storage database. When this issue occurs, all data is stored within the data collection database and is forwarded onto the storage database upon resolution.

As will be discussed further in Section 6, the gaps in the data caused by transmission issues do not mean that the data cannot be used. For example, if there is a gap in cumulative metered data but the data prior to and after the gap is as expected, the data either side of the gap may still be used for periods of longer term analysis. When analysing short periods of data or non-cumulative data, if a gap exists then the property in question may not be useful for that specific analysis.

4.3.2 Monitoring Equipment Issues

Another issue with monitoring equipment experienced throughout this project has been with faults to individual components. Generally, these issues can fall into two categories:

1. Equipment installation issues.
2. In-situ failures or partial failures.

For equipment installation issues, the equipment either sends no reading, or sends an obviously false reading from the point that it begins recording data. Where these occur, generally installers go back to the property to rectify the monitoring equipment installation. Depending on the equipment which was incorrectly installed, and nature of the installation issue, these issues may cause the data to be unusable or partially unusable for the period of time prior to the issues being rectified. In the case that the data is unusable, it will be removed from the dataset through the data cleansing process described in Section 6.2.

An example of an installation issue is the miscalibration of a heat meter. In this example, the issue would be picked up by the SPF data checks.

In some cases, the installation issue is easily resolved within the data and then the data may be used. If this is possible, then it is completed during the data cleansing process discussed further in Section 6.2. One example of where cleansing may take place is if the flow and return temperature readings are reversed.

When in-situ failures occur, it is generally down to equipment failure rather than an installation problem. In this case, often periods of good data quality exist, followed by periods of poor data quality. As with installation issues, if in-situ failures occur, engineers will visit the property to check and (where necessary) replace the equipment to ensure any periods of poor data are as short as possible. If in-situ failures occur, the data before and after the failures may be useable but, during the failure period data becomes erroneous and depending on the length of the failure period, it may render the overall dataset unusable. If it is the case that a failure occurs and is unresolved for a prolonged period, it will be sifted out by the quality checks discussed in Section 6.3.

An example of an equipment failure in-situ which may cause the data to be unusable is if a heat meter stops cumulating or falls out of calibration and this is not resolved within a short timeframe. An example of an equipment failure which has a smaller effect on the data quality overall is if the internal temperature sensor stops recording.

5. Supplementary Data

5.1 Supplementary Data Description

Throughout the recruitment, home survey, heat pump system design and installation phases of the EoH project, a variety of participant, home and heat pump data was collected. For the purposes of monitoring data analysis, this data will be referred to herein as "supplementary data". The supplementary data is documented in the Property, Design and Installation Data Documentation Report [11] and the dataset is accessible via the Electrification of Heat Project Database [13]. The supplementary data and monitoring data can be cross-referenced using the Property ID number as this is consistent across all datasets.

All supplementary data elements are defined in a data dictionary which is available in the Additional Information section at the bottom of the USmart dataset (accessed via the project database [13].) The data dictionary is laid out as shown in Table 5.1.

Table 5.1: Data Dictionary columns.

Data Item	Field Name	Type	Description	Units	Acceptable values	Attributes/ Notes
Name of the parameter in plain English	Name of the parameter as it appears in the dataset	Numerical, text, etc	Plain English description of the parameter	Units if applicable	If applicable, a list of standard values / ranges acceptable for the parameter	Any information about how the data should appear or notes/ caveats relating to the data

Examples of supplementary data which was collected are provided within Table 5.2. The data can be separated into 3 key data types:

- Numerical – numerical data will reflect counts (e.g. no. storeys), measurements or sizes (e.g. floor areas), calculation outputs (e.g. MCS heat loss values) or scales (awareness of heat pumps).
- Fixed Text – used for text inputs where the data dictionary defines a fixed number of allowable answers, for example defined categories (e.g. house type) or codes assigned to define reasons or categories.
- Free Text – used for text inputs which provide additional information to support assessments or decisions. Within the project, all free text fields were optional at the point of data collection.

For qualitative analysis, the numerical and fixed text data is the most useful as this can be categorised more easily. To collate the supplementary dataset, a rigorous quality checking and issue resolution process was followed. This is outlined within the Property, Design and Installation Data Documentation Report [11] and the Quality Assurance Log which is available in the Additional Information section at the bottom of the USmart dataset (accessed via the project database [13].)

The specific data which has been used to assist with the interim data analysis is discussed further within the following sections of this report but includes installed heat pump data, home data (such as house type or age) and participant data. To utilise some of the data, it may have been cleansed (e.g. aligning house ages). Where any cleansing has been done, it is discussed within Section 6.2.

For full analysis and findings from the recruitment, survey, design and installation stages of the project please see the Participant Recruitment Report [10] and Home Surveys and Installation Report [4].

5.2 Data Collection Methods and Timing

The data contained within the supplementary dataset was recorded at different stages of the participant journey throughout the project. The exact journey differed slightly between each DC, however the key stages and the data gathered from each is illustrated in Figure 5.1 below:

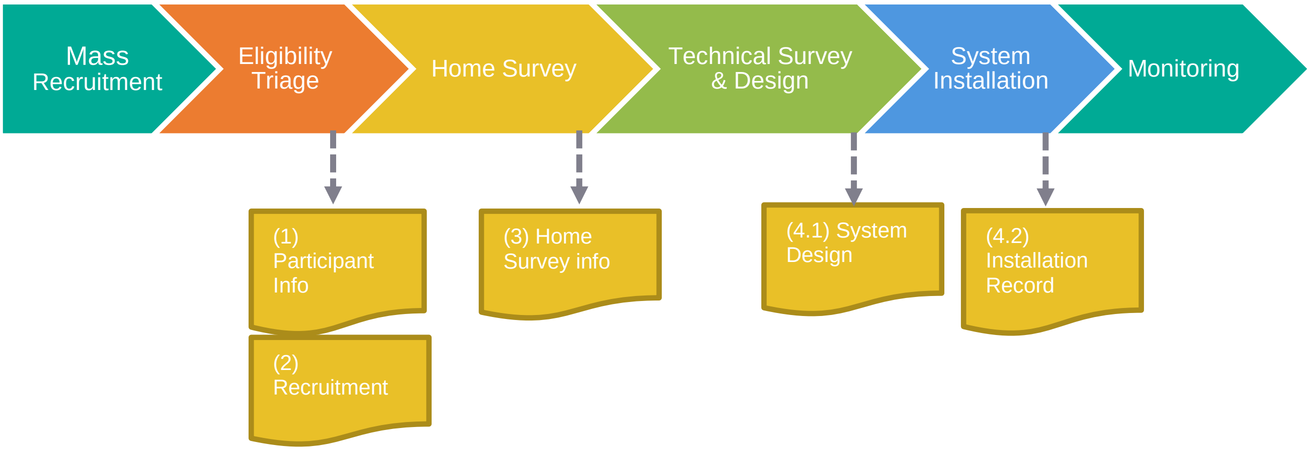

Figure 5.1: Supplementary data collected at each project stage.

The method to collect supplementary data was mostly manual and undertaken by different parties for each DC. The method of data collection at each stage (post-triage) is summarised in Table 5.2.

Table 5.2: Methods of collecting supplementary data at each project stage.

Stage	Description	Example Data	Method of Collection
1	Participant Information	Name, Address, Age, Occupation.	Online registration form, questionnaire, or phone call
2	Recruitment Information	Reasons for interest in the project, social group.	Online registration form, questionnaire, or phone call
3	Home Survey	House type, age, size, SAP rating, fabric.	Varies by DC but in all cases data may have been supplemented by information from sources other than those listed below. **E.ON** – Combined survey for both project suitability and heat pump system design conducted during home visit by a heat pump design/install surveyor. **OVO** – Initial "Remote Survey" using EPC data combined with analytical software. If home passed project suitability checks, a home visit was conducted by a surveyor. **Warmworks** – Home survey only conducted during home visit by a trained retrofit surveyor (including a full EPC assessment.)
4.1	System Design	MCS calculation outputs, design decisions.	Assessment of which heat pumps may be suited for installation in the home, as assessed by the surveyor and/or system designer. Design information and recommendations are the output from the design process from the system designer Recorded decisions and reasons/rationale are from either the designer and/or from discussions with the participant depending on outcome.
4.2	Installation Record	Heat pump manufacturer, model, size, home upgrades undertaken, costs.	Populated by installer following installation completion

All properties which have monitoring data will also have an installation record within the supplementary dataset however, as is discussed further in Section 6, not all installations have usable monitoring data.

6. Data Quality Checks and Cleansing

6.1 Process

To analyse the monitoring data, an iterative process of quality checking, cleansing, and analysing was followed. This process has been automated and it is repeatable for future analysis.

Initially a high-level quality check on the monitoring data was conducted to look for any gaps in the data and find any erroneous property ID numbers. If available, data was backfilled into the gaps, and ID errors were rectified. The data was then sorted by timestamp and sensor type to form the final "raw" dataset for this interim analysis.

Once finalised, the "raw" data was cleansed. This cleansing makes minor adjustments to the data to prepare it for analysis. These adjustments include aligning timestamps, removing anomalies and (where necessary) correcting known data issues. All adjustments made to the data are discussed in Section 6.2. In some cases where the cleansing activity is performed to resolve quality issues, this is flagged by adjusting the data quality score described in Section 6.3.

Once the "cleansed" dataset was produced, a second set of quality checks were performed. These checks, described in Section 6.3, were more rigorous than the first and resulted in a data quality score for each property, based on various quality metrics. The best scoring data window for each property was then selected for the analysis. Each property was either included in or excluded from the analysis based on a variety of thresholds including the quality of data within the selected window, (i.e. any property where the best scoring window is still of insufficient quality was excluded) and the feasibility of the SPF over the selected window.

Once the data quality was confirmed, the analysis calculations were conducted as described in Section 7. Discussion of the analysis results is provided in Sections 8, 9 and 10.

6.1.1 Quality Assurance

As part of their Technical Third Party Support (TTPS) framework contract, Frazer Nash Consultancy (FNC) was commissioned by DESNZ to perform QA checks on the data cleansing and data quality checking process. They were also asked to assess the validity of the analysis findings, activity which was subcontracted to TÜV Nord.

The findings of this QA activity are that the cleansing and quality checking process was sufficient and the majority of issues identified by FNC were sufficiently addressed and resolved prior to the end of the QA activity. A few minor outstanding matters were identified during the output review however, these have since been resolved.

6.2 Data Cleansing

As described above, data cleansing is the process of taking a "raw" dataset and making slight adjustments to ensure it is ready for analysis. Below is a list of the cleansing activity which was undertaken to prepare the data for analysis, additional detail and reasoning is provided in the following subsections.

- Timestamp alignment to exact 2-minute periods.
- Cumulative meter data reversals.
- Anomalous cumulative data removal – single point.
- Anomalous cumulative data removal – from start of monitoring.

- Relevelling data following a meter reset.
- Incorrect column assignment for non-cumulative (temperature) data
- Removal of out-of-range temperatures.
- Supplementary data cleansing – amending spelling or grammar variations.
- Supplementary data cleansing – aligning property age ranges.

6.2.1 Timestamp Alignment

Each sensor and meter in the monitoring system sends readings at an average frequency of around 2-minutes. There is however, some variation in the period between each reading and two readings from the same sensor can be up to a maximum of 4-minutes apart. In addition, the timestamps are not synchronised between sensors, meaning that each sensor takes its readings at different times, independent of the other sensors.

As a result of the above, to compare the readings from different sensors and perform analysis on the heat pump data, it is necessary to align the timestamps. The following process was followed to realign the timestamps for the cleansed dataset::

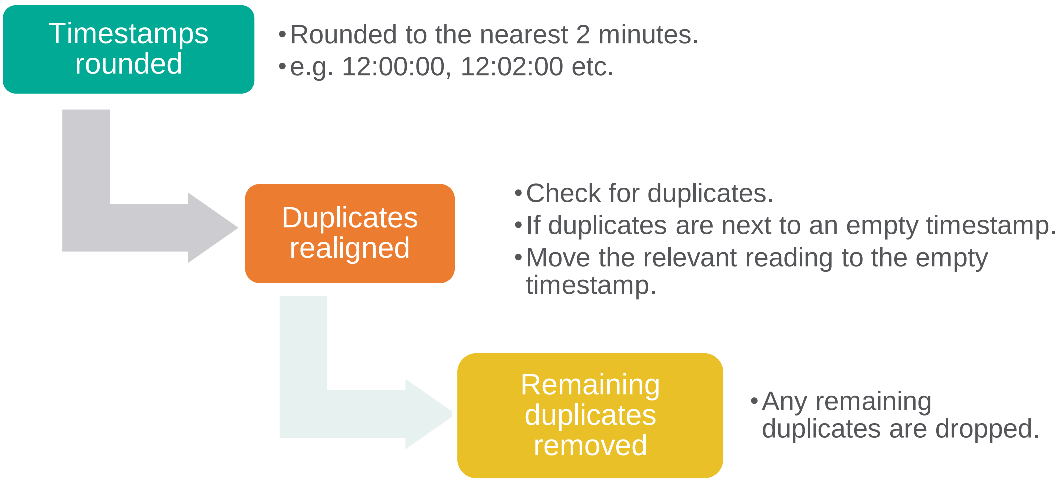

Figure 6.1: Timestamp alignment process.

As a result of the timestamp alignment, it is important to note that **the cleansed dataset may not always give the correct instantaneous readings.**

6.2.2 Cumulative Meter Reversals

Some monitoring equipment installation issues which can be seen within the raw dataset are the occasional installation of meters or sensors in the wrong orientation. The result of installing a cumulative meter in the wrong orientation is that the readings decrease over time. To check for this issue, daily differences in the cumulative meter readings are assessed. For situations where the daily differences are mostly decreasing, the readings are reversed within the cleansed dataset (for example, a reading of -1kWh is changed to 1kWh). This is demonstrated within Figure 6.2 and Figure 6.3.

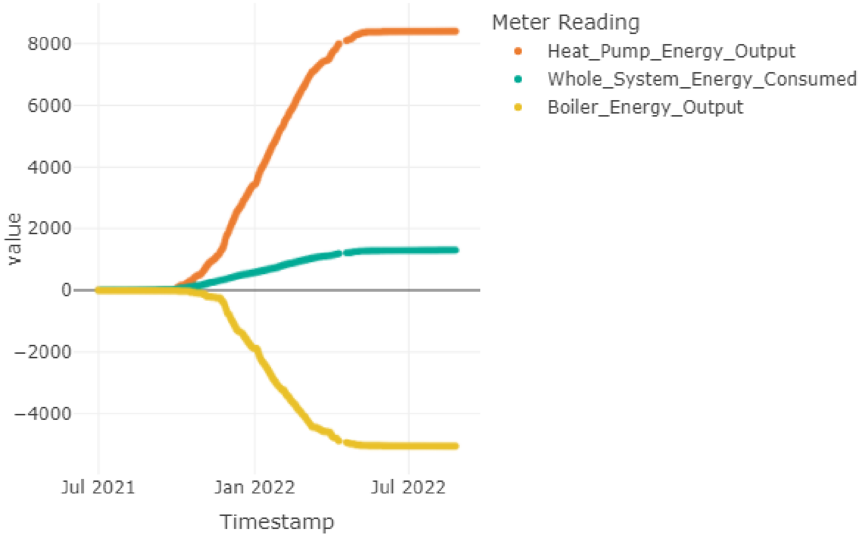

Figure 6.2: A graph showing a reversed boiler heat meter resulting in consistent negative readings within the raw data.

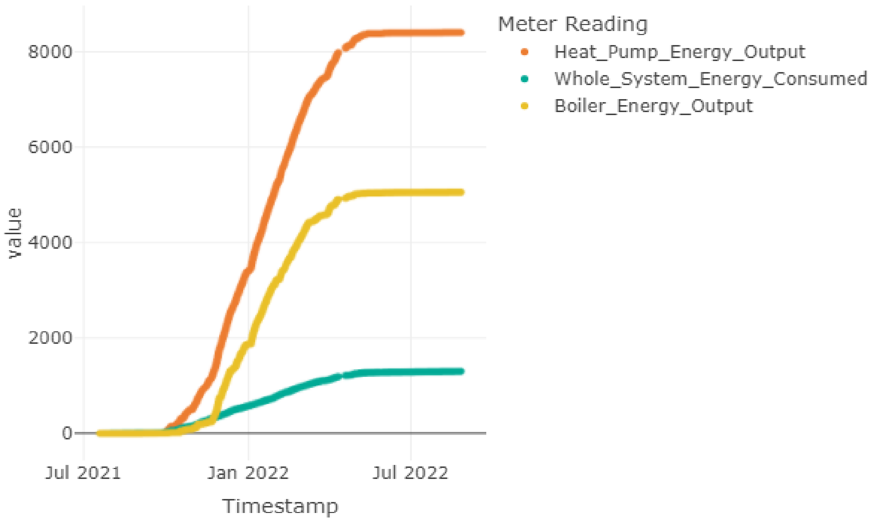

Figure 6.3: A graph showing the reversed values within the cleaned dataset.

6.2.3 Anomalous Cumulative Data Removal

6.2.3.1 Anomalous Points within Cumulative Dataset

Another issue sometimes witnessed within the raw dataset is anomalous data points. These occur when a single datapoint is randomly much higher or lower than the surrounding datapoints. These are identified by having a value outside the range of:

- 95% of the minimum of the 3 values prior to the point, and
- 95% of the maximum of the 3 values after the point.

This differs from a meter reset (discussed in Section 6.2.4) as when a meter is reset or replaced, generally the meter reading will reduce significantly and then continue from the new start point along a similar trend to before.

To ensure ease of analysis, and eradicate the chance of false results, the single anomalous points are removed from the cleansed dataset. The method described above removes all single anomalous points from the cleansed dataset however, it does not account for and will not remove multi-point anomalies.

Multi-point anomalies occur when a series of datapoints is randomly much higher or lower than the surrounding data. Within the raw dataset, the multi-point anomalies which exist occur when the data readings reduce significantly for a short period of time before returning to the expected level. In this scenario, the reduction in data readings is read by the automated cleansing process as a meter reset, so initially the data is re-levelled as described in Section 6.2.4.

For multi-point anomalies, the data already returns to the expected level, so the re-levelling process may cause a sharp upward tick in the data. As a result of this, it is necessary to check the gradient of the cumulative data immediately after re-levelling. If the gradient is much greater than expected then a multi-point anomaly is assumed and the data is brought back in line with the previous point.

This single and multi-point anomaly removal process is demonstrated by Figure 6.4, Figure 6.5 and Figure 6.6. In Figure 6.4, four anomalies can be seen.

Figure 6.5 shows that, as anomalies 1, 2 and 4 are single point anomalies, they are removed however, anomaly 3 is a multi-point anomaly so is not removed. Instead, the figure shows that to resolve anomaly 3, the first anomalous point is re-levelled as described in Section 6.2.4. This then risks the data following the anomalous period to be erroneous (shown by the sharp increase in data readings). As there is a large gradient between two readings at the end of the anomalous period, the multi-point anomaly is identified and the last anomalous point is re-levelled to ensure it is aligned as expected.

Figure 6.6 shows the cleansed data with all anomalies resolved.

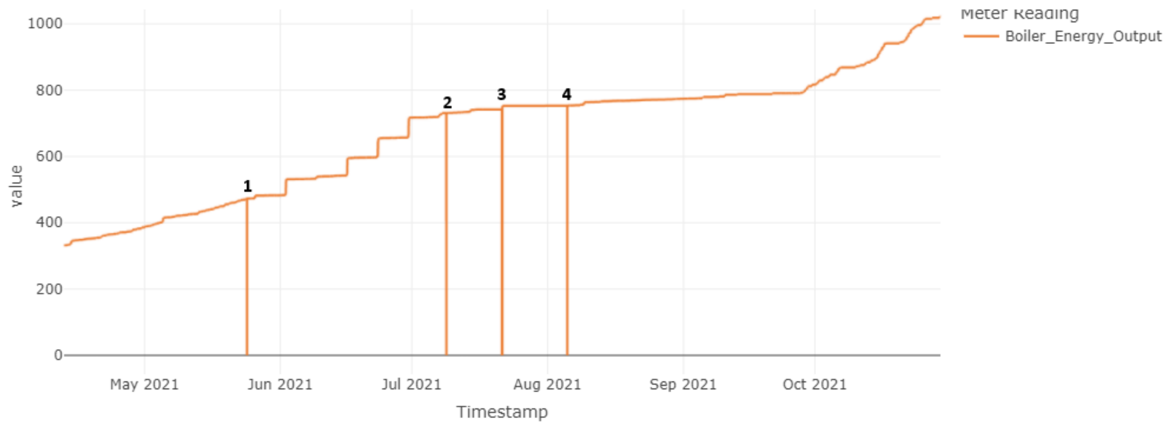

Figure 6.4: Four anomalies in a set of cumulative raw data.

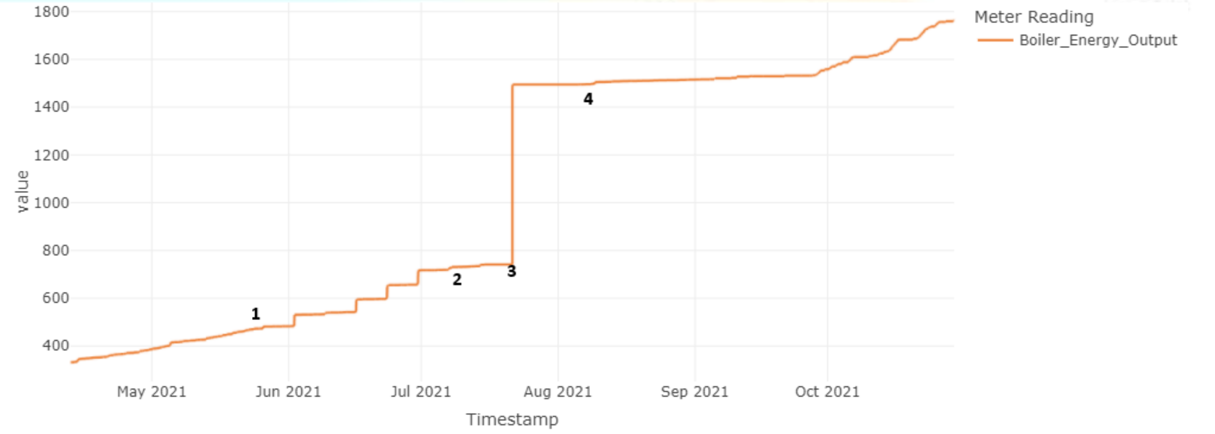

Figure 6.5: Shows the single point anomaly removal for anomalies 1, 2 and 4 as well as an automated "meter reset" re-levelling for anomaly 3. (intermediate data cleansing stage)

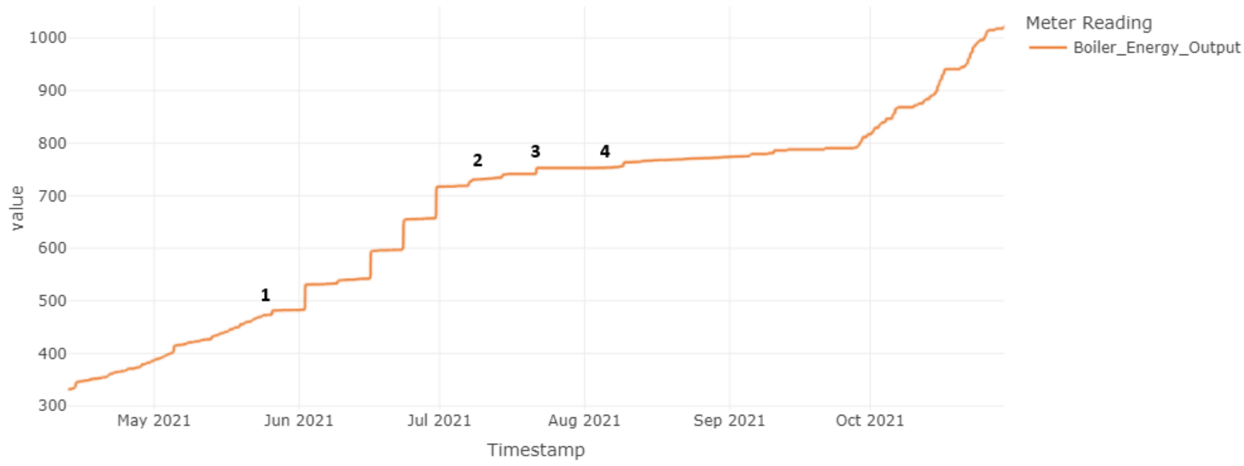

Figure 6.6: Shows the re-levelling at the end of anomaly 3 due to a high gradient, thus resolving the multi-point anomaly in the cleansed data.

6.2.3.2 Anomalous Cumulative Data from Start of Monitoring

As noted in Section 4.3.2, for some of the properties there were issues with the initial installation of the monitoring equipment resulting in either no reading being recorded or erroneous readings being recorded by the equipment. When these issues result in erroneous readings, they are generally represented by continuous anomalous data from the beginning of the monitoring period until the physical equipment issue is resolved.

The result of this anomalous data is that, for a given duration at the beginning of the monitoring period, the Heat Pump Energy Output readings appear to track higher or lower than expected given the Whole System Energy Consumed. To find these periods, the Coefficient of Performance (COP) for each day was calculated (same calculation as SPF_{H2} but over the duration of a day rather than a year) and compared to the expected result.

The data was rejected and removed if the daily COP was outside of the range 0.75-7.5. The data was only removed from the beginning of the monitoring period until the point where the daily COP falls within the range 0.75-7.5.

This range is wider than the accepted range for annual SPF calculations or the COP values used for gap scoring. This is because a larger variation in heat pump efficiency is expected over a shorter timeframe.

This issue is demonstrated by the graph shown in Figure 6.7. In the figure, the data is anomalous within the time period indicated by the gray box. To form the cleansed dataset, this data was removed and the meters relevelled to 0kWh, leaving only the non-anomalous data.

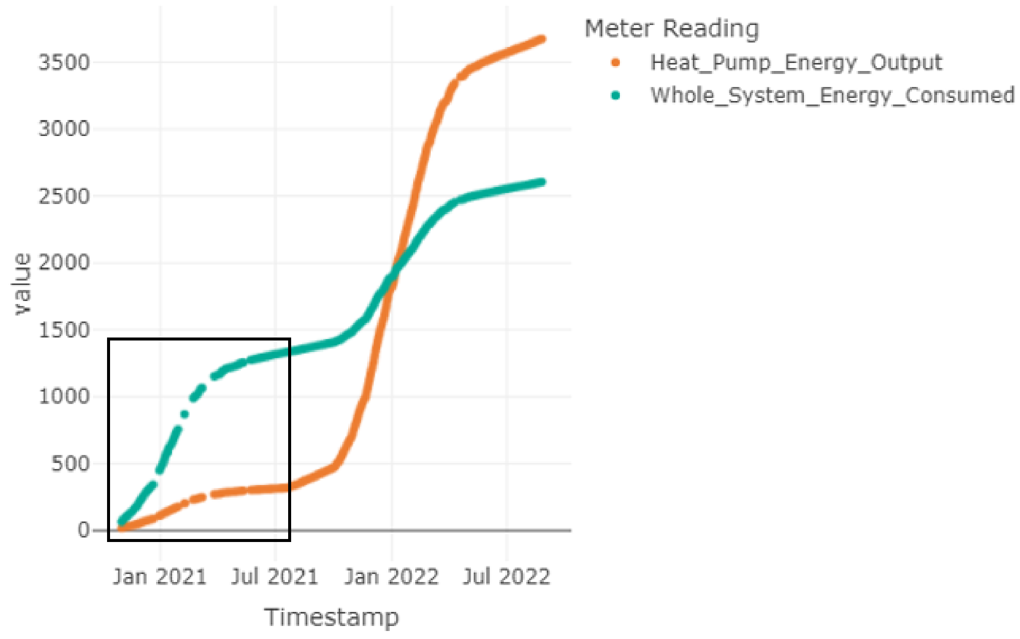

Figure 6.7: Cumulative energy data from a given property whereby the data is anomalous from the start of the monitoring period, but then becomes aligned with expectation following this initial period.

6.2.4 Relevelling Data Following Meter Reset

A significant decrease in cumulative meter readings which does not return to the expected level is a likely result from a meter fault or meter replacement (where the readings immediately return to the expected level, this is an anomalous point, see Section 6.2.3.1). Small decreases in heat meter readings may be explained by the heat pumps running a defrost cycle, where the system draws energy from the home to defrost ice from the heat pump unit. A defrost cycle is part of the normal operation of a heat pump and it may be interesting to analyse the heat pump behaviour during these cycles. As such, it is necessary to differentiate between meter faults or replacements and defrost cycles when amending the data.

Meter faults and replacements often result in the meter being reset to (or near to) 0kWh. This reset usually occurs after a long gap in the data. A defrost cycle however will often result in a short, gradual decrease in the meter reading before the reading continues to increase along its previous trend. Meter resets have therefore been identified as decrease in the data where the reading drops by more than 95% of the previous reading and does not immediately return to the expected level.

If a meter reset is identified, the data is amended by relevelling all data following the meter reset such that the readings before and after the reset align. This means that the reading across the reset is flat, rather than increasing. If a gap exists prior to the reset, then energy usage across the gap is not considered. Instead, the gap is scored through the quality checks described in Section 6.3 and only a reset after a gap of less than 21 days of lost data may be included in the SPF analysis.

6.2.5 Non-cumulative Data – Incorrect Column Assignment

For technical reasons relating to the monitoring system configurations (Section 4.14), the most likely data to be in the wrong columns are heat pump heating flow (HPHF), heat pump return (HPR) and hot water flow (HWF) temperatures.

This is because the HPHF and HWF temperatures are recorded using the same sensor, and the position of the control valve determines the direction of water flow and therefore which column the data should be recorded in.

HPHF and HPR temperatures are recorded by different sensors however, these sensors can be attributed to the wrong column due to equipment installation issues or an issue with the transmission of the data. The flow and return temperatures tend to be very similar and the return temperature can regularly exceed the flow temperature when the heat pump is not operational. This makes the issue difficult to identify. In addition, this issue is very rare within the data. As a result of this, there have been no column reassignements made between HPHF and HPR temperatures.

6.2.5.1 Heating Flow and Hot Water Flow Assignment

As the same sensor was used to measure HPHF and HWF temperature, it is sometimes the case that they are recorded in the same column. Alternatively, the data in these columns may be erroneously swapped (i.e. HPHF recorded in HWF column and vice versa). For some homes, these issues were fixed whilst monitoring was ongoing. The result of this is that, part way through the monitoring period, the data is correctly separated into the two columns or it is swapped so that the data are in the correct columns from the point of the fix onwards.

To evaluate whether the data was in the correct columns, data in each column was characterised using the following metrics:

- mean: value, (mean of the values for one sensor)
- mean: difference, (mean of the differences between chronologically consecutive values for one sensor)
- standard deviation (std): value, (standard deviation of values for one sensor)
- standard deviation (std): difference, (standard deviation of the differences between chronologically consecutive values for one sensor)
- spikiness, (Root mean square difference of differences of the values of one sensor. A full definition of the function used can be found on Github [20])
- spikiness of the differences, (Root mean square difference of differences of the difference between values of one sensor.)
- mean: daily max, (mean of the daily maximum values for one sensor)
- mean: daily min, (mean of the daily minimum values for one sensor)
- mean: count per day. (mean of the daily number of readings for one sensor)

As there is generally a distinct difference between the nature of the recorded “Hot Water” temperatures and “Heating” temperatures, the data and associated metrics were labelled “Hot Water” (for HWF) and “Not Hot Water” for HPHF and HPR.

The metrics were then used to train two decision trees (one using all of the metrics except "mean: count per day" and the other using all of the metrics). These decision trees can be seen in Figure 6.8 and Figure 6.9. These trees were used to identify data which had different characteristics to the data with the same sensor label. For example, some sensors labelled as "Hot Water" were grouped by the tree as "Not Hot Water"). Where sensors were mis-grouped, this suggests that the sensor data are more similar to those of the other type and therefore the data may have been mislabelled. As a result of this, these sensors were flagged for review.

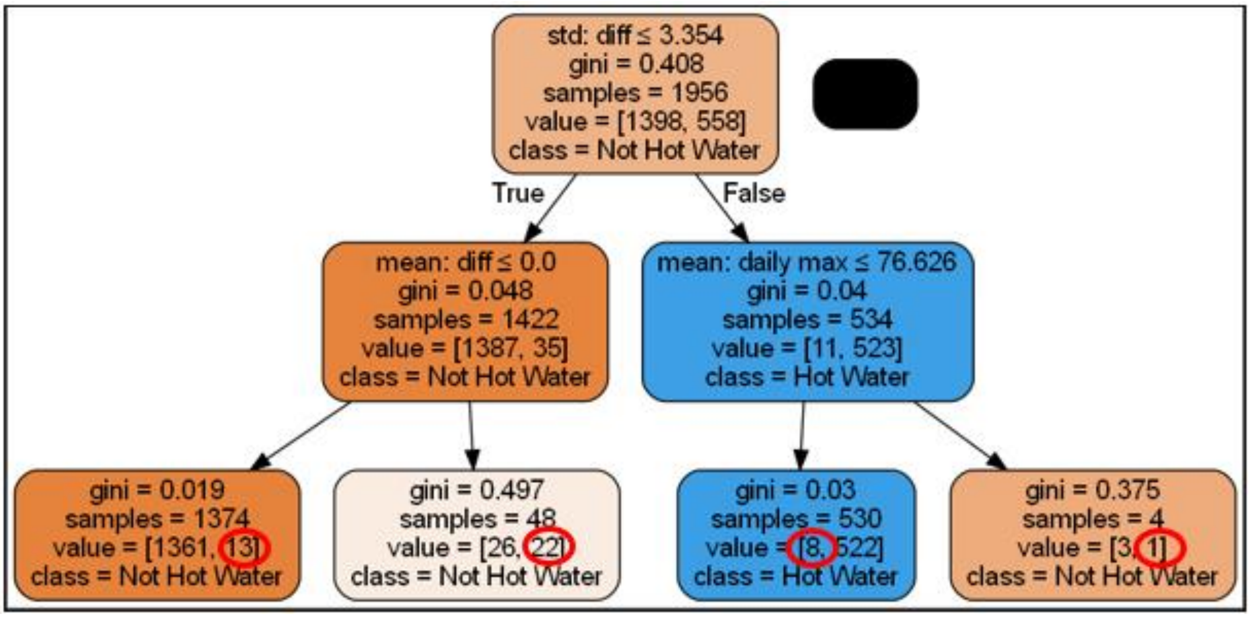

Figure 6.8: Non-cumulative data grouping decision tree (excluding "mean: count per day"). Red rings have been used to highlight number of sensors which have been classified by the tree as different from how it is labelled.

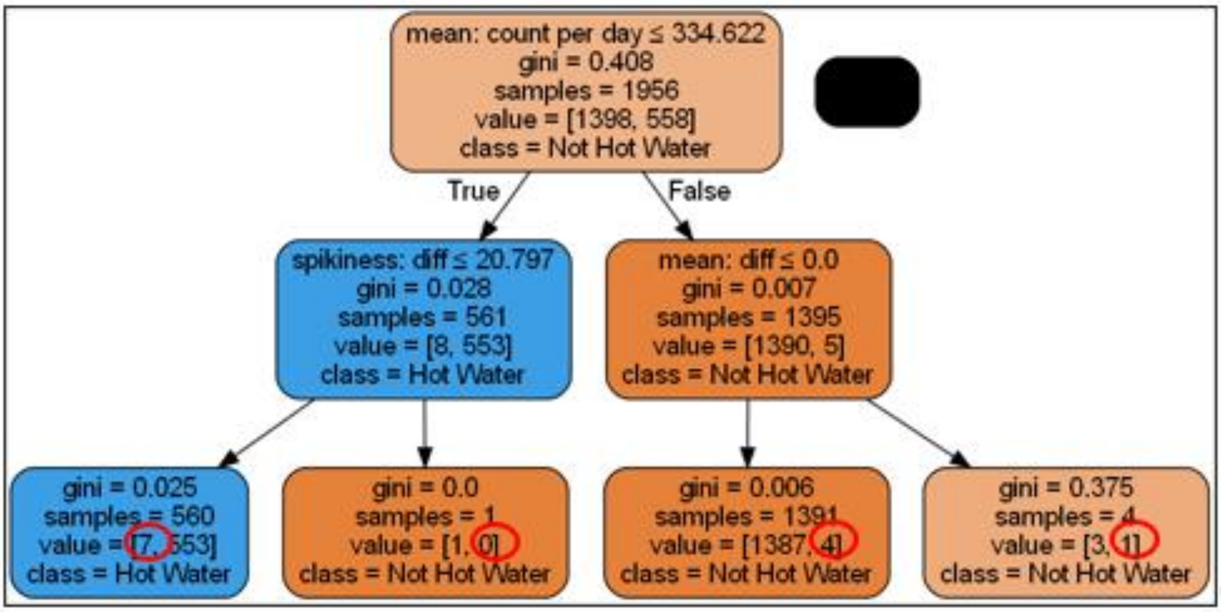

Figure 6.9: Non-cumulative data grouping decision tree (including "mean: count per day"). Red rings have been used to highlight number of sensors which have been classified by the tree as different from how it is labelled.

Most of the homes had 0 flagged sensors, indicating that the data was allocated to the correct column however, some properties were found to have a single flagged sensor and others had two. The homes were treated differently based on the number of flagged sensors.

The homes with two flagged columns were simpler to deal with as it was assumed that the data from these columns wholly assigned to the incorrect columns and so the data should be swapped. The swap was performed and sensors re-run through the decision tree to check that they had been correctly re-attributed. If these checks were passed, then the data was relabelled within the cleansed dataset.

Single flagged homes were assumed to be a case where one sensor was recording both HWF and HPHF and was then corrected by physically changing the monitoring setup within the property. For these instances, change point analysis was run on the “mean: count per day” of the data to detect the point where the physical change happened. If a change point was detected, then the data was split at that point, and allocated to the correct columns before and after the change. The sensors were then re-run through the decision trees to check that they had been correctly re-attributed.

For these data, it was assumed that the data before the change was from both the HPHF and HWF. It is difficult to confidently differentiate which data was from each use case and this issue affects very few homes so all data before the change is retained in the HPHF temperature column.

A graph of the change point detection is shown in Figure 6.10 whereby the vertical line marks the detected change point plotted alongside the “mean: count per day” in blue. Note that whilst it is physically less likely, the swapped sensors at the change point could be HWF and HPR temperatures.

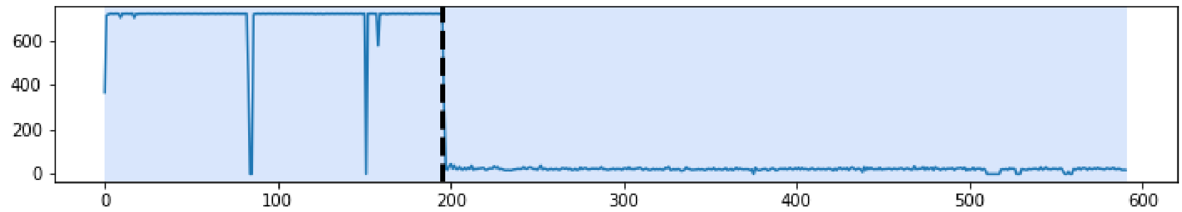

Figure 6.10: A graph of the change point detection used to identify when physical changes to the monitoring system were made.

6.2.6 Removal of Out-of-Range Temperatures

The range of expected temperatures recorded by each sensor within the heat pump monitoring system is relatively predictable and therefore it is possible to spot anomalous values. To search for anomalous values, it is necessary to set acceptable ranges. Within the cleansing process, these temperature ranges were wide, to maximise the temperature data which can be used and avoid removing any correct values. The acceptable temperature ranges are presented in Table 6.1.

There are a small number of anomalous temperature values which are vastly different to the usual expected ranges. These anomalous values are removed from the cleansed dataset and therefore not included within the analysis.

Table 6.1: Accepted temperature ranges for each data column.

Data Column	Min Value (℃)	Max Value (℃)	Notes
Internal_Air_Temperature	0	40	Based on Temperature Variations in UK Heated Homes Study [21] with a 5℃ variation on either side.
External_Air_Temperature	-27.2	40.3	Based on record UK temperatures [22].
Hot_Water_Flow_Temperature	5	80	Min value based on freezing temperature of water. Maximum value based on the highest temperature possible by the units installed as part of this study [23]. Both have an extra +5℃ variation.
Heat_Pump_Return_Temperature	5	80	See Hot_Water_Flow_Temperature
Heat_Pump_Heating_Flow_Temperature	5	80	See Hot_Water_Flow_Temperature
Brine_Flow_Temperature	-10	30	In the UK, GSHPs ground loop generally operate around 10℃ all year around [24]. A 20℃ variation has been allowed either side of this.
Brine_Return_Temperature	-10	30	See Brine_Flow_Temperature

6.2.7 Supplementary Data Cleansing

The supplementary data which is used to assist with the monitoring data analysis has undergone a rigorous quality checking and cleansing process. This is described within the Data Documentation Report [11] which is published alongside the dataset [13].

To ensure it is possible to use this data for analysis, the supplementary data should contain a consistent set of unique values. Table 6.2 provides the allowed variables for each column of supplementary data used at this stage of the monitoring data analysis.

Table 6.2: Each supplementary data field used and the accepted unique values after data cleaning.

Field Name	Description	Unique Values (Post Cleaning)
House_Income	House income	'Prefer not to say', '£0 - 12,500', '£12,501 - 16,200', '£16,201 - 20,000', '£20,001 - 25,000', '£25,001 - 30,000', '£30,001 - 40,000', '£40,001 - 50,000', '£50,001 +'
Social_Group	Social group	'AB', 'C1', 'C2', 'DE"
House_Form	House type	'Detached', 'End-Terrace', 'Flat', 'Mid-Terrace', 'Semi-Detached'
House_Age	House age	'Pre-1919', '1919-1944', '1945-1964', '1965-1980', '1981-1990', '1991-2000', '2001+'

In addition to ensuring the data used from the supplementary dataset is consistent with expectations, to perform the monitoring data analysis, it was also necessary to collate additional refrigerant data which was collected by analysing the datasheets from the installed heat pumps. This data is provided in the analysis summary datasets.

The majority of the data cleansing conducted was relating to spelling and grammar variations between properties however, due to variations in the data collected the house ages required a more considered cleansing approach, this is discussed further in the sub-section below.

6.2.7.1 House_Age Cleansing

During the home survey stage of the project, the home ages were gathered slightly differently by all of the DCs. The ITT stipulated that the ages should be presented within the ranges:

Pre-1919; 1919-1944; 1945-1964; 1965-1980; 1981-1990; 1991-2000; 2001+.

OVO and Warmworks collected and presented the home ages within these ranges however, E.On collected the home ages within the EPC ranges which are:

Pre-1900; 1900-1929; 1930-1949; 1950-1966; 1967-1975; 1976-1982; 1983-1990; 1991-1995; 1996-2002; 2003-2006; 2007-2011; 2012+.

As these bands overlap and are inconsistent, the house ages required cleansing to enable data analysis. As with other supplementary data cleansing, this cleansing was performed prior to publication of the published Heat Pump Installation Data [13]. This cleansing is highlighted again as it may have some baring on the monitoring data analysis results. To attain consistent data, the EPC House_Age ranges used by E.On were adjusted to align with the ITT ranges as shown in Table 6.3 below.

Table 6.3: The EPC House_Age ranges used by E.On listed alongside the ITT House_Age Ranges which they were converted to for publication and analysis.

EPC House_Age Range	ITT House_Age Range (new range for analysis conclusions)
Pre-1900	Pre-1919
1900-1929	Pre-1919
1930-1949	1919-1944
1950-1966	1945-1964
1967-1975	1965-1980
1976-1982	1965-1980
1983-1990	1981-1990
1991-1995	1991-2000
1996-2002	1991-2000
2003-2006	2001+
2007-2011	2001+
2012+	2001+

6.3 Assessing Data Quality

Quality issues in the data arise where the monitoring equipment has not operated as intended. These can be categorised into transmission issues (where no data was received for a period) or equipment issues (where one sensor or meter sent anomalous readings or no readings). Some of the data quality issues are easily identifiable and amendable, these are discussed within the data cleansing section above. However, some of the quality issues may still exist within the data after cleansing, and some cleansing activity may reduce confidence in the data. As a result, it is necessary to assess and quantify the quality of the data to ensure that the best windows for data analysis are selected (see Section 6.4) and that the data are of sufficient quality to be analysed.

The quality checks undertaken for this data analysis are as follows:

- Assigning quality scores to all gaps in the cumulative data.
- Assigning quality scores to each calendar month of cumulative data.
- Reviewing the calculated efficiency over a selected analysis window.
- Assessing the percentage of data available in a selected analysis window.
- Assessing energy output over a given period (for coldest day only).

The below sub-sections give more details on each of the quality assessments.

Section 0 provides the outcome of the quality checks including quantifying why properties were excluded from the data analysis.

6.3.1 Data Gap Quality Scoring

The majority of data quality issues identified are related to gaps in the data. A gap in the data is defined as data being missing for longer than 30 minutes. As the energy meter data are cumulative, a gap in the data does not necessarily compromise the quality of the data around it. It is generally assumed that, where gaps in the data exist, they are as a result of transmission faults and that the meter has continued collecting data on it's cumulative trend through the gap period. Therefore, as long as the data before and after the gap are as expected, the data should be of sufficient quality to analyse.

Where data gaps exist, they are therefore assigned a quality score between 1 and 5 based on the length of the gap period and what happened to the data over the gap period. Higher scoring data gaps indicate worse data quality. The quality scores for both gaps and monthly data (See Section 6.3.2) are the main metric used to both select the best quality window (see Section 6.4) and to ensure the data is of sufficient quality to analyse.

All selected windows with a maximum quality score of greater than or equal to 4 are rejected from analysis. Quality scores between 3 and 4 were flagged for manual review; however, upon review of each of these cases, they have been included within this set of data analysis as the data appears as expected.

The expected data trend over a gap varies based upon which data the gap exists within and what trends occurred in the other data over the gap period. The scores given to each gap are provided in in the following tables.

Table 6.4 applies to any gaps within all cumulative data readings. Decreases in the data over a prolonged gap are re-levelled as discussed in Section 6.2.4 however, the data over the gap period is lost so where a long gap exists, the data is scored harshly and rejected from the analysis.

Table 6.4: The data quality score if a data gap of a given time period exists within any of the cumulative data and the reading reduces over the gap. (Higher scores = worse quality data)

Time Period / Value Change	Decrease
30 minutes – 7 days	3.1
7 days – 21 days	3.7
> 21 days	5

Table 6.5 applies to any gaps within the Boiler Energy Output, Immersion Heater Consumed, Back Up Heater Consumed or, Circulation Pump Consumed data readings. These are less harshly scored as the data is less predictable for the system ancillary components and it causes

less of an impact on the overall results. Note that “flat” denotes no change between the readings before and after the gap.

Table 6.5: The data quality score if a data gap of a given time period exists within the non-heat pump data and the reading remains flat or increases over the gap. (Higher scores = worse quality data)

Time Period / Value Change	Increase	Flat
30 minutes – 7 days	1	1
7 days – 21 days	2	2
> 21 days	3	3

Table 6.6 applies to any gaps within the Heat Pump Energy Output and Whole System Energy Consumed readings. These are COP dependent as it is expected that the heat pumps will operate within given efficiencies however, the allowable COP is wider than the allowable annual SPF as greater performance variation is expected over a shorter timeframe.

Table 6.6: The data quality score if a data gap of a given time period exists within the heat pump data and the reading increases with a given COP(H2) over the gap. (Higher scores = worse quality data)

Time Period / Value Change	Increase	Increase
	0.9 <= $COP_{(H2)}$ <= 6.5	$COP_{(H2)}$ < 0.9 or, $COP_{(H2)}$ > 6.5
30 minutes – 7 days	1	2
7 days – 21 days	2	3.6
> 21 days	3	5

Table 6.7 applies to any gaps within the Heat Pump Energy Output (HP Output) and Whole System Energy Consumed (WS Consumed) readings. These are varied based on the trends within all of the other data readings if the heat pump data remains flat over the given period. If all data is flat, it is assumed the system is either inactive or not working correctly. Where both heat pump readings are flat but other readings are increasing, this suggests the heat pump is inactive but other equipment within the system is operating instead. Where one of the readings is not flat and the other is flat over a prolonged period of time, this suggests there may be an equipment issue. The gaps are scored accordingly.

Table 6.7: The data quality score if a data gap of a given time period exists within the heat pump data and the other data trends as per the additional rules outlined. (Higher scores = worse quality data)

Time Period / Value Change	WS Consumed Flat	HP Output Flat	WS Consumed Flat	HP Output Flat
	All other readings flat	WS Consumed flat	One or more other readings not flat	WS Consumed not flat
30 minutes – 7 days	1	1	2	2
7 days – 21 days	2	2	3.5 / 3.4	3.5 / 3.4
> 21 days	4	3	5	5

Gap periods, and particularly longer gaps are scored more harshly than continuous data as, because the data gap exists, there is less certainty over what occurs within the system during the gap period. An upper limit of 21 days is selected as this is the period during which a trial participant might reasonably take a holiday and power down their heat pump system.

An example of the data gap scoring is shown in the graphs in Figure 6.11.

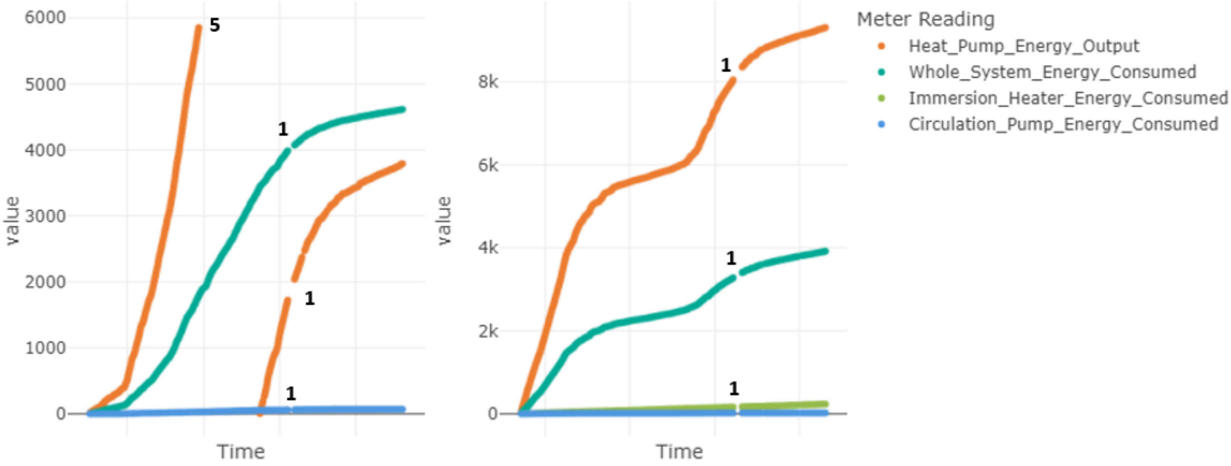

Figure 6.11: Two graphs showing unacceptable data (left) and acceptable data (right). The data shown on the left is rejected as it contains a max gap score of 5 due to meter reset following a large data gap.

6.3.2 Monthly Data Quality Scoring

As well as assigning quality scores to all gaps within the data, it is necessary to assess the quality of the data where gaps do not exist. There are significant variations in the monitoring data over shorter timescales, therefore the assessment of data quality was made over each calendar month. To assess the data, the energy used and $COP_{(H2)}$ over each calendar month was analysed.

If the monthly $COP_{(H2)}$ falls within the range of 0.9-6.5 and the energy used over the month is greater than 1kWh, a quality score of 0 is assigned to this month of data (indicating there are no quality issues). If the monthly $COP_{(H2)}$ is outside of the range of 0.9-6.5, a quality score of 3.3 is assigned to this month of data. If the monthly energy recorded across all cumulative sensors is less than 1kWh, a quality score of 3.2 is assigned to this month of data. These scores are shown in Table 6.8.

Table 6.8: Monthly data quality scores based on the value changes in cumulative data listed. (Score of 0 indicates no quality issues and higher scores = worse quality data).

Monthly Value Change	Monthly Data Quality Score
$COP_{(H2)}$ between 0.9-6.5 and energy recorded across any cumulative sensors greater than 1kWh.	0
$COP_{(H2)}$ outside of range of 0.9-6.5.	3.3
Energy recorded across all cumulative sensors lower than 1kWh	3.2

The COP range assessed is wider than the 12-month SPF range (see Section 6.3.3) as more performance variations are expected through the months. For example, in the autumn or spring, when the heat pump is operating consistently but the external temperatures are moderate, higher COPs may be seen. Equally, in the summer the heat pump may be operating less frequently and therefore less efficiently to produce hot water.

In addition to the above, there may be data quality issues if all cumulative readings are flat as this may signify error in measurement or lack of human presence. A lack of human presence over shorter periods is acceptable however, if the period becomes too long it may invalidate the

SPF result. For this analysis, periods of flat data are defined as periods where less than 1kWh is consumed or output.

As both of these issues may be subjective, they are scored between 3 and for to allow for manual checks. The manual checks undertaken for the properties where this is the highest scoring issue have ensured confidence that these properties can be included for analysis. In all instances where data was flagged as having these issues and manual checks highlighted it as erroneous, the SPF was also out-of-range so data was excluded for other reasons.

6.3.3 Calculated Efficiency – Acceptable Ranges

Once a given window is selected based on the data scoring (see Section 6.4), the system efficiency across that window is calculated using the analysis calculations in Section 7. The data is excluded from the analysis if these calculated efficiencies are outside of the accepted ranges. The accepted efficiency ranges for each efficiency calculation are provided in Table 6.9.

Table 6.9: Accepted efficiency ranges for each calculation window, outside of which properties are excluded from the analysis.

Calculated Value	Timeframe	Accepted Range
SPF_{H2} or SPF_{H4}	12 months	1.5 – 4.5
$COP_{(H4)}$	24 hours	0.75 – 7.5
$COP_{(H4)}$	30 minutes	0.75 – 7.5

The reason for filtering the data in this way is due to it's simplicity for the removal of outliers as, despite the rigorous checking and quality scoring process it is still possible for outliers to exist within the data. This filtering method was primarily the method used within the RHPP trial [25].

The SPF range used was selected based upon the RHPP trial range. To assess these ranges are still fit for purpose for the EoH project, a manual check was undertaken on all of the properties which have SPF values between 1 and 1.5 and between 4.5 and 5. The majority of these properties had clear issues within the cumulative data and so the range of 1.5 to 4.5 was maintained. This range will be revisited and may be amended when undertaking further data analysis later in the project.

Due to wider performance variations over shorter timeframes, the accepted daily $COP_{(H4)}$ ranges are wider than that used for the SPF_{H4}. The reason for performance variations in monthly data is discussed in Section 6.3.2 and variations are more prominent over a shorter timeframe as the performance becomes more of a function of the operational profile as well as the pre-conditioning of the property leading up to the selected period. Thus, the expected efficiency ranges are much wider for these periods.

6.3.4 Percentage Data Available – Acceptable Ranges

The final quality criteria used to ensure a chosen analysis window is sufficient to be included in the analysis is the percentage of expected data available in that window. This check is only performed on the annual data as, for the coldest day, a pre-requisite to window selection is that the heat pump is operational and the data exists to prove this.

This check is necessary as a selected window may have multiple short gaps which means a significant portion of the data is missing. In this scenario, each of the short gaps may have minimal impact on the data quality (low scoring gaps) however, the overall effect of the missing data is that confidence in the data is reduced.

As a result of this, properties are filtered out of the SPF analysis if less than 50% of the expected Whole System Energy Consumed or Heat Pump Energy Output data readings are available. Upon review, there are no properties where less than 50% of the expected Whole System Energy Consumed or Heat Pump Energy Output data readings are available which are not excluded by the other metrics; so, whilst this check is performed, no properties are excluded as a result of it.

Where sufficient heat pump data is available but less than 50% of the temperature data is available, the properties are not included within the temperature related analysis but are included in the wider SPF analysis.

6.3.5 Energy Output – Acceptable Ranges

For the coldest day analysis, it is important that only periods where the heat pump is operational are selected. Initially, the window selection process checks heat pump operation prior to selecting the analysis window however, there may be selected windows where the home is pre-conditioned prior to the selected period and therefore the heat pump is operational only for a very short period. There may also be selected periods where the monitoring equipment is not operating as intended and recording erroneously high or low values.

As a result, the data are filtered based on the heat pump energy output within the coldest day window. The energy use over the coldest periods is highly variable. As previously stated, it may be a function of the pre-conditioning of the property. None extensively, it may also be a function of the internal temperature setpoint chosen by the occupants, and the external temperature within the coldest period. As a result of these variations a statistical approach has been taken to the inclusion criteria of energy output during the cold periods.

The properties are excluded from the analysis if the Heat_Pump_Energy_Output over the selected window is outside of 2 interquartile ranges (IQR) of the first and third quartiles (Q1 and Q3) with an ultimate lower boundary of 0kWh.

This correlates to Heat_Pump_Energy_Output outside of the range of 0kWh and 195kWh for the coldest day.

6.3.6 Data Quality Assessment Outcomes

Using the data quality assessment results, the best window of data can be selected and certain properties can be included in or excluded from different parts of the data analysis. Window selection is discussed further in Section 6.4. This section outlines the number of properties included in the analysis or excluded based on the various quality metrics.

For the annual SPF analysis, properties are excluded for the following reasons (in order):

- If they have less than one year of data,
- If they have less than one year of usable data (due to data being removed as a result of early monitoring issues),
- If they have no valid one year windows due to gaps at the start or end of all possible windows,
- If the SPF is outside of the range 1.5 to 4.5,
- If the maximum data quality score in the SPF window is greater than 4, and
- If there is less than 50% of the expected Whole System Energy Consumed or Heat Pump Energy Output readings available.

Figure 6.12 indicates the number of properties which were excluded from the SPF analysis for each of these reasons and the number of properties remaining in the SPF analysis.

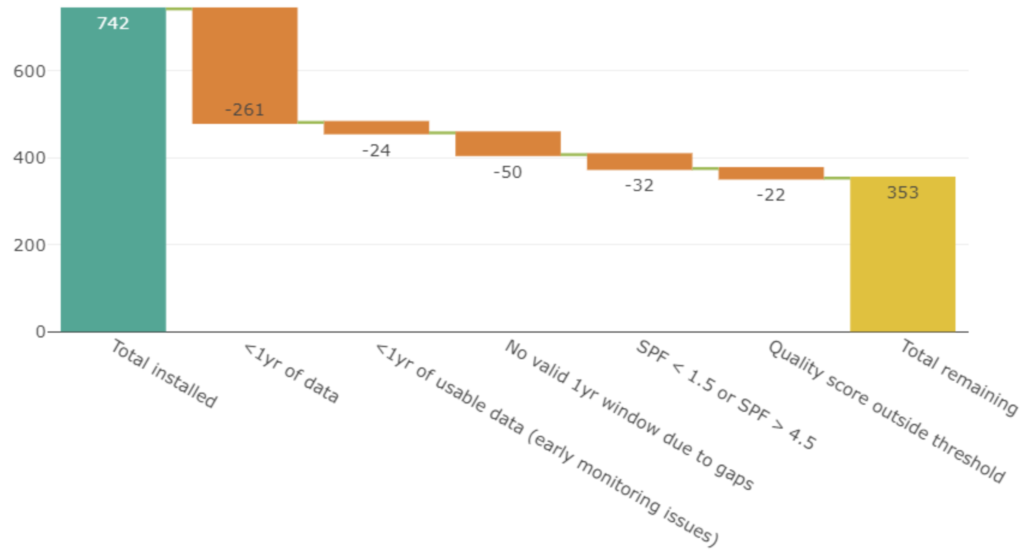

Figure 6.12: A graph showing the number of properties excluded from the SPF analysis for each reason as well as the number of properties remaining.

Figure 6.13 provides SPF and Energy Output performance metrics for all properties, those shown by solid dots are included in the analysis and those shown by hollow symbols are excluded from the analysis.

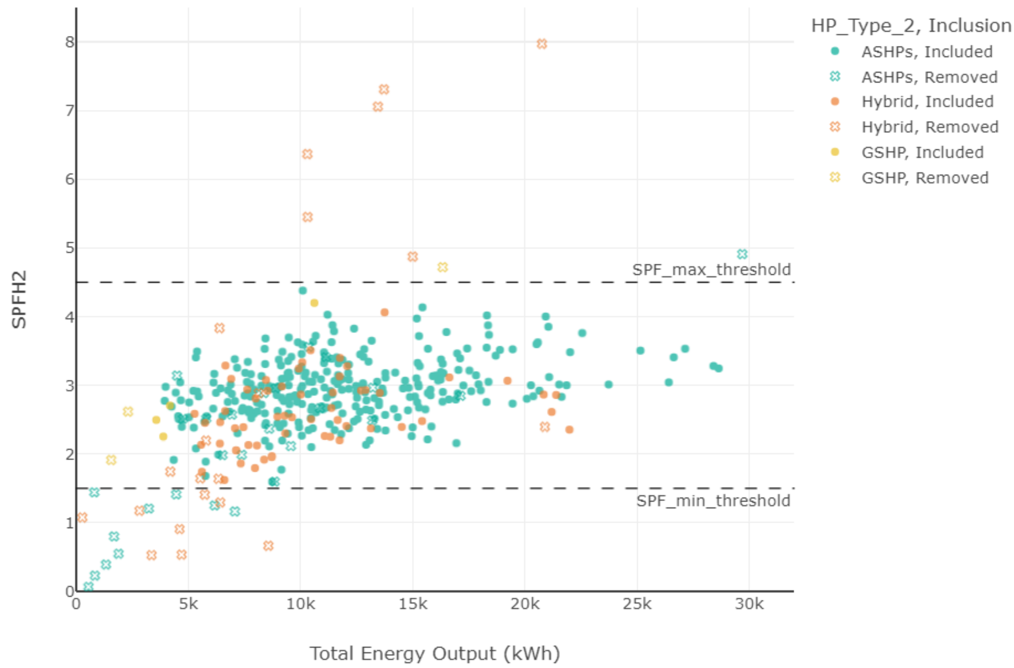

Figure 6.13: A scatter graph of SPF_{H2} against Total Energy Output for all properties with a 12 month data window, indicating where the SPF boundaries are and which properties were included in or excluded from the analysis.

For the coldest day analysis, the coldest period in which the heat pump was operational was found. The quality checks listed in the previous subsections were applied as well as a check on the time and date of the coldest day. Properties were then included in the analysis only if sufficient data was available and they passed all of the checks listed within Table 6.10.

Table 6.10: Criteria for including properties in the coldest day analysis as well as the number of properties included after each check.

Inclusion criteria	No. properties remaining
ASHP sample size	547
Sufficient data available	535
$COP_{(H4)}$ value inside of the range 0.75 to 7.5	518
Timestamps within winter months (Nov and Mar inc.)	487
Total heat pump energy output inside of 2 interquartile ranges (IQR) of Q1 and Q3.	484
Final Analysis Sample Size	484

6.4 Analysis Window Selection

6.4.1 12-month Window Selection

A unique 12-month analysis window of data was selected for each property which was included within the SPF analysis. Initially, to choose the best 12-month window all potential data windows are found by finding all potential start and end dates. For the window to be considered, the start and end dates must be separated by 1 year and both must contain data (i.e. not be situated within a data gap).

The best 12-month window is then selected for each home based on the quality of data within the window.

- Initially, windows with the lowest maximum data quality score are selected;
- From these, if more than one window for any properties exist, windows with the lowest mean data quality score are selected;
- From these, if more than one window for any properties still exist, the most recent window is selected.

The first two stages in the window selection are based on the data quality, the maximum score is criteria for whether the data is useable, so this is prioritised above the mean quality score. The final check is selected based on confidence in the data. Some monitoring equipment exhibited hardware, calibration or setup issues early in the project which have been rectified during the project, as a result it is assumed that the most recent data is most likely to be of good quality.

6.4.2 Coldest Day Window Selection

To assess heat pump performance during the coldest day, it is necessary to find the coldest periods where the heat pump is operational. In order to do this, the mean external temperature was calculated for each day (beginning and ending at 00:00:00).The change in the heat pump energy output reading was also calculated over these windows..

With these calculations complete, initially, all periods where the heat pump was operational were identified (where the change in heat pump energy output was greater than 0kWh). Then, the coldest of these periods was selected (lowest mean external temperature) as the one to take forward for analysis.

During the analysis, to avoid skewing the overall result, the period is rejected if it is not in the winter period (between November and March). A list of the most common 10 selected periods is given in Section 10.

6.5 Analysis Process Bias Check

It is noted that when more than 12-months of data exist, the method chosen to select a 12-month analysis window may cause bias in the results. An example of an obviously bias method would be to select the 12-month period with the highest SPF for each home. When choosing the window selection method, the potential to cause bias results was noted and the method was selected based on providing an unbiased result. It is however still necessary to check whether the method selected did create any bias within the results.

To make this assessment, the SPF values for each possible window for each property were calculated. The median of all SPF values was then taken for each property. The number of possible windows and median of the SPF values calculated across each possible window is provided (for each property) in the summary dataset [8].

The median of the SPF values was then compared to the SPF value calculated for the selected analysis window to provide a metric by which to assess bias.

The average (mean) result across all homes is provided in Table 6.11.

Table 6.11: The average variation between the median of all windows SPF values and the SPF calculated within the analysis window, across all homes.

SPF Value	Mean variation
SPF_{H2}	-0.0015
SPF_{H3}	-0.0026
SPF_{H4}	-0.0032

These results are sufficiently low that, after rounding the maximum impact they could have on the SPF figures presented within this report is a variation of 0.01. This provides a clear indication that the method chosen to select the analysis window does not instil significant bias within the results presented.

6.6 Known Quality Issues

Despite the extensive cleaning and quality checking process, there are still some minor quality issues within the data which are not resolved. These are discussed in the following subsections.

6.6.1 Data Gaps

As already noted in Section 4.3, data gaps may exist due to transmission errors or monitoring equipment errors. These result in either a lack of all data for a period or a lack of one type of data for a period.

Within the cleaning process, the decision was taken not to rectify data gaps with assumed or interpolated data. This is because, whilst gaps may cause issues with certain analysis during certain periods, backfilling the gap with assumed or calculated data would reduce confidence in the data. As such, data gaps still exist in the cleansed dataset. This is not an unsurmountable issue for most of the analysis performed on the data, which is outlined in this report, however, it should be noted as it may cause issues with other future analysis.

6.6.2 Timestamp Alignment Issues

As noted in Section 6.2.1, due to the alignment of the timestamps to every 2-minute period, analysis of instantaneous readings or readings over short periods may return false results. For example, a heat pump energy output of 1kWh over a 2-minute period in the cleansed dataset may appear to indicate an average thermal output of 30kW however; the period in the raw dataset may actually be up to 4-minutes, giving an average thermal output of 15kW (-50% impact).

As the maximum variation for any window is 2-minutes either side of the first and last datapoints, this issue is minimised when analysis is undertaken over a wider timescale. As such, the impact is negligible on the SPF analysis. The shortest analysis window used for the analysis in this report is 24 hours and the impact over a 24 hour period is also negligible.

To assess the potential impact of aligning the timestamps in the cleansed dataset, should it be used to derive “instantaneous” readings; the timestamp difference between one data point and the next was calculated for each sensor in each home. 99.1% of all the data points had timestamp differences in the 1.8 - 2.2-minute range (1 min 48 secs to 2 min 12 secs). So, given the 1kWh 2-minute period example above, the average thermal output for 99.1% cases would fall between 33.33 - 27.27kW.

This impact is still a 9-11% variation on the instantaneous result which is not insignificant. As such, if the heat pump monitoring data is used to perform instantaneous analysis, it may be necessary to use the raw dataset.

6.6.3 Circulation Pump Reading Issue

Some of the circulation pumps electricity meters did not provide readings. As a result of the metering strategy, the energy used by the circulation pump is still recorded by the Whole System Energy Consumed electricity meter. Therefore, the impact of this is that the SPF_{H2} and SPF_{H3} results are skewed lower than their true value. This is because, to calculate the Heat Pump Unit Energy Consumed, the Circulation Pump Energy Consumed is subtracted from the Whole System Energy Consumed reading. This subtraction reduces the denominator in the SPF_{H2} and SPF_{H3} calculations.

To decide whether to address this issue within the data cleansing, analysis was done on the potential impact of this issue. In total, of the 353 ASHP and Hybrid systems included in the analysis, 60 of them returned an erroneous circulation pump energy consumed value of 0kWh. The average Circulation Pump Energy Consumed across all other systems was 146.5kWh. Taking this average and applying it to the properties which returned a reading of 0kWh, the average SPF_{H2} across the trial increases by 0.021 and the average SPF_{H3} across the trial increases by 0.011.

Since this impact is relatively small, the decision was made not to add estimated circulation pump readings into the data to replace zeros.

6.6.4 Negative Cumulative Data Readings

On some occasions, the data values recorded by the cumulative meter reduce. The most significant reductions are clear errors and are dealt with by the processes outlined within Section 6.2.2 and 6.2.4.

Not all of the reduced readings are erroneous, however, as some of the minor reductions in may be a result of the heat pump defrost cycle[4]. As a result, the cleansing process does not remove all reductions in cumulative meter readings and small reductions are maintained within the cleansed dataset. For the heat pumps, during colder periods all these variations can be assumed to be normal operation, however, some of the variations occur in the boiler heat meter readings in hybrid systems.

There is no technical reason for the boiler to absorb heat from the home, so these readings are assumed to be erroneous. The likely cause for this error is minimal backflow through the boiler circuit when the heat pump is operational. The impact of these minor erroneous readings is minimal, so they have not been rectified but should be noted.

6.6.5 Mislabeled temperature readings

From examination of the data, it appears that some temperature sensors for some durations have been mislabelled. This is due to the physical installation of the sensors, and in some cases these have been corrected part way thought the monitoring period. Where it was possible to be confident in identifying the mislabelled data, the sensors have been relabelled temperature sensors as described in Section 6.2.5.1. There are however some cases where temperature sensors may have been mislabelled but it is not possible to confidently relabel them. This could be the case for Heat_Pump_Heating_Flow_Temperature and Heat_Pump_Return_Temperature for a small number of homes.

6.6.6 Back-up heater energy consumed recording

There may be instances where the back-up heaters have not been metered independently or where the heat meter records the back-up heater energy generated as well as heat pump energy generated. An example where this may occur is if a monobloc heat pump includes the back-up heater within the external heat pump unit.

In these instances, the total energy generated and energy consumed by the system is still recorded however, the efficiency breakdown across the SPF boundaries may not be accurate. These instances do not occur in the majority of the heat pumps installed and the impact on an individual home basis is likely to be the reporting of a slightly lower SPF_{H2}. As the SPF results are averaged across a large sample, this impact is dampended and the overall effect is likely minimal.

[4] The defrost cycle occurs when condensed water on the heat pump turns to ice. The heat pump operates in reverse, pumping warm water through the heat exchangers in order to defrost this ice. This process abosorbs a small amount of heat from the home heating system, so negative heat meter readings are expected.

7. Analysis Calculations

7.1 Assumptions

To perform SPF and COP calculations, certain assumptions must be made. These assumptions broadly relate to the heat gains from different components in the heat pump system and the physical configuration of each monitoring system. Where assumptions are made on the physical configuration of the monitoring system, these are backed up by the installation Quality Assurance checks (refer to Section 3.3). Whilst the QA checks give some assurance of the physical configuration, they were only carried out on 20% of the properties, so listed assumptions are still necessary.

When performing the analysis calculations, it is assumed that:

- The circulation pump causes negligible heat gain on the system.
- The back-up heater energy consumed is equal to the back-up heater energy output.
- The immersion heater energy consumed is equal to the immersion heater energy output.
- Where no back-up heater energy consumed value is recorded independently, it is combined with the immersion heater energy consumed.
- The back-up and immersion heaters are located downstream (on the flow side) of the Heat Pump heat meter;
  - As such, the Heat Pump heat meter records only the Heat Pump Energy output.
- Any boiler heat meters are located in parallel to the heat pump heating circuit;
  - As such, they do not record the boiler heat output.
- Boiler heat meters do not account for the heat energy output for hot water provision.
- The electricity meters are located as indicated within Section 4.1 of this report;
  - I.e. There is one whole system electricity meter which records all energy consumed and all other components are sub-metered aside from the heat pump.
- The circulation pump electricity sensor accounts for all (primary and secondary) circulation pumps.
- The heat pump unit electricity consumed is equal to the Whole_System_Energy_Consumed minus all other energy consumed values.

7.2 Calculation Variables

The majority of the variables required for the analysis calculations are directly recorded by the meters and sensors in the heat pump monitoring system described in Section 4.1. There are, however, a few variables which need to be pre-calculated prior to performing the main analysis calculations. Table 7.1 lists the calculation variables required for the SPF and COP calculations described in Sections 7.3 and 7.4.

Table 7.1: A full list of the variables used to perform the SPF and COP calculations.

Data Item	Symbol	Source
Heat_Pump_Energy_Output	Q_{HP}	Meter reading
Whole_System_Energy_Consumed	E_{HPS}	Meter reading
Back-Up_Heater_Energy_Consumed	E_{BU}	Meter reading
Immersion_Heater_Energy_Consumed	E_{IH}	Meter reading
Circulation_Pump_Energy_Consumed	E_{CP}	Meter reading
Heat_Pump_Energy_Consumed	E_{HPU}	$E_{HPU} = (E_{HPS} - E_{BU} - E_{IH} - E_{CP})$
Back-Up_Heater_Energy_Output	Q_{BU}	$Q_{BU} = E_{BU}$
Immersion_Heater_Energy_Output	Q_{IH}	$Q_{IH} = E_{IH}$

The Back-Up_Heater_Energy_Output and Immersion_Heater_Energy_Output are derived based on the assumption listed in Section 7.1. The Heat_Pump_Energy_Consumed is derived by subtracting the sub-metered component energy consumed values from the Whole_System_Energy_Consumed value.

To derive the specific value for each of the cumulative data variables, the first and last recorded values within the selected analysis window were attained. The first value was then subtracted from the last value and resultant used within the SPF and COP calculations.

7.3 Seasonal Performance Factor Calculations

The seasonal performance factor (SPF) of a heat pump is the ratio of the total heat supplied to a building (by the heating system) to the electricity used by the heat pump and other components of the heating system over the year. This ratio is usually expressed as a numerical value which correlates directly to an efficiency percentage (i.e. an SPF of 2.90 means the heat pump operation over the year was 290% efficient.)

SPF values are calculated over four different boundaries, depending on which components of the heat pump system are assessed. These boundaries, were originally defined by the SEPEMO project (**SE**asonal **PE**rformance factor and **MO**nitoring for heat pump systems in the building sector) [1]. Further clarification of the SPF boundaries was made during the Energy Saving's Trust Heat Pump Trial [15] [16] for systems which may include an immersion heater for hot water provision.

The SPF system boundaries used for the calculations herein are derived directly from those derived by the studies listed above. Figure 7.1 applies these system boundaries to the EoH project monitoring system.

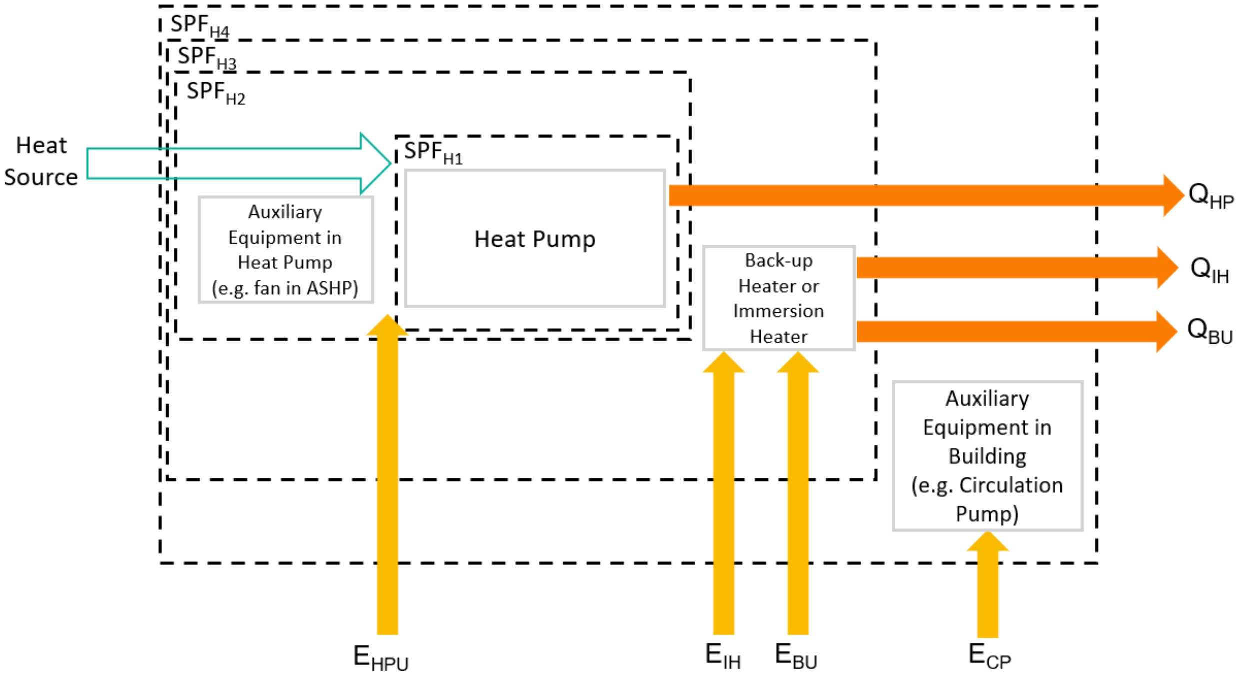

Figure 7.1: SPF system boundaries applied to the EoH monitoring system.

Note that within the EoH monitoring system, the pumps located within the heat pumps (denoted in Figure 7.1 as “Auxiliary Equipment in Heat Pump”) are not separately monitored. As such, an SPF_{H1} values cannot be calculated using the data collected by this project.

The SPF_{H2}, SPF_{H3} and SPF_{H4} calculations used for this project are provided below.

$$SPF_{H2} = \frac{(Q_{HP})}{(E_{HPU})}; \quad SPF_{H3} = \frac{(Q_{HP} + Q_{BU} + Q_{IH})}{(E_{HPU} + E_{BU} + E_{IH})}; \quad SPF_{H4} = \frac{(Q_{HP} + Q_{BU} + Q_{IH})}{(E_{HPU} + E_{BU} + E_{IH} + E_{CP})}$$

All SPF calculations were carried out over the 12-month data window selected for the analysis. For each property, this window is provided within the analysis summary datasets.

7.4 Coefficient of Performance Calculations

The Coefficient of Performance (COP) of a heat pump is similar to the SPF in that it indicates the heat pump efficiency over a period of time. However, whilst the required conditions and calculation boundaries for SPF are clearly defined, the term COP can be used to describe the heat pump efficiency over a variety of conditions or timeframes.

For this analysis, the term COP is used for any efficiency calculation which is performed over a timeframe that is not exactly 12-months. Other than the variation in the analysis window timeframe, the COP calculations performed in this analysis are identical to the SPF calculations quoted above. Where the COP calculations are performed over a certain system boundary, they are denoted with (H2), (H3) or (H4) in a similar fashion to the SPF. The COP calculations are listed below.

$$COP_{(H2)} = \frac{(Q_{HP})}{(E_{HPU})}; \quad COP_{(H3)} = \frac{(Q_{HP} + Q_{BU} + Q_{IH})}{(E_{HPU} + E_{BU} + E_{IH})}; \quad COP_{(H4)} = \frac{(Q_{HP} + Q_{BU} + Q_{IH})}{(E_{HPU} + E_{BU} + E_{IH} + E_{CP})}$$

7.5 Statistical Significance and Confidence Intervals

Where this report indicates statistical significance, it refers to whether a result can be attributed to a change in the population rather than being attributable to random variation. The threshold used in this report when testing for statistical significance is 5%.

When this report refers to a mean 95% confidence interval, it refers to the confidence intervals (range) in which, when calculated from 95% of random samples, the true mean value would be contained.

8. Seasonal Performance Factor

This section provides the SPF analysis. This analysis takes the average SPF across the various heat pump types, operational patterns, home types and participant groups to conclude the average performance, the performance variation and potential reasons for this variation.

8.1 SPF by Heat Pump Type

Table 8.1 provides a breakdown of the median and mean SPF values for all ASHPs and heat pumps within hybrid systems separately. It is necessary to separate these systems out as Hybrid systems have different operating patterns compared with ASHP systems. This is due to the inclusion of a gas boiler in the former. These results are also presented in graphical format within Figure 8.1.

Table 8.1: Median and mean SPF values for all ASHPs and all heat pumps in Hybrid systems. (Note Hybrid SPF_{H3} excluded as it is equal to SPF_{H2})

Heat Pump Type	SPF Type	Sample Size	Median [IQR]	Mean [95% CI]
ASHP	SPF_{H2}	291	2.94 [2.66, 3.20]	2.95 [2.90, 3.00]
	SPF_{H3}	291	2.89 [2.62, 3.17]	2.90 [2.85, 2.95]
	SPF_{H4}	291	2.80 [2.53, 3.09]	2.82 [2.77, 2.87]
(Heat Pumps within) **Hybrid systems**	SPF_{H2}	58	2.54 [2.25, 2.93]	2.60 [2.47, 2.73]
	SPF_{H4}	58	2.37 [2.01, 2.81]	2.42 [2.28, 2.55]

Note that when calculating SPF values for the Hybrid systems, only the electrical components are considered (i.e. the boiler is excluded). The inclusion of the boiler in the calculation would reduce the overall system efficiency significantly, this is discussed further in Section 9.2.

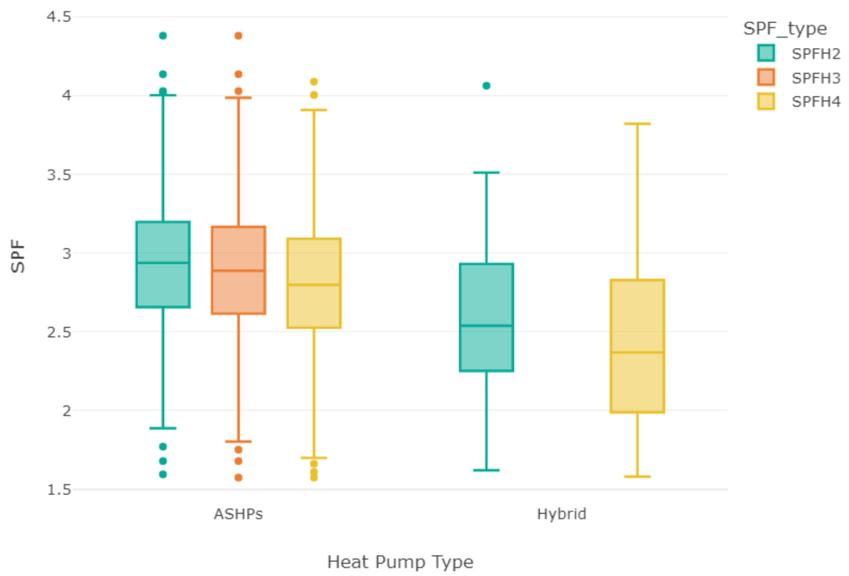

Figure 8.1: Q1, Q3 and median SPF values for ASHPs and heat pumps within hybrid systems.

Figure 8.2 shows the empirical distribution of the ASHP and heat pumps within hybrid systems. This figure shows the distribution to be significantly different between the two heat pump systems. Both SPF_{H2} and SPF_{H4} perform worse in Hybrids than ASHPs and the variance amongst Hybrids is also visibly higher.

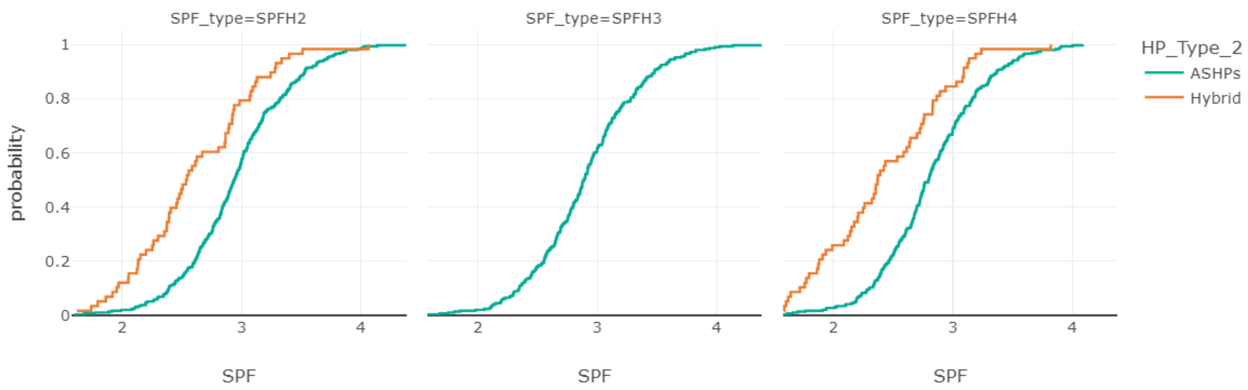

Figure 8.2: Empirical distribution of SPF for ASHPs and Hybrids, split by SPF type.

8.1.1 GSHP SPF analysis has not been undertaken at this stage as the current sample size of GSHPs containing 12-months of usable data has been deemed too small to make any conclusions. Comparison with Past Studies

The most recent taxpayer funded heat pump monitoring trial prior to the EoH project was the monitoring of 700 heat pumps installed as part of the Renewable Heat Premium Payment (RHPP) Scheme [25]. This monitoring programme included both ASHPs and GSHPs but did not include any Hybrid systems. As the EoH project does not have a sufficient data sample to draw any interim conclusions on GSHP operation, a comparison of results can only be made for ASHPs.

A comparison between the interim EoH SPF results and the RHPP SPF results is provided in Table 8.2. Note that no adjustment has been made for weather variations within the analysis windows when comparing the EoH and RHPP heat pump performance figures.

Table 8.2: A comparison of the interim EoH ASHP performance against the RHPP scheme results.

SPF Value	Interim EoH Sample	EoH Median SPF	EoH SPF [Q1, Q3], IQR	RHPP Sample	RHPP Median SPF	RHPP SPF [Q1, Q3], IQR
SPF_{H2}	291	2.94	[2.66, 3.20], 0.54	292	2.65	[2.33, 2.95], 0.62
SPF_{H4}	291	2.80	[2.53, 3.09], 0.56	292	2.44	[2.15, 2.67], 0.52

It is clear reviewing the table that the median SPF for heat pump installations has improved significantly since the RHPP findings were released in 2017. The median SPF_{H2} from EoH is 0.29 higher than that calculated through the RHPP trial and the median SPF_{H4} is 0.36 higher.

Despite the higher heat pump efficiency, the variance in SPF across installations remains similar to that observed through the RHPP scheme. The IQR for the both EoH and RHPP (SPF_{H2} and SPF_{H4}) lie between 0.52 and 0.62. This represents a large variation in performance – more than half of installations were at least 10% higher or lower than the median.

This high degree of variation in performance may be due to a number of factors. Some of these may include variation in heat pump unit efficiencies, variation in system design efficiencies, variation in quality of installation and variation in consumer control or usage patterns.

8.1.2 Comparison of Low and High Temperature ASHP

It is necessary to consider the difference between performance of the HT and LT ASHPs based on the pre-project definitions. The pre-project definition of a HT ASHP is an ASHP which can achieve flow temperatures greater than 65°C.

It should be noted that just because the heat pump can achieve these temperatures, it does not mean that temperatures greater than 65°C are required to keep the property warm. In addition, even where temperatures greater than 65°C may be required to keep the property warm, the ASHPs inherent weather compensation controls may mean that the heat pump rarely operates at these higher flow temperatures.

As such, there may be HT ASHPs installed through the project which are operating in a similar manner and with similar flow temperatures to LT ASHPs. Despite this observation, the breakdown of SPF by LT ASHP and HT ASHP is provided in Table 8.3 below. These results are also presented as an empirical distribution within Figure 8.3.

Table 8.3: Median and mean SPF values broken down for LT ASHPs and HT ASHPs based on pre-project definitions.

Heat Pump Type	SPF Type	Sample Size	Median [IQR]	Mean [95% CI]
LT ASHP	SPF_{H2}	187	2.94 [2.63, 3.26]	2.94 [2.88, 3.01]
	SPF_{H3}	187	2.86 [2.56, 3.19]	2.87 [2.81, 2.94]
	SPF_{H4}	187	2.74 [2.47, 3.09]	2.77 [2.71, 2.84]
HT ASHP	SPF_{H2}	104	2.94 [2.71, 3.15]	2.96 [2.88, 3.04]
	SPF_{H3}	104	2.94 [2.67, 3.15]	2.95 [2.87, 3.03]
	SPF_{H4}	104	2.89 [2.66, 3.07]	2.89 [2.82, 2.97]

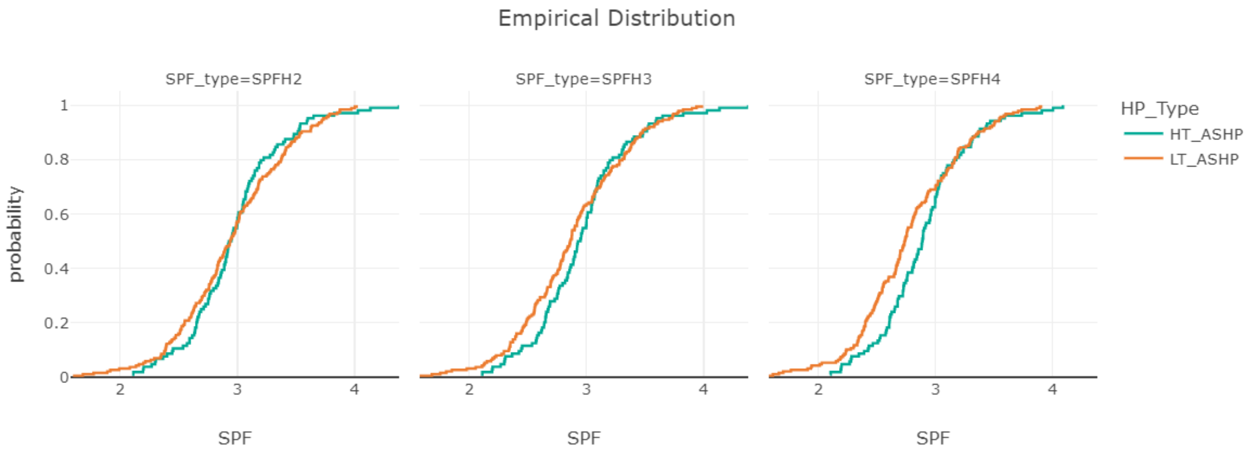

Figure 8.3: Empirical distribution of SPF for all HT and LT ASHPs, split by SPF type.

Reviewing these results, the HT ASHP units are observed to be performing with a similar SPF_{H2} to the LT ASHP units. As the calculation boundary increases for the SPF_{H3} and SPF_{H4} calculations, the HT ASHP systems are observed to be operating slightly more efficiently than the LT ASHP systems.

It should be noted that the sample of heat pumps installed as part of this trial may not be indicative of all heat pumps on the market, and therefore it should not be concluded that HT ASHP systems have a greater or equal efficiency compared with LT ASHP systems. Rather, other factors such as actual heat pump operational temperatures, mechanical design and the refrigerant used can have a bigger impact on real world heat pump performance than the maximum temperature that a heat pump is capable of.

8.2 SPF by Refrigerant

Heat pumps contain a fluid, known as a refrigerant, that facilitates the transfer of heat from the heat source to the heat sink as it circulates through the heat pump. In selecting a refrigerant, manufacturers need to make trade-offs between a range of factors, including performance at different temperatures, global warming potential (GWP), cost and safety.

Due to the Fluorinated Greenhouse Gas (F-Gas) Regulations 2015 [26], manufacturers are moving away from traditional refrigerants to those with a lower GWP. Meanwhile, manufacturers are also striving to ensure the performance of the heat pumps is improving, so there is often a correlation between the use of newer refrigerants and higher heat pump performance.

The ASHPs installed through this project utilised three refrigerants, these are listed in Table 8.4 alongside their GWP and the sample of ASHPs used in the analysis.

Table 8.4: The refrigerants used in heat pumps installed through this study.

Refrigerant	GWP	Analysis Sample Size
R410a	2,088	111
R290	3	98
R32	675	82

Figure 8.4 provides an indication of the median SPF_{H4} for all ASHPs broken down by refrigerant type as well as an indication of the results variance and IQR. Table 8.5 provides the median and mean SPF_{H4} values for each refrigerant type.

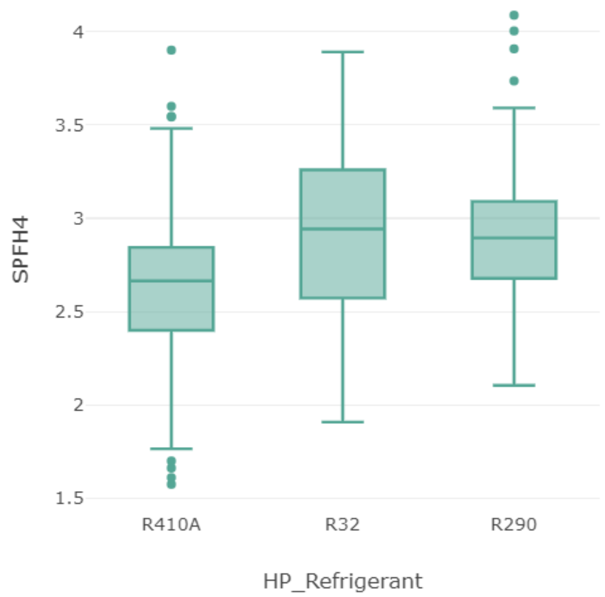

Figure 8.4: Q1, Q3 and median SPF_{H4} for all ASHPs broken down by refrigerant type.

Table 8.5: Mean and median SPF_{H4} broken down by refrigerant type.

Refrigerant	Median [IQR] SPF_{H4}	Mean [95% CI] SPF_{H4}
R290	2.89 [2.68, 3.08]	2.92 [2.84, 2.99]
R32	2.94 [2.57, 3.25]	2.93 [2.83, 3.03]
R410a	2.66 [2.40, 2.84]	2.64 [2.56, 2.72]

Considering no other factors, these results suggest that differing refrigerants by heat pump type contributes to the differences in heat pump efficiency. However, other factors such as the efficiency of mechanical equipment and control strategy may also impact the SPF observed. As noted above, as the manufacturers move towards newer refrigerants, they also strive to improve unit efficiency; it is difficult in a field trial to assess one of the potential factors affecting system efficiency independently of the others.

Reviewing Figure 8.4, it is also clear that the variance in the results for R290 is significantly lower than those for R32 and R410a. Table 8.6 below provides the number of each ASHP type which utilises each refrigerant type. It is evident that the HT ASHPs installed through this project mainly utilise R290 whilst the LT ASHPs mainly utilise R410a and R32.

Table 8.6: Mean and median SPF_{H4} broken down by heat pump type and refrigerant type.

Heat Pump Type	Refrigerant	Sample Size	Median [IQR] SPF_{H4}	Mean [95% CI] SPF_{H4}
HT ASHP	R290	98	2.89 [2.68, 3.08]	2.92 [2.84, 2.99]
	R32	6	2.50 [2.25, 2.58]	2.53 [2.08, 2.98]
LT ASHP	R32	76	3.00 [2.66, 3.27]	2.96 [2.86, 3.06]
	R410a	111	2.66 [2.40, 2.84]	2.64 [2.56, 2.72]

As so many of the HT ASHPs utilise what is observed as a more efficient refrigerant, the superior performance of the HT ASHPs compared with the LT ASHPs may be partially attributable to the choice of refrigerant (as well as other performance factors noted within this section).

It is notable that the difference between the R32 HT and LT ASHP SPF results is significant. However, the R32 HT ASHP sample is very small, so no conclusions should be drawn from this insight at this stage in the project.

Figure 8.6 in Section 8.3 shows the relationship between heat pump flow temperature and SPF_{H4} broken down by the different refrigerants. This shows that the efficiency of those heat pumps utilising the R410a refrigerant is significantly worse than the others.

8.3 SPF by Operating Flow Temperature

The operating flow temperature of a heat pump has a direct impact on the heat pump efficiency. For this reason, heat pumps have in-built weather compensation controls which adjust the flow temperature based on the external temperature[5] to maintain the appropriate thermal output from the emitters for the comfort of the occupants whilst ensuring optimal efficiencies. To assess the scale of the impact the operating flow temperature has on the heat pump efficiency, it is first necessary to quantify the average operating flow temperature.

The EoH heat pump monitoring systems (see Section 4.1) records a flow temperature reading every 2-minutes on average, regardless of whether the heat pump is operational. As such, there is a lot of noise within the flow temperature data which should be ignored if trying to calculate an average.

To calculate the average flow temperature for each property, only the flow temperature readings when the heat pump was operational were considered (i.e. when the Heat Pump Energy Output was increasing). Heat pumps take time to heat the water from its ambient condition to the desired flow temperature, as such, the flow temperatures calculated will be skewed slightly downward as the method chosen to calculate the average includes the heating up period. The mean flow temperature across all ASHPs and heat pumps in hybrid systems was 38.3°C.

Through this study, it has been observed that, as expected when considered in isolation, the heat pumps which operate with a higher mean flow temperature generally have a lower SPF. Figure 8.5 shows this relationship for all ASHPs. This graph indicates a lot of variation (or scatter) in the results however, the relationship is statistically significant.

[5] When external temperature is higher, a lower flow temperature is required to overcome the building heat loss given the size of the heat emitters present within the property.

Figure 8.6 further breaks down the scatter graph to show each refrigerant and heat pump type. The scatter is much broader for the heat pumps utilising the R410a refrigerant, with many of the lower performing heat pumps being within this category.

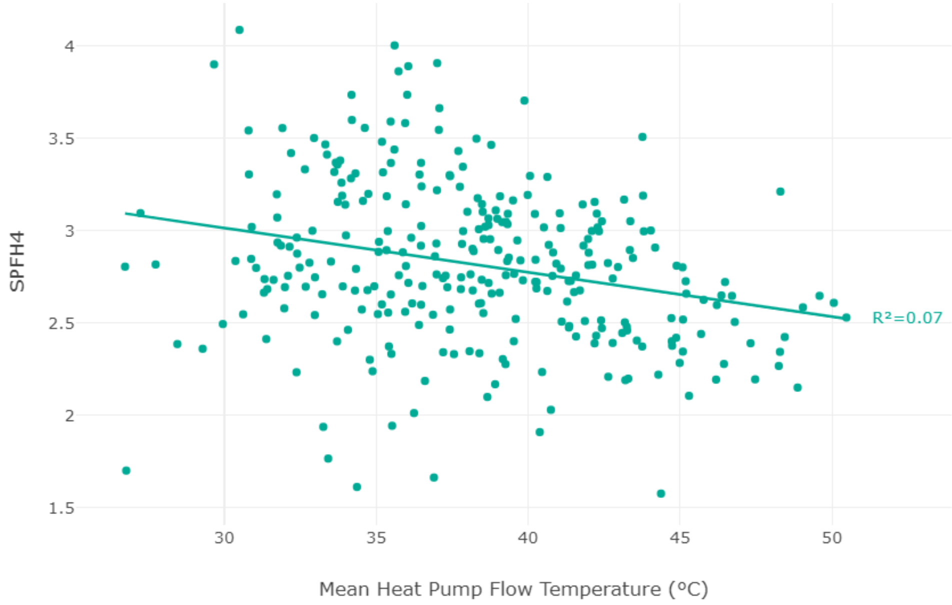

Figure 8.5: SPF_{H4} by mean heat pump flow temperature for all ASHPs. Note that flow temperatures when the heat pump was not outputting heat have been excluded from the mean.

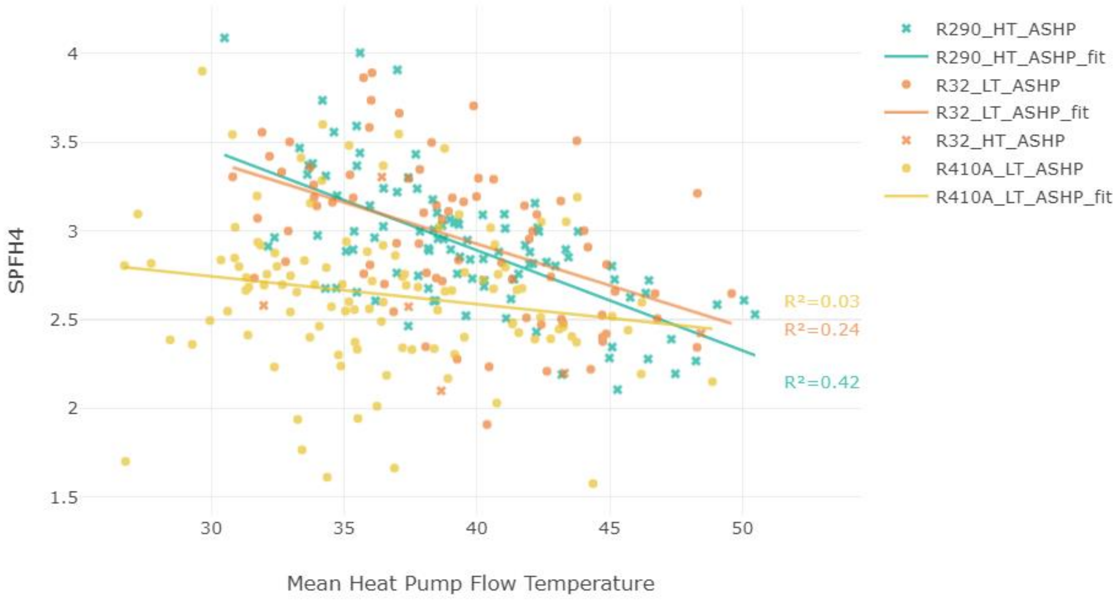

Figure 8.6: Scatter chart of mean heat pump flow temperature (˚C) and SPF_{H4} by refrigerant and heat pump type. A line was not included for HT ASHPs with the R32 refrigerant as there are presently only 6 heat pumps in this category.

The relationship between flow temperature and SPF_{H4} is more simply shown within Figure 8.7. This histogram shows the number of heat pumps which fall within each temperature range (25 to 35°C; 35 to 45°C and 45 to 55°C) and the average SPF_{H4} across all of the heat pumps in these ranges.

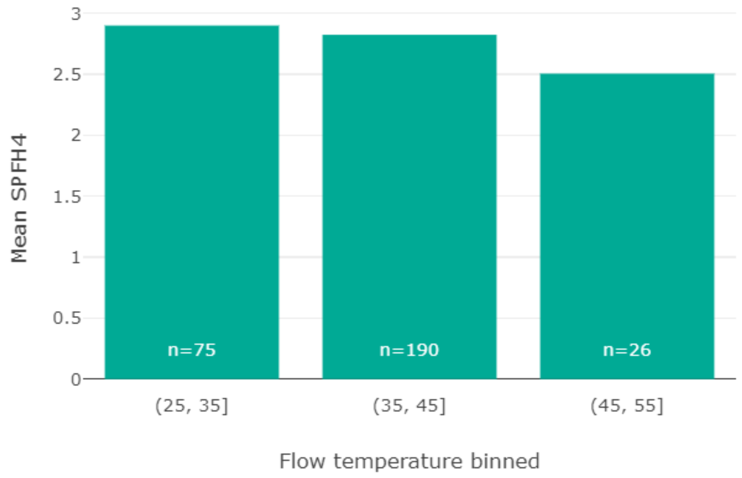

Figure 8.7: Histogram showing the mean SPF_{H4} by binned mean flow temperature (℃).

It was noted in Section 8.1.2 that, based on pre-project definitions, HT ASHPs have been observed to operate at a similar efficiency to LT ASHPs through this study. To assess reasons why this may be the case, more analysis has been undertaken. Section 8.2 indicates that the most of the HT ASHPs are more efficient units and that this may be a result of the refrigerant used within those units. This section assesses how the HT ASHPs operating temperatures compare to the LT ASHPs.

Figure 8.8 shows that whilst HT ASHPs are less likely to have a very low mean flow temperature, there is a significant overlap in typical operating temperatures for HT ASHPs and LT ASHPs.

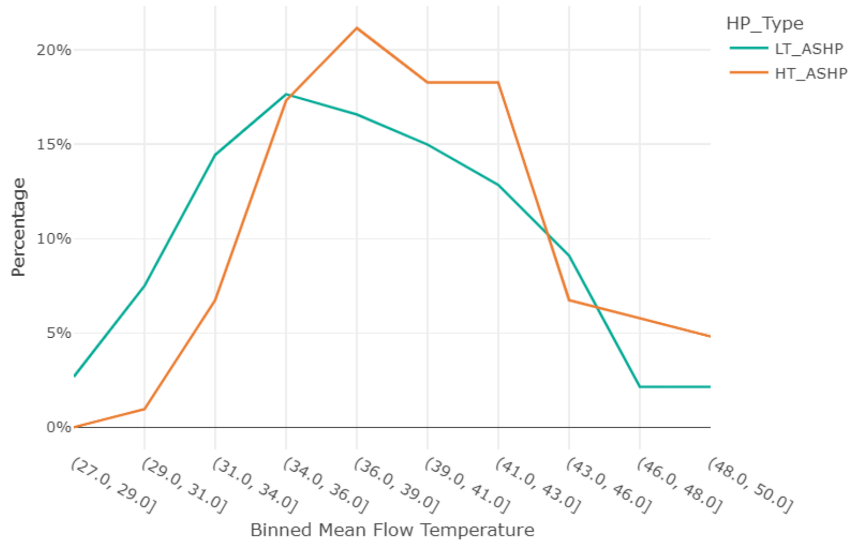

Figure 8.8: Frequency distribution of mean flow temperature by heat pump type.

Where HT operation is defined as a heat pump which operates above 65°C at any point over the 12-month period; Table 8.7 indicates that only 96 of the 106 HT heat pumps actually operates at a high temperature.

Table 8.7: ASHP SPF values broken down by HT operation and LT operation. [6]

Heat Pump Type	SPF Type	Count	Median [IQR]	Mean [95% CI]
LT Operation (ASHP)	SPF_{H2}	197	2.94 [2.64, 3.25]	2.95 [2.88, 3.01]
	SPF_{H4}	197	2.74 [2.48, 3.07]	2.77 [2.71, 2.84]
HT Operation (ASHP)	SPF_{H2}	94	2.92 [2.69, 3.15]	2.96 [2.88, 3.05]
	SPF_{H4}	94	2.89 [2.66, 3.09]	2.90 [2.82, 2.98]

The table does however still indicate the trend that the LT and HT ASHPs (by operation) have similar SPF, and that the SPF_{H4} of the HT ASHPs is higher than LT ASHPs. As such, it is necessary to assess how common the HT Operation ASHPs actually reach high temperatures.

Figure 8.9 shows that operating above 65°C is not a common occurrence, with 81 of the 94 heat pumps operating above 65°C flow temperature less than 1% of the time.

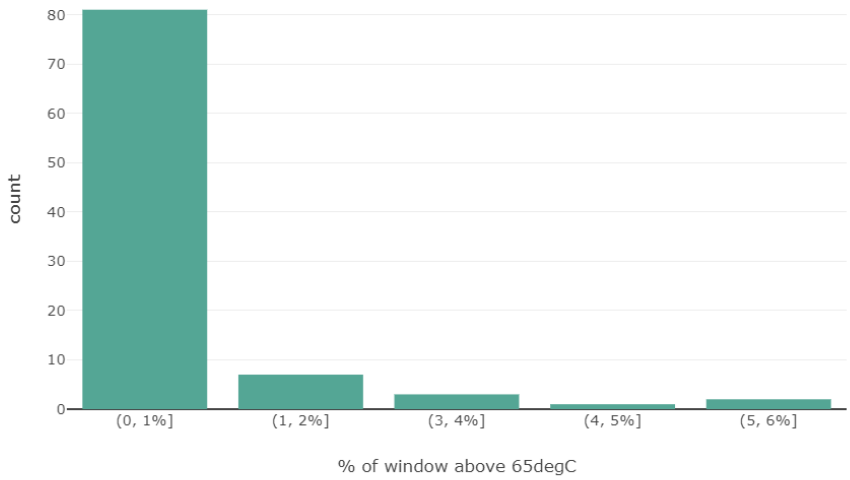

Figure 8.9: Percentage of heat pump operation above 65°C in the heat pumps observed to operate at high flow temperatures.

This indicates that the weather compensation controls are only demanding higher flow temperatures a very small amount of the time to maintain good heat pump efficiencies. It may therefore be concluded that, most of the time, the HT ASHPs are operating at similar flow temperatures to the LT ASHPs. This provides an additional explanation for their similar performance.

8.4 SPF by Property Type

As noted in Section 3, the EoH project successfully installed heat pumps in a variety of different home types and ages. All of these homes were deemed suitable for a heat pump installation by trained designers and installers, so the results of the following analysis may not be representative of the whole UK housing stock. Nonetheless, this analysis provides valuable insight into the performance of heat pumps in homes which are recommended for an installation by trained designers and installers.

[6] Note that 14 ASHPs have been excluded from the flow temperature related analysis compared with the SPF only analysis as they had insufficient temperature data quality.

A breakdown of SPF by home type is provided in Table 8.8 below.

Table 8.8: Median and mean SPF values broken down for house form.

Home Type	Sample Size	Median [IQR] SPF_{H4}	Mean [95% CI] SPF_{H4}
Detached	137	2.88 [2.58, 3.18]	2.90 [2.83, 2.98]
Semi-Detached	89	2.73 [2.48, 2.93]	2.72 [2.63, 2.81]
End-Terrace	28	2.76 [2.50, 3.03]	2.74 [2.58, 2.90]
Mid-Terrace	31	2.69 [2.48, 3.02]	2.77 [2.62, 2.92]
Flat	6	2.63 [2.49, 3.29]	2.84 [2.08, 3.61]

In both the tabulated results and those shown in Figure 8.10 detached homes are observed to have a higher SPF compared to semi-detached homes. The reasons for this are assessed at the end of this section.

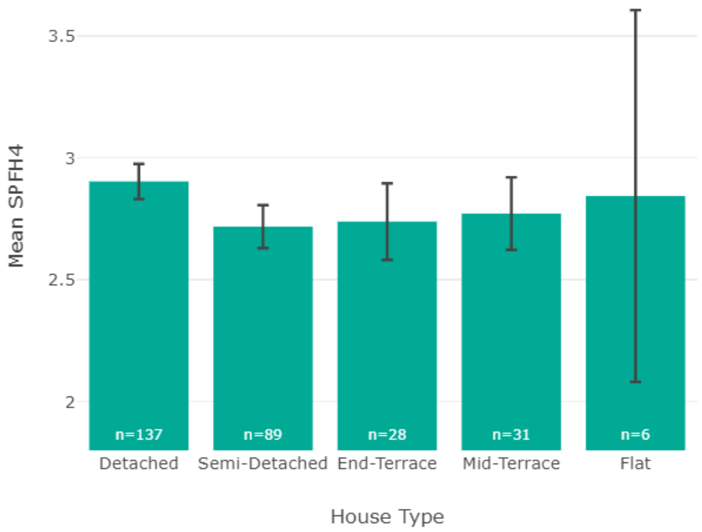

Figure 8.10: Mean SPF_{H4} of all ASHPs by house type with 95% CI. (Excluding Hybrids).

Figure 8.11 indicates the mean heat energy output per day for all ASHPs and Hybrids split by home type. This shows that detached homes demand the most energy as expected however, it also shows that flats have demanded more energy than mid-terrace properties. As shown in the above figure, the sample size for flats is 6. This small sample size is likely the reason for the unexpected result.

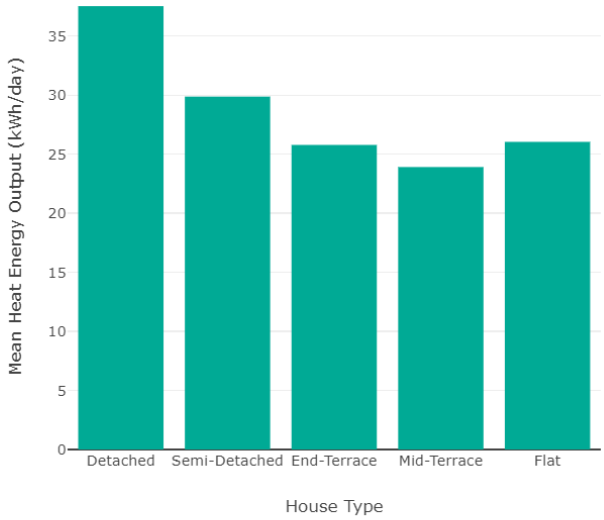

Figure 8.11: Mean heat energy output per day for each property form (including all ASHPs and Hybrids).

Figure 8.12 shows the distribution of LT and HT ASHPs by house type. This figure indicates that detached homes had the greatest proportion of HT ASHPs installed however, the proportional variation is within minimal across all other house types.

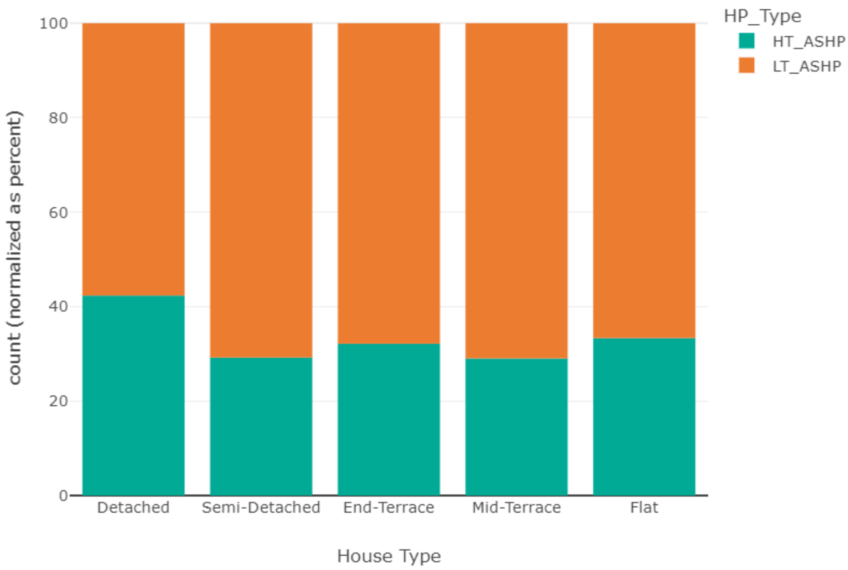

Figure 8.12: Split of ASHP type by house type.

To further assess the potential reason for the detached homes exhibiting a higher SPF than the others, the breakdown of heat pump refrigerant type per house type can be analysed. Figure 8.13 shows the distribution of refrigerant by house type. The figure shows that detached homes have the lowest proportion of heat pumps which use R410a. This, combined with the results presented in Section 8.2, provides a good reason for why the detached homes are observed to have a higher SPF than other home types.

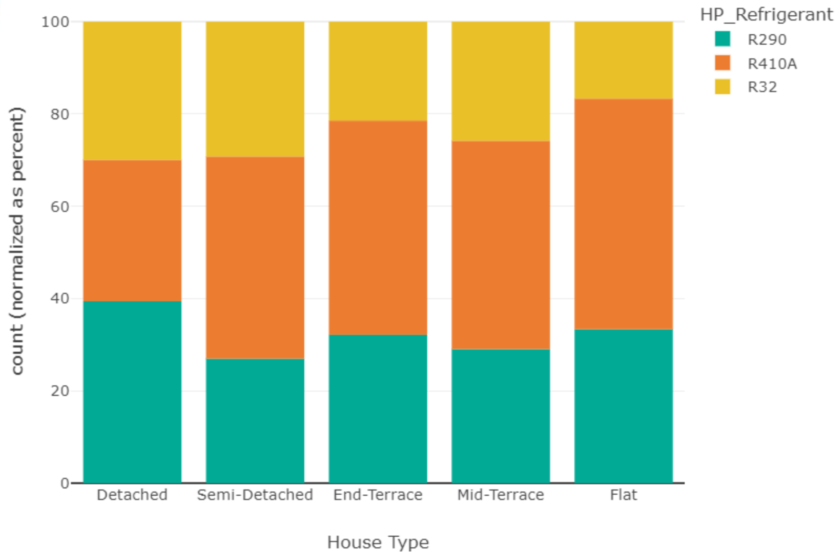

Figure 8.13: Breakdown of refrigerant type by house type.

Table 8.9 and Figure 8.14 show the breakdown of SPF_{H4} by house age. These results indicate that, where a trained heat pump designer or installer has deemed a home to be suitable for a heat pump installation there is no significant variation in performance based on house age. This result should not be assumed to be indicative of the whole UK housing stock.

Table 8.9: Median and mean SPF values broken down by house age.

House Age	Sample Size	Median [IQR] SPF_{H4}	Mean [95% CI] SPF_{H4}
Pre-1919	22	2.94 [2.66, 3.26]	2.90 [2.65, 3.14]
1919-1944	38	2.77 [2.50, 3.11]	2.81 [2.68, 2.94]
1945-1964	74	2.76 [2.47, 3.08]	2.77 [2.66, 2.88]
1965-1980	64	2.75 [2.55, 3.03]	2.79 [2.70, 2.89]
1981-1990	31	2.77 [2.61, 2.95]	2.81 [2.68, 2.94]
1991-2000	24	2.83 [2.50, 3.05]	2.80 [2.63, 2.97]
2001+	38	2.89 [2.56, 3.16]	2.91 [2.78, 3.05]

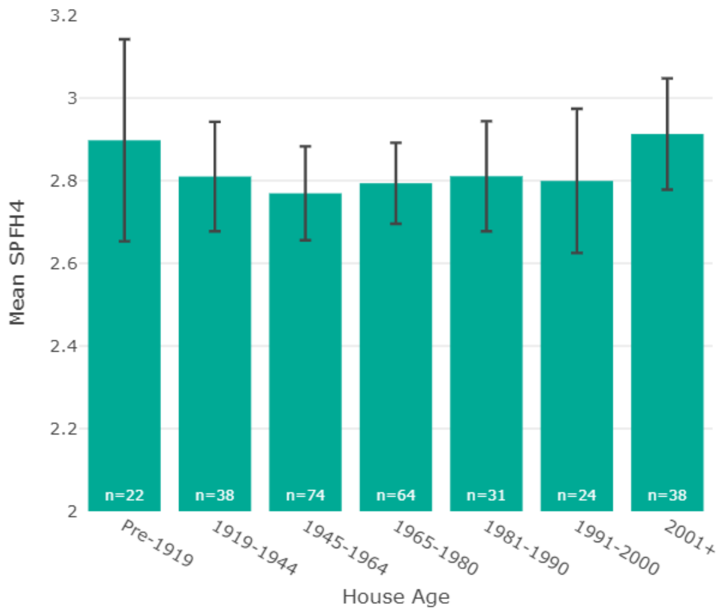

Figure 8.14: Mean ASHP SPF_{H4} by house age with 95% CI. (Excluding Hybrids)

9. Hybrid Heat Pump System Operation

9.1 Heat Pump to Boiler Operating Ratio

When assessing hybrid heat pump operation using the data from this project, it is necessary to reiterate that the domestic hot water provision is not metered and that any proportions of heat pump to gas boiler operation are those for space heating only. In addition, there were two types of hybrid systems installed through this project:

- ”Integrated” systems, which consist of a single unit containing a heat pump and a boiler.
- ”Separate” systems, which consist of a separate heat pump and boiler. The split system heat pumps installed through this project were all external ASHPs and the boilers were all sized to be capable of the full heating load.

The majority of the Hybrids installed include a separate heat pump and boilerhowever, some have an integrated heat pump and boiler in one unit. For this analysis, they have all been included under the banner of Hybrid. However, when the sample size becomes larger towards the end of the project, more granular analysis may be conducted.

The Hybrid systems installed through this project were installed to operate cost-optimally, with the heat pump undertaking the base space heating load and the boiler operating to cover the peaks. The point at which the boiler takes over the space heating is different for each home and generally correlates with a certain external temperature.

Noting the above, the heat pump energy output as a percentage of total space heating output (from the heat pump and gas boiler combined) in Hybrid systems (over the course of the 12-month SPF calculation window) is presented in Table 9.1 and Figure 9.1.

Table 9.1: The median and mean heat pump energy output as a percentage total space heating output in hybrid systems.

Sample Size	Mean	Median (50%)	Q1 (25%)	Q3 (75%)
53	41.7%	38.6%	31.4%	49.6%

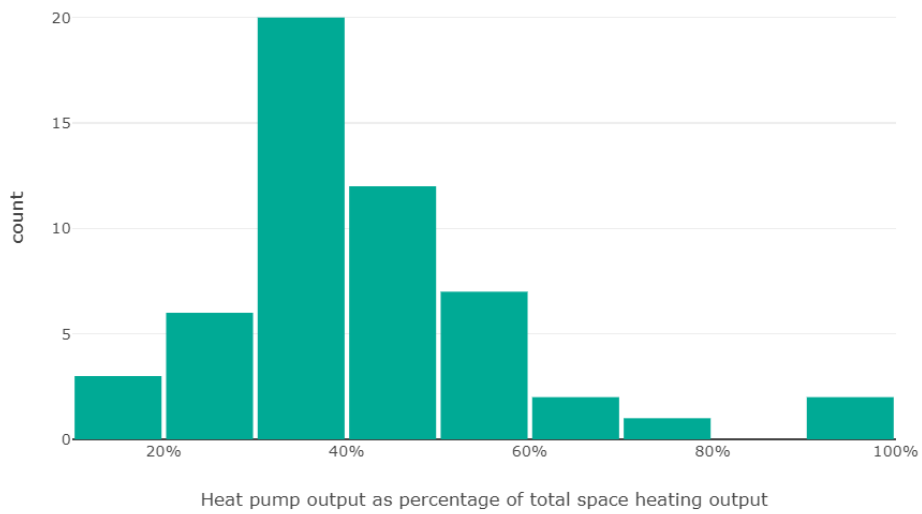

Figure 9.1: Frequency distribution of heat pump energy output as a percentage of total energy output in Hybrid systems.

When analysing these results, it should be noted that in spring 2022, a large proportion of the Hybrid systems installed through the EoH project had their controls optimised during a heat pump service visit. This optimisation may affect the energy output proportions and a reassessment of these proportions will be reported following the completion of the monitoring period.

9.2 Whole System Efficiency

Section 8.1 indicates the average SPF observed through this project for heat pumps within a hybrid systems. For ease, this result is shown in Table 9.2 below. This result does not present a full picture of system efficiency as it does not account for boiler performance.

Table 9.2: The average SPF for heat pumps within hybrid systems.

SPF	Sample	Median [IQR]	Mean [95% CI]
SPF_{H2}	58	2.54 [2.25, 2.93]	2.60 [2.47, 2.73]
SPF_{H4}	58	2.37 [2.01, 2.81]	2.42 [2.28, 2.55]

The hybrid system efficiency may be calculated as shown within the below equation:

$$System\ Efficiency\ (COP_{Hybrid}) = \frac{Total\ raw\ energy\ in}{Total\ heat\ energy\ out}$$

Where the total raw energy in includes both electricity and gas and total heat energy is that from the boiler and heat pump. Using the project data alone, the System Efficiency cannot be calculated, this is because the hybrid monitoring system does not monitor hot water production, nor does it monitor the gas consumed by the boiler. As a result of these two features, to calculate System Efficiency, the amount of hot water produced and the boiler efficiency would need to be assumed.

Using the space heating proportion and SPF_{H4} results from this project, Table 9.3 provides a matrix of estimated whole system efficiencies (COP_{Hybrid}) for hybrid systems based on assumed proportion of hot water production (compared to space heating) and gas boiler efficiencies.

Where:

- $\propto_{HP}$ = The proportion of heat pump operation for space heating only;
- SPF_{H4} = The annual system efficiency including all electrical components;
- $\propto_{GB}$ = The proportion of gas boiler operation for space heating only;
- η_{GB} = Boiler efficiency;
- COP_{SH} = System Effiency for space heating only;
- $\propto_{HW}$ = The proportion of heat produced for hot water provision;
- COP_{Hybrid} = Whole hybrid system performance.

$$COP_{SH} = (\propto_{HP} \times SPF_{H4}) + (\propto_{GB} \times \eta_{GB})$$

$$COP_{Hybrid} = \left((1 - \propto_{HW}) \times COP_{SH}\right) + (\propto_{HW} \times \eta_{GB})$$

Table 9.3: Hybrid system efficiency matrix with assumed boiler efficiency across the top, hot water production percentage down the left and therefore estimated hybrid system efficiency (COP_{Hybrid}) in the middle (blue cells).

COP_{Hybrid}		Boiler Efficiency (%)								
		76%	**78%**	**80%**	**82%**	**84%**	**86%**	**88%**	**90%**	**92%**
Hot Water	**10%**	138%	139%	140%	142%	143%	144%	146%	147%	148%
	12%	136%	138%	139%	140%	142%	143%	144%	146%	147%
	14%	135%	136%	138%	139%	140%	142%	143%	144%	146%
	16%	134%	135%	136%	138%	139%	140%	142%	143%	145%
	18%	132%	134%	135%	136%	138%	139%	141%	142%	143%
	20%	131%	132%	134%	135%	136%	138%	139%	141%	142%

9.3 SPF by Operating Ratio

The data indicates a statistically significant relationship between proportion of heat pump use (for space heating provision) in Hybrid systems and SPF_{H4}, with systems that have a higher heat pump usage tending towards higher SPFs. This relationship is shown in Figure 9.2.

This result indicates that operating a heat pump intermittently is less efficient. It should be noted that whilst a linear relationship has been assumed in Figure 9.2, the actual relationship is likely non-linear, particularly for higher heat pump output proportions where the SPF_{H4} is likely to converge with that of a typical ASHP at 100% output proportion.

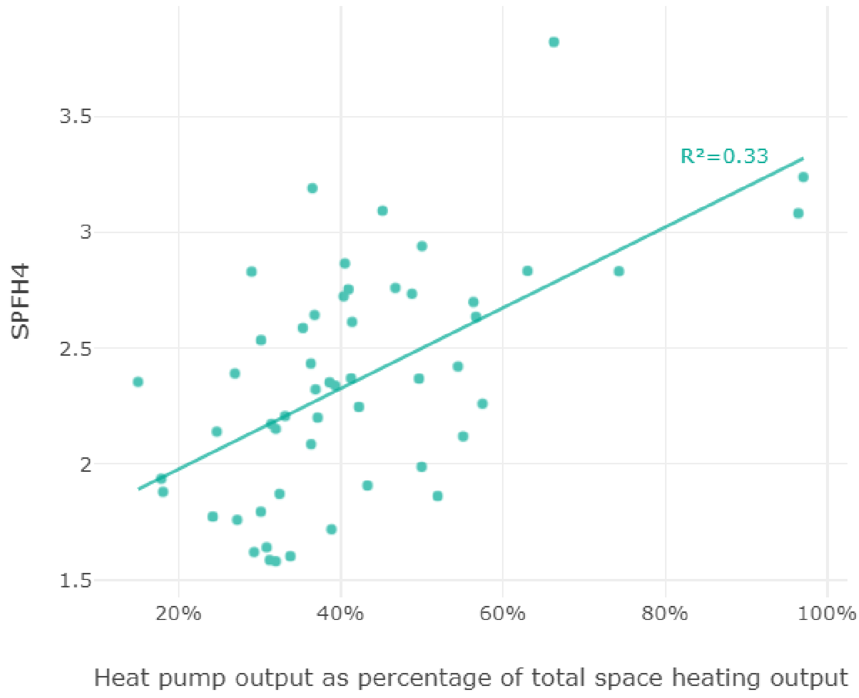

Figure 9.2: SPF_{H4} by heat pump output percentage in hybrid systems.

It should also be noted that as a result of the hybrid systems cost-optimal control strategy, the less efficient homes will likely experience a higher boiler percentage operation. This is because, the setpoint at which the boiler takes over the space heating load is likely lower for these homes. The SPF result therefore may be slightly skewed as the hybrid systems shown to use the heat pump less may be installed in less efficient homes with greater heat losses.

10. Cold Snap Analysis

10.1 Window Selection

To analyse heat pump performance during colder periods, it is first necessary to isolate the coldest periods of the year. The method of highlighting these periods is discussed within Section 6.4.2. The 10 most common coldest days across the range of homes is presented in Table 10.1 (selected based on mean external temperature).

Table 10.1: The 10 most common coldest days, including the mean external temperature across the analysis window.

Coldest day (YYYY-MM-DD)	Coldest day count	Mean external temp. (day)
2021-11-28	190	0.4°C
2022-01-04	113	-1.0°C
2021-12-22	44	0.5°C
2021-02-11	41	-5.8°C
2021-11-29	26	1.0°C
2022-01-18	11	0.2°C
2022-03-31	10	2.0°C
2021-12-18	8	-0.7°C
2022-01-07	6	0.9°C
2022-01-14	5	0.3°C

The distribution of mean external temperature on the coldest days is provided in Figure 10.1.

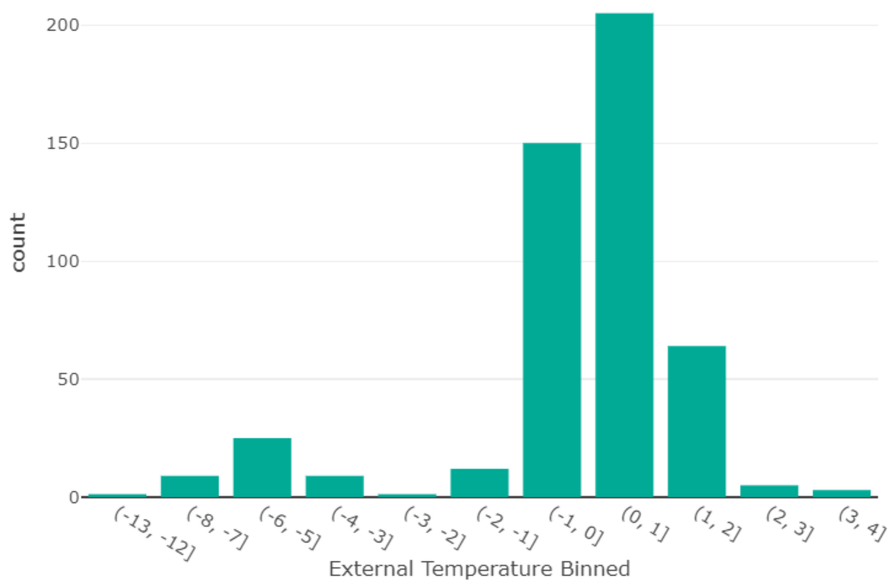

Figure 10.1: Distribution of mean external temperature in the coldest day analysis window.

10.2 Coldest Day Efficiency

The $COP_{(H4)}$ was calculated for each of the coldest day analysis windows to assess the heat pump performance over these cold periods. The median and mean COP across all of the ASHPs is given in Table 10.2. Figure 10.2 indicates the $COP_{(H4)}$ variation against the mean difference between internal and external temperatures on the coldest day.

Table 10.2: Median and mean COPs for the coldest day across all ASHPs.

Sample Size	Median [IQR] $COP_{(H4)}$	Mean [95% CI] $COP_{(H4)}$	Mean external temp.
484	2.44 [2.20, 2.70]	2.44 [2.40, 2.48]	-0.4

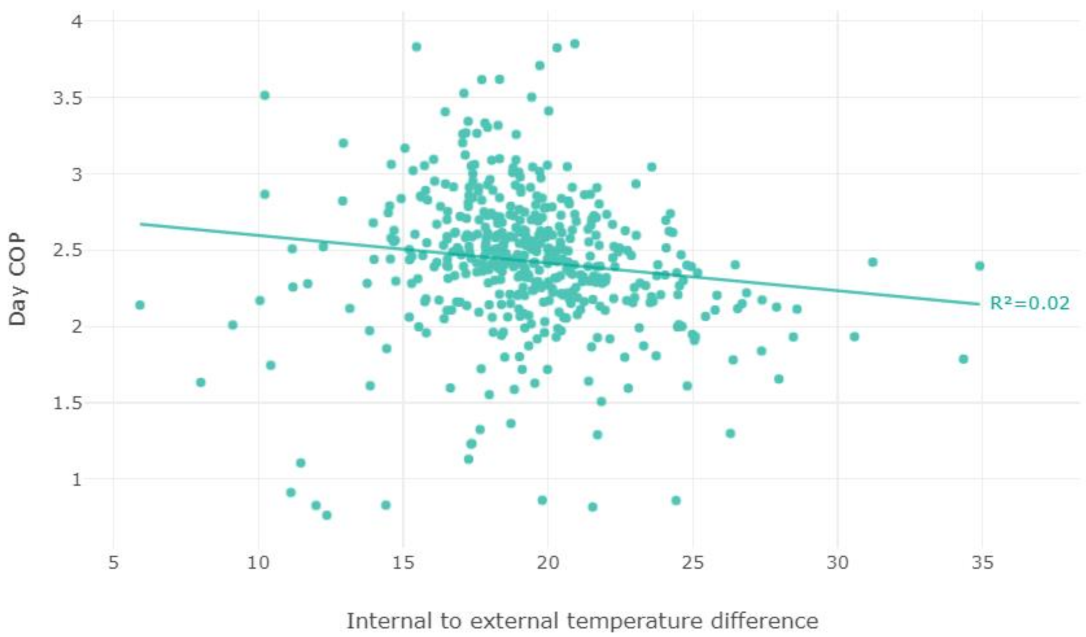

Figure 10.2: Scatter graph indicating the $COP_{(H4)}$ against the variation in internal and external temperature.

Reviewing this figure, there is a significant variation in the $COP_{(H4)}$ values, especially where there is a mean temperature difference of 15 to 20°C. Some of the reasons for this variation are likely similar to the reasons for variation in SPF however, when analysing a shorter time period, additional reasons for results variation become apparent.

These may include the pre-conditioning of the homes going into the analysis window and any factors affecting the properties heat gains and losses during the day. Despite these variations, it is evident that the trend in the results is expectedly such that as the difference in temperatures increases, the $COP_{(H4)}$ decreases.

11. Conclusions

The Electrification of Heat Demonstration Project has found that Air Source Heat Pump (ASHP) Seasonal Performance Factors (SPFs) have improved by ~0.3 to 0.4 compared with installations completed under the Renewable Heat Premium Payment Scheme. The median SPFs for ASHPs installed through the EoH scheme are provided in Table 11.1. The analysis clearly indicates that some of this improvement is related to efficiency improvements in the heat pump units as, the heat pumps using the R290 and R32 refrigerants generally have performed better than those using the older R410a refrigerant.

Table 11.1: Median ASHP SPFs.

SPF Type	Sample Size	Median [IQR]
SPF_{H2}	291	2.94 [2.66, 3.20]
SPF_{H3}	291	2.89 [2.62, 3.17]
SPF_{H4}	291	2.80 [2.53, 3.09]

This result may also suggest that the design (and installation) of heat pump systems has improved over the last seven years. However, the EoH project has also found that variation in performance between heat pump installations remains high. Some of the reasons for this variation are relating to the efficiency of heat pump units as noted above but, generally this variation is difficult to explain. This suggests that progress is still required on improving the quality and consistency of heat pump designs and installations to support a large-scale rollout of heat pumps in existing homes and deliver positive energy, carbon, and consumer outcomes. These findings should be factored into modelling and policy decisions.

High temperature ASHPs did not perform worse than low temperature ASHPs. This is likely in part due to the fact that they spend much of their time actually operating at similar temperatures, but may also be due to the use of a higher performing refrigerant in the models installed in this trial. Irrespective of the underlying cause, HT ASHPs should not be assumed to perform worse by default in modelling and purchasing decisions.

Heat pumps in hybrid systems were typically used to meet 32-50% of the space heating demand (median 39%). They had a median SPF_{H2} of 2.54 which is lower than ASHPs. Heat pumps in hybrid systems were also found to be less efficient the smaller the proportion of heating demand they met. These units were commissioned to run cost-optimally, so part of the reason for the lower performance with lower operating proportion may be because these units were installed in less efficient homes.

The median ASHP Coefficient of Performance ($COP_{(H4)}$) fell to 2.44 (mean) on the coldest day (-0.4°C) which quantifies the expected degradation in performance due to low temperature and could help to inform modelling of peak winter demand. These results may be impacted by pre-conditioning of the home or exceptional heat gains during the period tested.

This analysis will be refreshed, and additional analysis (including that on Ground Source Heat Pump performance) will be undertaken after the completion of the projects monitoring period in September 2023.

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