Department for Energy Security & Net Zero

Electrification of Heat Demonstration Project

Heat Pump Performance Data Analysis Report

Written by Energy Systems Catapult

DECEMBER 2024

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 (Air to water heat pump)
BEIS	Department for Business, Energy and Industrial Strategy
(the) Catapult	Energy Systems Catapult Ltd.
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
FNC	Frazer Nash Consultancy
FT	Flow Temperature
GSHP	Ground Source Heat Pump (Ground to water 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
OLS	Ordinary Least Square regression model trend line
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 was funded by the Department for Energy Security and Net Zero (DESNZ – previously Department for Business, Energy and Industrial Strategy (BEIS)) and sought to better understand the feasibility of a large-scale rollout of heat pumps across the UK. The main aim of the project was to demonstrate that heat pumps could be installed in a wide variety of homes and deliver high customer satisfaction across a range of customer groups.

The project team consisted of a Management Contractor (MC) consortium (including LCP Delta[1] 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 maintained the heat pump monitoring systems to ensure continuous performance data was collected. The MC was responsible for management of the project and collation of the data as well as associated analysis and dissemination of project findings.

The three DCs were: 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 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	32.8%	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	14.1%	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 included equipment which monitored the energy used and output by each component of the heat pump system and various system temperatures. The data collected by this equipment has been used to determine the performance of each heat pump throughout the project. Commentary on the mean and median performance across the heat pumps installed through the EoH programme is provided throughout this report.

[1] Formerly Delta-EE.

1.2 About this report

This report provides analysis of the heat pump performance data collected by the monitoring systems. It should be noted that this analysis is formed from a set of requirements which was prioritised by DESNZ and the project team. The project datasets provide the potential for much more analysis and as such are available open-source on the UK Data Archive [1] [2] [3] [4]. The analysis code used to conduct this analysis is also available open-source on Github [5].

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:

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

This report is intended to provide description of the whole data analytics process. For an overview of the results and insights, please refer to the Heat Pump Performance Insights Report. [6]

1.3 Data Cleansing, Quality Checks, and Analysis

To ensure the data was of sufficient standard to form analysis conclusions, a cleansing and quality checking process 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 two 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.
- Removal of long periods of constant temperature.
- 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 which was used was of sufficient standard to be included within the analysis. These quality checks scored each data quality "issue" (e.g. gaps in the data) 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 (SPF) (outside of the range of 1.25 to 5.5) or if less than 70% of the expected heat pump data was available.

Analysis was then conducted using the SPFs and Coefficients of Performance (COP) of the heat pumps.

SPFs are a measure of the heat pump's efficiency over one year. They are calculated by taking the ratio of the total heat supplied to the home to the electricity used by the heat pump and other devices of the heating system. The SPFs must be taken over a 1-year period and must be based upon pre-defined system boundaries (which include and exclude certain system components).

COPs are also a measure of the heat pumps efficiency based on the ratio of heat supplied to electricity consumed however, a COP can be taken over any time interval and any system boundary.

1.4 Key findings

1.4.1 Seasonal Performance Factor values

The median Seasonal Performance Factors (SPFs) observed in Air Source Heat Pumps (ASHPs) monitored throughout the EoH project have remained similar to those published at the interim project stage [7]. These results are consistent with the results from analysis of Ofgem data, conducted by RB&M, which were published at the same time as these EoH findings [8]. This marks a significant increase since RHPP (Renewable Heat Premium Payment scheme) [9] which published results in 2017. 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	EoH ASHP Sample	EoH Median ASHP SPF [IQR]	RHPP ASHP Sample	RHPP Median ASHP SPF [IQR]
SPF_{H2}	428	2.93 [2.67, 3.19]	292	2.65 [2.33, 2.95]
SPF_{H4}	428	2.78 [2.55, 3.05]	292	2.44 [2.15, 2.67]

The 25th and 75th percentile values (represented by the Inter-Quartile Ranges (IQRs) above) show that ASHP SPF_{H2} and SPF_{H4} have improved by between 0.24 to 0.4 compared with installations completed under the RHPP scheme. Note that when comparing the EoH figures against the RHPP figures, no adjustment has been made for weather variations within the analysis windows.

The improvements in heat pump performance are partially due to industry innovation and the heat pump units themselves becoming more efficient over the period between the two projects. This is demonstrated by the refrigerant based analysis in Section 1.4.2. The performance improvement may also be partially a result of improvements in the design (and installation) of heat pump-based heating systems. However, the EoH project has also found that (despite a much larger sample size) variation in performance between heat pumps remains high which indicates that some inconsistency in these factors may be retained (see Section 1.4.2).

As noted above, relative weather conditions may also account for some of the performance improvement however these conditions may also limit the improvements (if weather over the EoH windows was poorer for Heat Pump performance).

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	EoH Hybrid Sample	EoH Median SPF for Heat Pumps within Hybrid systems [IQR]
SPF_{H2}	94	2.68 [2.30, 3.03]
SPF_{H4}	94	2.50 [2.10, 2.84]

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 through this project. Section 9.2 provides an indication of the whole hybrid system efficiency with assumed average boiler efficiencies.

Note that as GSHPs were installed in a small number of properties (38) through the EoH project, the analysed sample was also small (23 properties). This sample contains both shared loop and individual GSHP installations (16 and 7 properties respectively), it is therefore not recommended that the GSHP results are used as a reference for median GSHP SPF. As a result of this, the EoH GSHP results are provided separately in the appendices to this report. The RB&M analysis of Ofgem heat pump data [8], published at the same time as this report, provides analysis on a sample of 286 GSHPs installed between 2017 and the end of 2022 and, as such, provides a more robust value which can be used as a reference for GSHP performance.

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

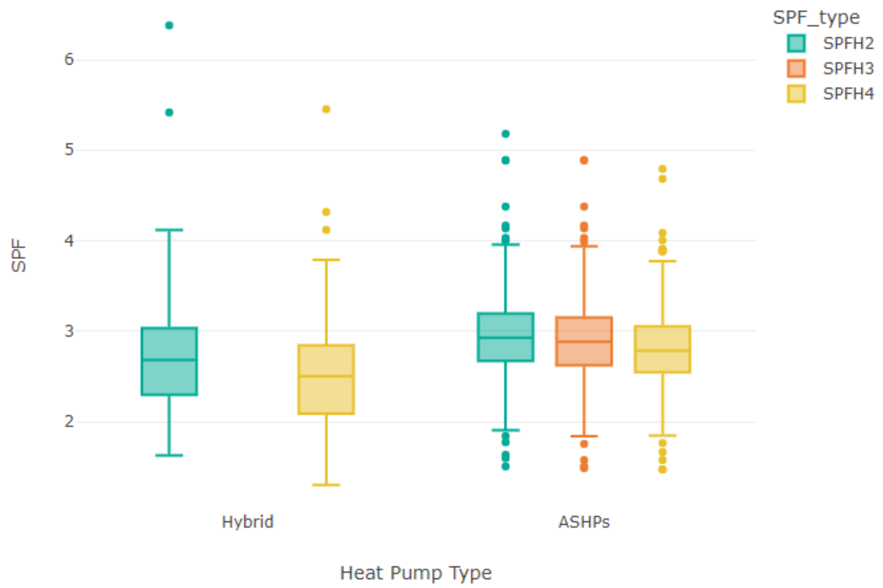

Figure 1.1: Box plot of SPF values for ASHPs and heat pumps within hybrid systems.

Reviewing this box plot, ASHPs have a much a narrower IQR than heat pumps in hybrid systems. The wider IQR for heat pumps in hybrid systems is an indication of the smaller sample size and larger variation across the results creating a lower level of confidence in the median result.

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.

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

Refrigerant	Sample	Median SPF_{H4} [IQR]
R32	125 (17 HT, 108 LT)	2.86 [2.60, 3.15]
R290	165 (all HT)	2.86 [2.66, 3.08]
R410a	138 (1 HT, 137 LT)	2.66 [2.40, 2.82]

The heat pumps using the R410a refrigerant operated with lower efficiencies 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.

Whilst this refrigerant comparison clearly indicates one reason for variation in ASHP performance, a significant variation can be seen within each of the three subsets of the data and, as such it does not explain the full range of variation.

Another reason for the performance variation is control strategy and flow temperature of the heat pumps. The observed SPF was higher for installations that had 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 flow temperatures most of the time.

House type and age did not have a statistically significant impact upon the heat pump performance results. Heat pumps installed in detached houses have been observed to have a slightly higher SPF compared to other house types however, this difference was not significant. The cause of this result may be because detached houses have the lowest proportion of heat pumps using the R410a refrigerant installed.

In terms of age, the highest performing age band was for heat pumps installed in pre-1919 properties which exhibited a median SPF_{H4} of 2.90, the lower performing were those installed between 1965 and 1990 which exhibited a median SPF_{H4} of 2.74. The difference in performance between any set of house ages was not statistically significant. 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

The hybrid heat pump systems installed through the EoH programme are systems which utilise a gas boiler alongside a heat pump. In this project, the hybrid system control was cost-optimised according to static energy prices with the boiler taking over the heating load when it was deemed cheaper to do so by the system controls (note systems were commissioned prior to energy price changes in 2022). The point at which the boiler took over the heating load was different for each property and, some of the properties had control issues through part of the project, meaning the boiler was utilised more than necessary. As a result, the system performance results varied across the range of properties.

The median measured heat pump energy output as a proportion of total space heating energy output in hybrid systems was 40%. The IQR for this statistic was [30%, 56%] indicating that whilst there was a big variation, the majority (75%) of the heat pumps in hybrid systems produced less than 56% of the space heating energy output. As the proportion of energy output by the heat pump decreased, the observed SPF of the heat pumps also decreased.

1.4.4 COP Temperature Dependency

Heat pump COP varies based on external temperature. This trend was observed through the EoH project as, at more moderate temperatures during the heating season, the heat pumps exhibited very high COPs (e.g. the median 30-minute $COP_{(H4)}$ across all ASHPs when external temperatures were 10°C was 3.37).

Figure 1.2 indicates the median $COP_{(H4)}$ against the mean (1°C interval) external temperature across all ASHPs and GSHPs.

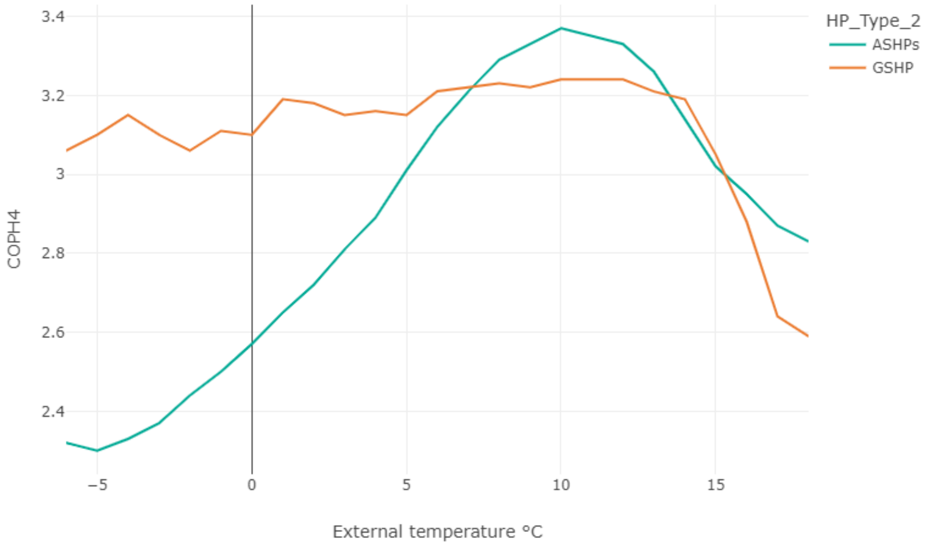

Figure 1.2: 30-minute mean external temperature plotted against median $COP_{(H4)}$ across all ASHPs and GSHPs, across all periods.

As the external temperature rose above 10°C, the COP decreased but it should be noted that, due to the primary operation of many of the heat pumps switching from heating to hot water mode, the energy consumed also decreased.

Most importantly, as external temperatures decreased, the COP of ASHPs also decreased. As the temperature reached the common GB design conditions of around -3°C and -5°C, the 30-minute $COP_{(H4)}$ reduced to 2.37 and 2.30 respectively. As already noted, the GSHP sample was much smaller so there is less certainty in the statistical results however, it is notable that the GSHP $COP_{(H4)}$ remained above 3.0 even down to external temperatures of -5°C. The lack of performance deterioration observed in GSHPs in the coldest periods indicates that GSHP deployment may mitigate some of the power system impacts of a large-scale heat pump roll-out.

The COP of heat pumps also decreased as the flow temperature increased. This was assessed by evaluating the 30-minute mean flow temperature vs the $COP_{(H2)}$ for a given 30-minute period. When producing flow temperatures of 35°C the median $COP_{(H2)}$ across all heat pumps was observed to be 3.50. This reduced as the temperature increased such that when producing flow temperatures of 55°C the median $COP_{(H2)}$ across all heat pumps was 2.38 and across all flow temperatures above 65°C, the median $COP_{(H2)}$ was 2.02. The impact was similar across both ASHPs and GSHPs.

Both of these results varied based on the heat pump refrigerant used, a breakdown can be seen in Section 10.

These results highlight the potential increase in peak electricity demands which the large-scale rollout of heat pumps could impose. To mitigate any disruption, network designers should design for heat pump loads in the coldest periods and heating systems should be designed and set up to operate at low flow temperatures for as much of the time as possible, regardless of their maximum temperature.

1.4.5 Comparing Designed and Actual Performance

A comparison between the designed SCOP and in-situ SPF_{H2} may be expected to demonstrate similar or correlated values as these two factors utilise the same system boundary and are representations of heat pump efficiency over a 1-year period. However, whilst an SPF indicates real-world, in-situ performance; the designed SCOPs are calculated using the MCS design standard which uses the Energy Related Products independent lab test data as its source.

Whilst this study has found that for many homes, the real-world performance of heat pumps is good; it is clear when comparing the in-situ SPF_{H2} to "as designed" SCOP that there is a discrepancy between operational heat pump efficiencies and those provided at the design stage. For 91.9% of the properties considered, the SPF_{H2} was lower than the SCOP. The mean difference between the two was -0.66 meaning the median SPF_{H2} was 17.9% lower than the median SCOP.

Whilst exact results varied, the performance gap was consistent across all heat pump types and refrigerants used. This indicates that there may be issues in the design process resulting in this difference between the calculated 'as designed' SCOP and in-situ SPF.

In addition to general overestimation of performance, there was little correlation between SPF_{H2} and SCOP values. This suggests that the methods for estimating 'as designed' SCOP might fail to predict whether a given heat pump installation will perform well compared to others. Analysis of Ofgem's heat pump performance data also noted a significant performance gap between the design SCOP and in-situ SPF_{H2} values across both ASHPs and GSHPs [8].

There are examples in both the EoH and Ofgem data of a few heat pumps where the real-world performance is comparable to or better than the as-designed SCOP. This shows that achieving the SCOP calculated at design stage is possible given the correct conditions. It is likely that utilising SCOPs which were derived from lab test results does not account for variations which occur during the installation process or the heat pump operation.

Note that whilst in theory monitoring issues could account for some of this performance gap, both the rigorous data quality checks and the fact the performance gap has been observed in previous studies renders this unlikely to be a major factor. Equally, whilst this result is assumed to be due to the simplified SCOP selection used in most designs, the project analysis did not directly evaluate the accuracy of the designs or the quality of all installations and so contribution of installation quality to the performance gap compared to design accuracy cannot be quantified.

2. Introduction

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

EoH was funded by the Department for Energy Security and Net Zero (DESNZ – previously BEIS). The project sought to better understand the feasibility of a large-scale rollout of heat pumps into existing homes across the UK. To support this, the project aimed 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, could 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 to help improve awareness across the renewable heating supply chain, raise acceptance and support wider deployment of heat pumps in Great Britain.

The results presented herein supersede the interim results which were released in March 2023. [10]

2.1 Aims

The aim of this report is to provide:

- Detailed heat pump performance and monitoring insights from the EoH project.
- 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 performance data used for the analysis was of a high standard.
- A detailed description of all analysis conducted on the heat pump performance data, including all calculation methodologies and assumptions.
- Basic statistics of the heat pump systems installed.
  - For detailed statistics see the Heat Pump Installation Statistics Report [11].
- 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 [12].

The main insights detailed in this report are summarised in a separate Insights Paper [6].

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 collected the operational heat pump data and stored it in its raw form.
  - This data was then downloaded, cleansed and analysed to form all insights.
  - The raw and cleansed performance datasets are accessible to the public through the UK Data Archive. [1] [2] [3] [4]
  - Summary datasets showing the analysis outcomes are accessible to the public via the UK Data Archive or USmart. [13]
- **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. [14]
- **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 was made up of a number of key contracts as illustrated below:

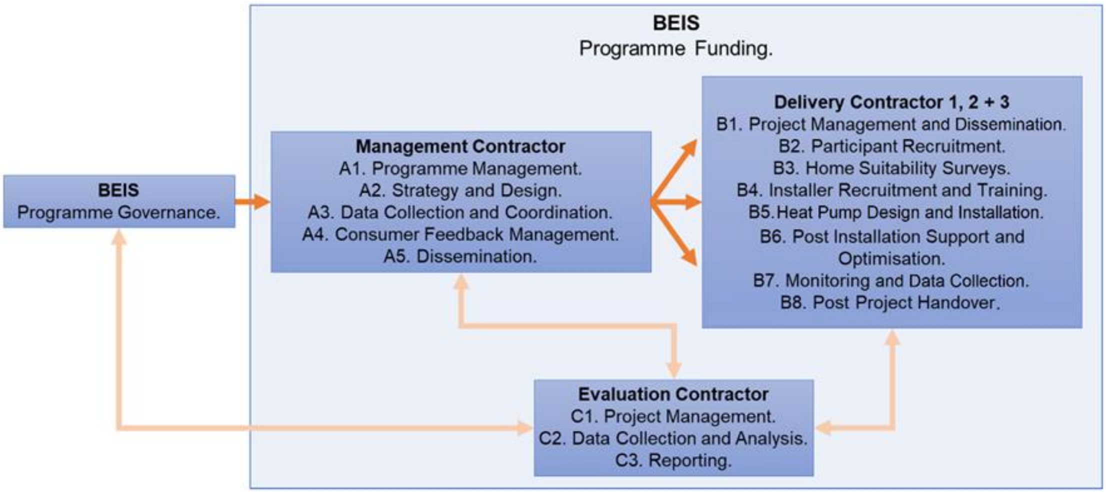

Figure 2.1: EoH project structure.

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 (the Catapult) 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 management of the programme (including quality assurance of a sample of surveys and installations) and, 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 could be monitored.

See [12] and [15] 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 and quantity of the performance datasets, 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 ceased earlier whilst the majority ceased on 28th September 2023.

Figure 2.3: Project timeline.[2]

[2] 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.

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 (with only limited upgrades to building fabric and the wider heating system, such as new radiators, loft insulation and draft-proofing). 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 [12]. 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.
- While multiple models with differing capacities and thermal outputs were included, 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 [16]. As a result of this, the mean and median results may not be representative of all heat pumps available in the UK.
- The installation of these heat pumps was undertaken in 2020 and 2021 and, the survey, design and installation phases of this project aimed to closely represent business as usual at that time. Between that stage of the project and the time of writing, there has been a lot of innovation in the implementation of these processes as well as the training and experience of designers and installers which may lead to improvements in the performance of more recently installed heat pumps.
- All of the heat pumps installed through this project were in three climatically diverse Nomenclature of Territorial Units for Statistics level 1 (NUTS1) regions. Therefore, a geographical bias may exist in the results.
- For some properties, the analysis presented in this report utilises only one year worth of collected data (due to shorter collection windows or issues with data collection). Additional collection of data may have led to a wider range of weather conditions being sampled.
- 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 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).
- Due to a small, (largely geographically localised) sample and details relating to the GSHP utilisation there is a high degree of uncertainty in relation to the representativeness of the GSHP data.

3. Heat Pump Installations

3.1 In-Scope Heat Pump Types

The project targets required a range of heat pump systems to be 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) unit designed to provide water at an outlet temperature of no more than 65°C[3].
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 natural gas 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 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.

[3] Note that just because the manufacturers designs indicate a heat pump is low temperature, it does not mean higher temperatures are impossible.

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.[4]

Criteria	Group	Installations (%)	Installations (No.)
Heat Pump Type	LT ASHP	41.2%	306
	HT ASHP	32.8%	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	14.1%	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

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.

[4] Note that one hybrid installation was replaced by a HT ASHP in March 2022 however, the installation numbers here are true as of the end of the installation period. Note also that the percentages may not add up to 100% due to rounding.

The hybrid system installations can be further broken down as follows:

- 5 integrated hybrid systems comprising of the boiler and heat pump in one unit.
- 11 systems with a separate gas boiler and heat pump which utilised a pre-existing boiler.
- 139 systems with a separate gas boiler and heat pump which included a new boiler installed as part of the project.

The heat pump installation statistics are covered in more detail in the Installation Statistics Report [11] and all design and installation data can be found on the EoH Project Database [17] [18].

3.3 Installation Quality

As described in Table 2.1, the Catapult 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 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. Not all installations were reviewed but 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 Catapult 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 would 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 enabled the project delivery team to track heat pump performance and, some of the heat pump systems performances have been optimised as a result. Some of this optimisation activity was contractor led, where the delivery team has noticed low performance and contractors have visited the property to try to improve system efficiency. Other activity was 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 several of the hybrid systems installed through the EoH project had control adjustments during a heat pump service visit. This is because they were not performing as expected.

The optimisation performed throughout the project should have positively affected the performance of some of the heat pumps but no extraordinary changes to the system hardware or operating patterns have been made so, the analysis results still provide a valid representation of heat pump performance. In addition, the analysis windows are selected based on median performance across all possible windows with high quality data, so the analysis is not significantly skewed by performance improvements due to optimisation (please see Section 6.3 for more detail on the quality scoring and window selection process).

On occasion, the optimisation of heat pump operation (for the participant) may have resulted in lowering performance for comfort reasons. For example, a participant may have increased their flow temperature to warm their house up more quickly or may have chosen to use the immersion heater to re-heat their thermal storage quickly. This is the nature of real-world performance and in-home trials which account for participant interaction with their system.

More details on system optimisation are provided in the Optimisation Report. [19]

4. Performance Data Monitoring

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) [20] PassivSystems metering equipment collected all data points in 2 minute intervals; enabling the calculation of the Coefficient of Performance (COP), Seasonal Performance Factor (SPF_{H2}, SPF_{H3} and SPF_{H4}, as defined by the SEPEMO Build Project [21] and clarified for Energy Saving Trust's heat pump field trial [22] [23]) and heating demand for any period.

The equipment was equivalent to the Metering and Monitoring Service Package (MMSP) available under the Domestic Renewable Incentive (RHI) [24] [25] and complied with the technical specification set out in the MCS Domestic RHI Metering Guidance Document [26].

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

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

The key components of this process are shown in Figure 4.1

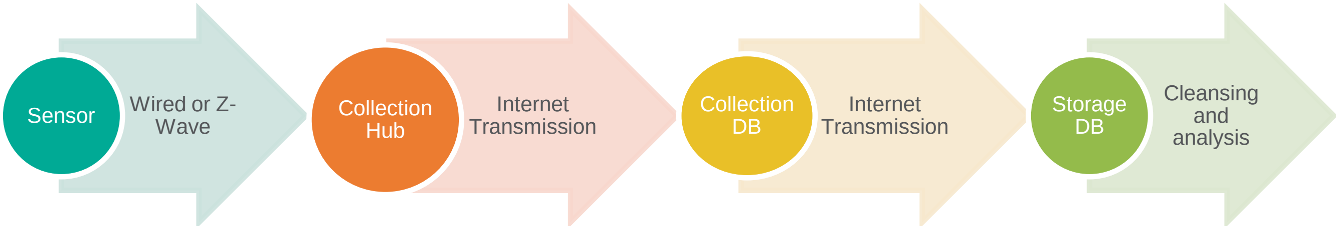

Figure 4.1: Key components of the performance data monitoring system and how they transmit data.

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

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

4.1.1 ASHP Configuration

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

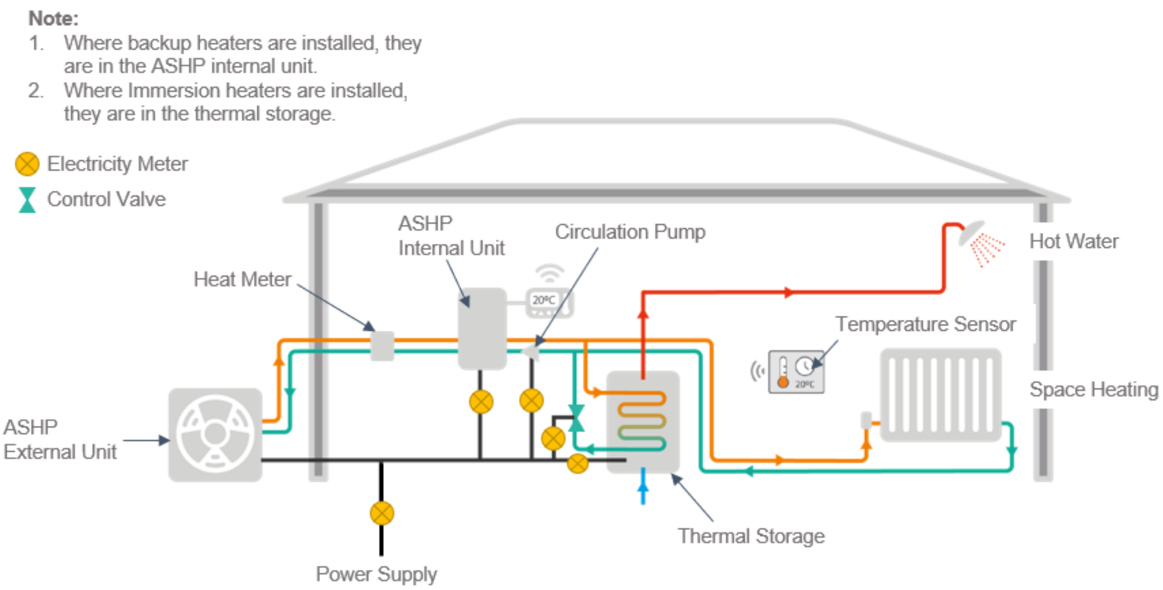

Figure 4.2: Typical arrangement of sensors in ASHP monitoring solution.

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

- The whole heat pump system energy consumed.
- Back-up heater energy consumed.
- Circulation pump energy consumed.
- Immersion heater energy consumed.
- Position of the control (diverter) valve, to inform whether the heat pump is in space heating or hot water mode.[5]

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 was recorded alongside the immersion heater energy consumed by a single electricity meter.

It should be noted that the heat pump unit energy consumed was 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 was a single heat meter. The heat meter recorded the flowrate, flow temperature and return temperature to derive heat pump energy output. The heat meter was installed inside the home, as close to the external heat pump unit as possible, prior to any additional heating equipment.

[5] The electricity meter connected to the diverter valve did not send an energy use reading to the dataset. It only monitored the position of the valve to assign whether the flow temperature measurement was for heating or hot water.

As such, the heat meter should have only recorded the heat produced by the heat pump unit and not that which is produced by a back-up or immersion heater.

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

4.1.2 GSHP Configuration

The EoH project deployed GSHPs 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 was 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 were brine temperature sensors for each individual property.

This system arrangement is illustrated by Figure 4.3 below.

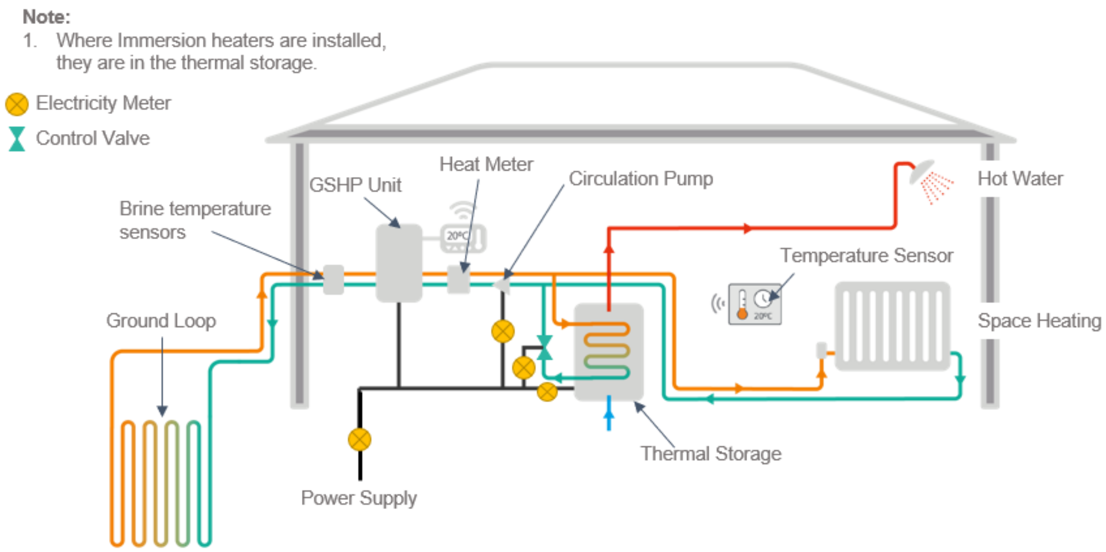

Figure 4.3: Typical arrangement of sensors in GSHP monitoring solution.

None of the GSHP systems installed through this project included a back-up heater so only a maximum of four electricity meters were present. These recorded 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 included a heat meter which was 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 was used, the system also included a thermal store for the provision of hot water.

In all hybrid heat pump system configurations, the monitoring system was 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 was generated by the gas boiler alone, and hot water provision from the boiler was not metered. As such, only the space heating provision from the hybrid systems could be determined.

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.

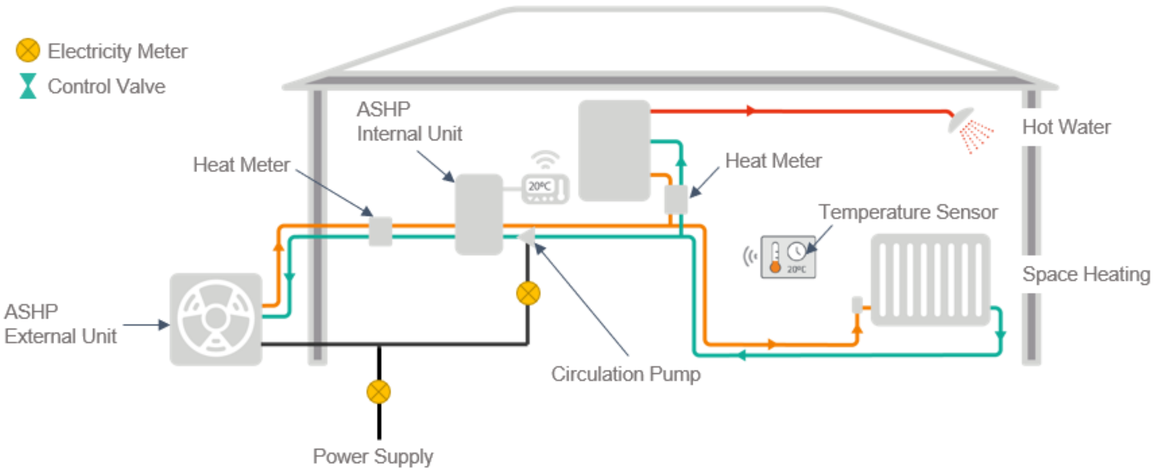

Figure 4.4: Typical arrangement of sensors in hybrid heat pump system monitoring solution.

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

a. Whole heat pump system energy consumed.
b. Circulation pump energy consumed.

As noted above, the hybrid monitoring system also included two heat meters, these recorded the heat output from the heat pump and boiler for space heating provision. As with the ASHP and GSHP configurations, the heat meters were 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 above, the configurations shown in Figure 4.2, Figure 4.3 and, Figure 4.4 are that of a typical installation and they varied dependent upon the heat pump models. One case where the configuration varied significantly is that of the SIME integrated hybrid heat pump systems.

Five SIME hybrid heat pumps were deployed by E.ON as an innovation measure aimed at overcoming the lack of external space in some mid-terraced housing. These units comprised 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 was 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 was installed downstream of the unit to measure overall heat output, however this measurement needed to 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 was always identical. In the event of simultaneous heat pump and boiler operation, the water in the heating system flowed through the heat pump heat exchanger where it was heated to an intermediate temperature. The water then flowed through the boiler where it was heated to the desired flow temperature. The monitoring system accessed the three temperature probes via the SIME OpenTherm module and then split 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.

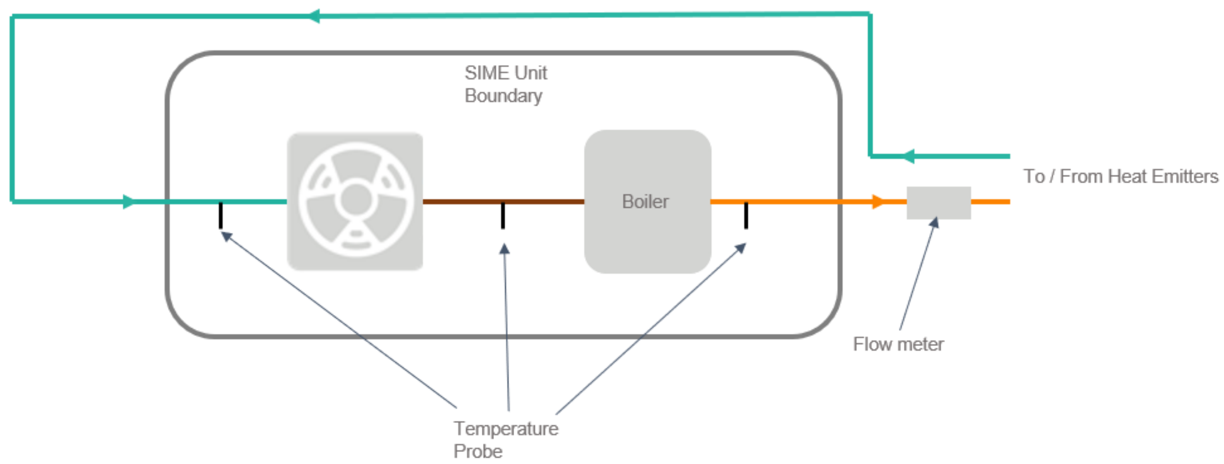

Figure 4.5: A simplistic representation of the internal components of a SIME hybrid heat pump solution. Indicating how the heat meter components are distributed to split the heat output between the boiler and heat pump.

In the event of the heat pump or boiler operating on their own, the entire heat was 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. Measures only the gas boiler output for space heating.
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 record cumulative data (i.e. the measurements provided are the total consumption or generation since the equipment started recording). The consumption over a two-minute period can therefore be deduced by subtracting one measurement from the one preceding it.

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

4.3 Monitoring Issues

Whilst there were not issues with the majority of the data collected through this project, there were situations where issues occurred in the monitoring systems in some of the properties. Generally, these were minor however, in some cases they rendered 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 was as expected may indicate an issue with the transmission 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 was unrecoverable as the data was 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 were disconnection of the hub from the internet or the powering down of the hub entirely. In the situation when there was an internet connection error, up to 10 days' worth of data from all sensors were stored on the local hub. When the internet connection resumed, the most recent 10 days of data was then sent to the collection database and was eventually forwarded onto storage database so not all data was lost.

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

As 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 was a gap in cumulative metered data but the data prior to and after the gap was 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 existed 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 during the project was individual component faults. 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 sent no reading, or an obviously false reading from the point that it began recording data. Where these occurred, generally installers returned 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 have caused 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 was unusable, it was removed from the cleansed datasets through the data cleansing process described in Section 6.2.

An example of an installation issue is the miscalibration of a meter. In this example, if the issue produced significantly erroneous data, it should be picked up in the cleansing and quality checking process by the SPF data checks.

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

When in-situ failures occurred, it was 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 occurred, engineers visited the property to check and fix or (where necessary) replace the equipment to ensure any periods of poor data were as short as possible. If in-situ failures occurred, the data before and after the failures may be useable but, during the failure period data became erroneous and, depending on the length of the failure period, it may have rendered the overall data window or dataset unusable. If it is the case that a failure occurred and was 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 stopped cumulating or fell out of calibration and this was not resolved within a short timeframe. An example of an equipment failure which had a smaller effect on the data quality overall is if the internal temperature sensor stopped 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 the performance data analysis, this data is referred to herein as "supplementary data". The supplementary data is documented in the Property, Design and Installation Data Documentation Report [16] and the dataset is accessible via the Electrification of Heat Project Database [18]. The supplementary data and performance 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 [18].) 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 the collected supplementary data 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 [16] 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 [18].)

The specific data which has been used to assist with the 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 [15] and Home Surveys and Installation Report [12].

5.2 Data Collection Methods and Timing

The data contained within the supplementary dataset was recorded at different stages of the participant journey through 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:

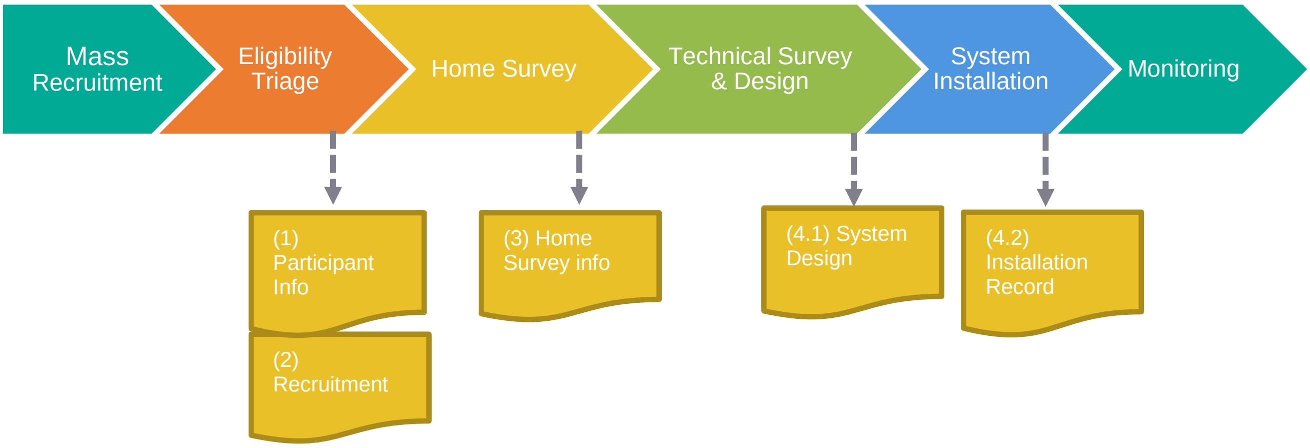

Figure 5.1: Supplementary data collected at each project stage.

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	Property Location (1st half of post code), Participant age, Participant 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 performance data will also have an installation record within the supplementary dataset however, as is discussed further in Section 6, not all installations have usable performance data.

6. Data Quality Checks and Cleansing

6.1 Process

To analyse the performance data, a process of quality checking, data cleansing, and analysing was followed. The code to enable this process has been published open-source [5] such that it may be replicated by others.

Initially a high-level quality check on the performance 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.

Once finalised, the “raw” data was cleansed. The cleansing process made 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 was performed to resolve quality issues, this was 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. A Seasonal Performance Factor (SPF) was then calculated within all of the best scoring data windows and the window exhibiting the median SPF for each property was 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 for the interim analysis [10]. The process has been retained with only small alterations for this final analysis. They were also asked to assess the validity of the interim analysis findings, this activity which was subcontracted to TÜV Nord.

The findings of this QA activity were that the cleansing and quality checking process was sufficient and any issues identified by FNC were sufficiently addressed and resolved prior to the end of the QA activity and publication of the EoH project data and reports.

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 two 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.
- Removal of long periods of constant temperature.
- 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 sent readings at an average frequency of around two minutes. There was, however, some variation in the period between each reading and two readings from the same sensor could be up to a maximum of four minutes apart. In addition, the timestamps were not synchronised between sensors, meaning that each sensor took 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 was necessary to align the timestamps. The following process was followed to realign the timestamps for the cleansed dataset:

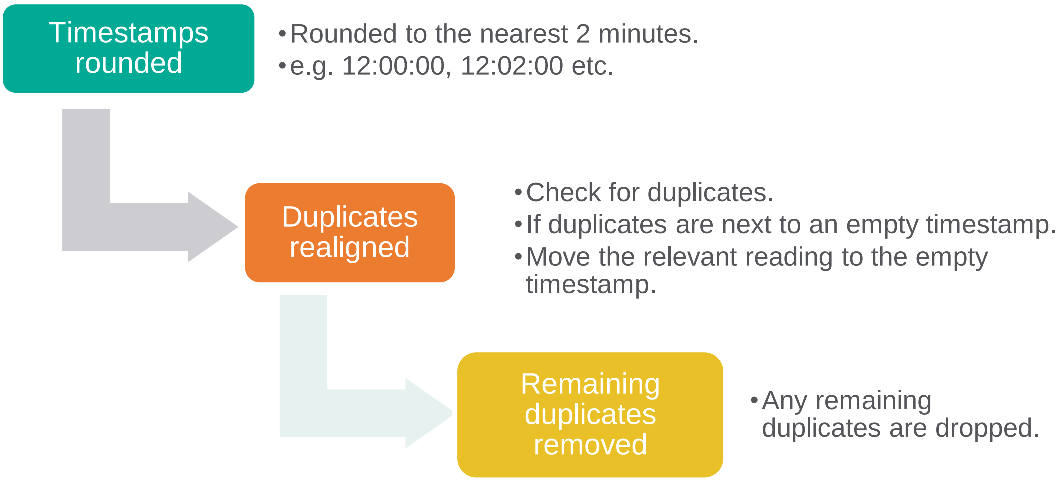

Figure 6.1: Timestamp alignment process.

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 (usually by installing the flow and return temperature probes in the wrong pipes). 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 were assessed. In situations where the daily differences were mostly decreasing, the readings were 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.

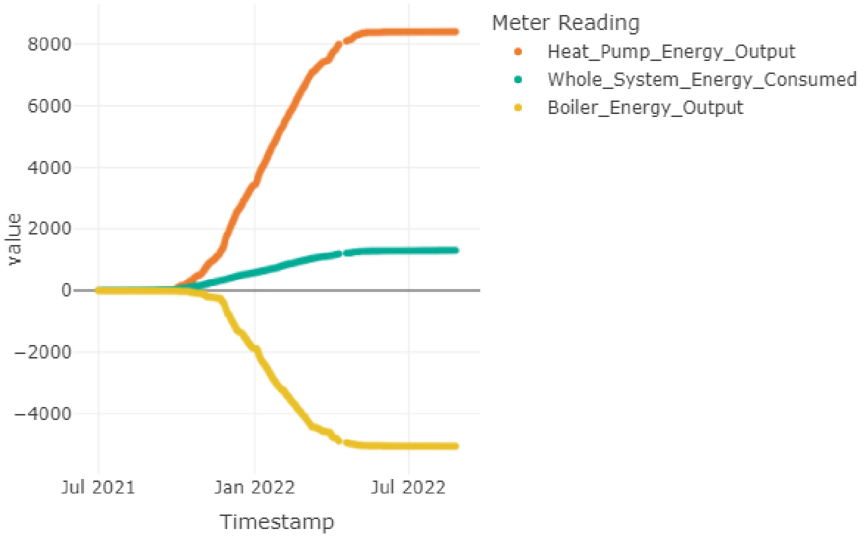

Figure 6.2: A graph showing a reversed boiler heat meter resulting in consistent negative readings within the raw data.

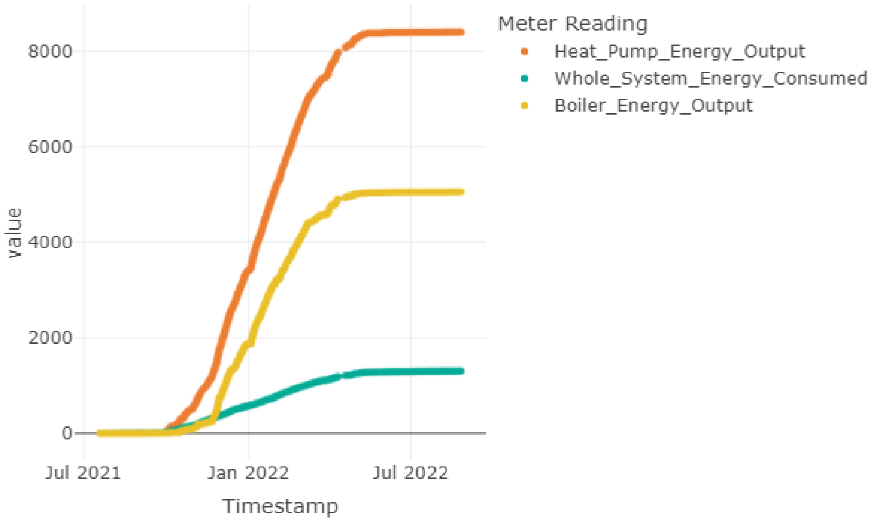

Figure 6.3: A graph showing the reversed values within the cleaned dataset.

6.2.3 Anomalous Cumulative Data Removal

6.2.3.1 Anomalous Points within Cumulative Dataset

Another issue sometimes witnessed within the raw dataset was anomalous data points. These occurred when a single datapoint was randomly much higher or lower than the surrounding datapoints. These were 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 was reset or replaced, generally the meter reading reduced significantly and then continued 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 datasets. The method described above removed all single anomalous points from the cleansed datasets however, it did not account for and will not remove multi-point anomalies.

Multi-point anomalies occurred when a series of datapoints was 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 was read by the automated cleansing process as a meter reset, so initially the data was re-levelled as described in Section 6.2.4.

For multi-point anomalies, the data already returned to the expected level, so the re-levelling process may cause a sharp upward tick in the data. As a result of this, it was necessary to check the gradient of the cumulative data immediately after re-levelling. If the gradient was much greater than expected then a multi-point anomaly was assumed and the data was 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 were single point anomalies, they were removed however, anomaly 3 was a multi-point anomaly so was not removed. Instead, the figure shows that to resolve anomaly 3, the first anomalous point was re-levelled as described in Section 6.2.4. This then risked the data following the anomalous period to be erroneous (shown by the sharp increase in data readings). As there was a large gradient between two readings at the end of the anomalous period, the multi-point anomaly was identified and the last anomalous point was re-levelled to ensure it was aligned as expected.

Figure 6.6 shows the cleansed data with all anomalies resolved.

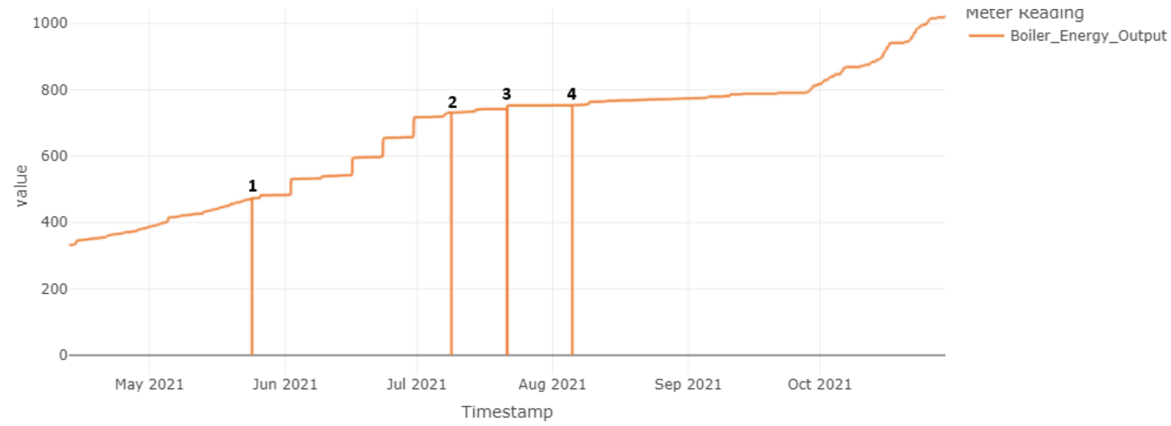

Figure 6.4: Four anomalies in a set of cumulative raw data.

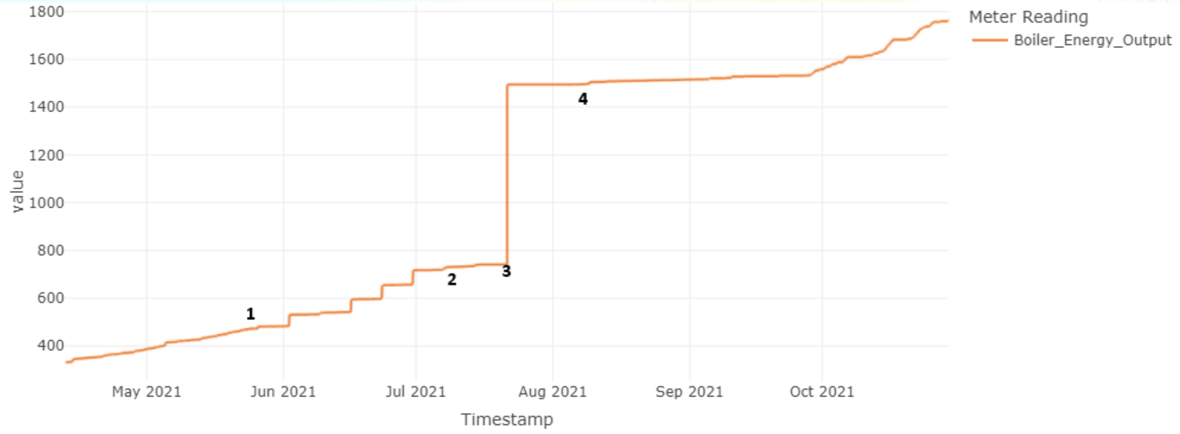

Figure 6.5: Shows the single point anomaly removal for anomalies 1, 2 and 4 as well as an automated "meter reset" re-levelling for anomaly 3. (intermediate data cleansing stage)

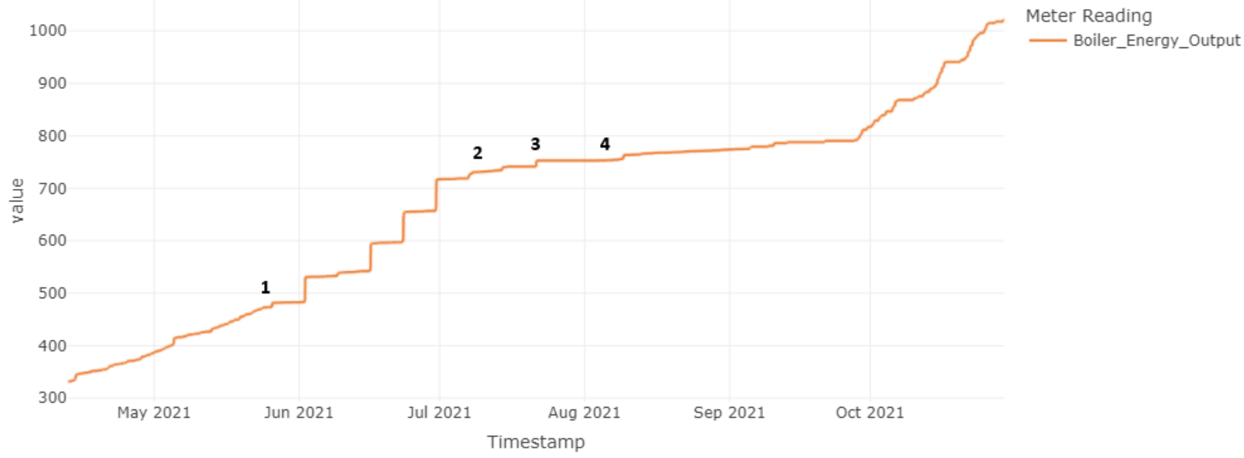

Figure 6.6: Shows the re-levelling at the end of anomaly 3 due to a high gradient, thus resolving the multi-point anomaly in the cleansed data.

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 resulted in erroneous readings, they were generally represented by continuous anomalous data from the beginning of the monitoring period until the monitoring equipment issue was resolved.

The result of this anomalous data was that, for a given duration at the beginning of the monitoring period, the Heat Pump Energy Output readings appeared 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 (using the 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 fell 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 was expected over a shorter timeframe.

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

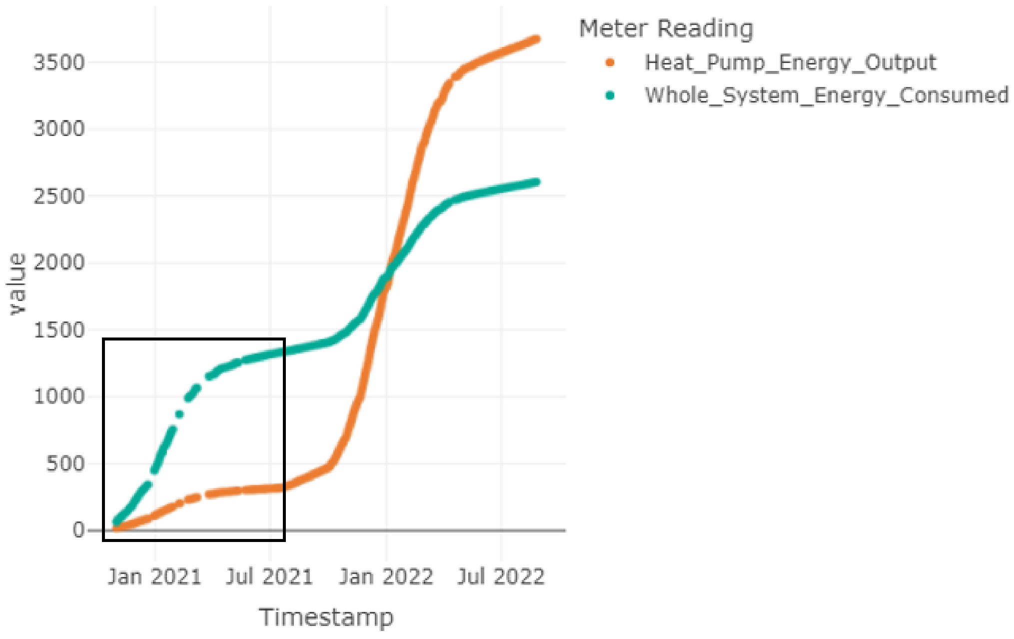

Figure 6.7: Cumulative energy data from a given property whereby the data is anomalous from the start of the monitoring period, but then becomes aligned with expectation following this initial period.

6.2.4 Relevelling Data Following Meter Reset

A significant decrease in cumulative meter readings which did not return to the expected level is a likely result from a meter fault or meter replacement (where the readings immediately returned to the expected level, this is an anomalous point, see Section 6.2.3.1). Meter resets have been identified as a decrease in the data where the reading dropped by more than 95% of the previous reading and did not immediately return to the expected level.

If a meter reset was identified, the data was 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 was flat, rather than increasing. If a gap existed prior to the reset, then energy usage across the gap was not considered. Instead, the gap was scored through the quality checks described in Section 6.3. 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 were heat pump heating flow (HPHF), heat pump return (HPR) and hot water flow (HWF) temperatures.

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

HPHF and HPR temperatures were recorded by different sensors however, these sensors could easily 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 tended 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, manual checks showed this issue to be very rare to non-existent within the data. As a result of this, there have been no column reassignments made between HPHF and HPR temperatures.

In some cases, the column reassignment checks required manual inspection. Upon manual inspection, many of the issues were resolved with column reassignments as outlined in the below sub-section however, in instances where we manually inspected the home and found that either all of the data looked erroneous or all of the data was incorrectly assigned to one column we dealt with this by either dropping the data from the cleansed dataset or assigning all data to the HPHF temperature column.

Upon manually checking the data, the flow temperature data was dropped from the dataset for property EOH0590. Table 6.1 lists the properties for which all data was assigned to the HPHF temperature column.

6.2.5.1 Heating Flow and Hot Water Flow Assignment

As the same sensor was used to measure HPHF and HWF temperature, it was sometimes the case that they were 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 was correctly separated into the two columns or it was 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 [27])
- 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 was 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 could 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 was 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.

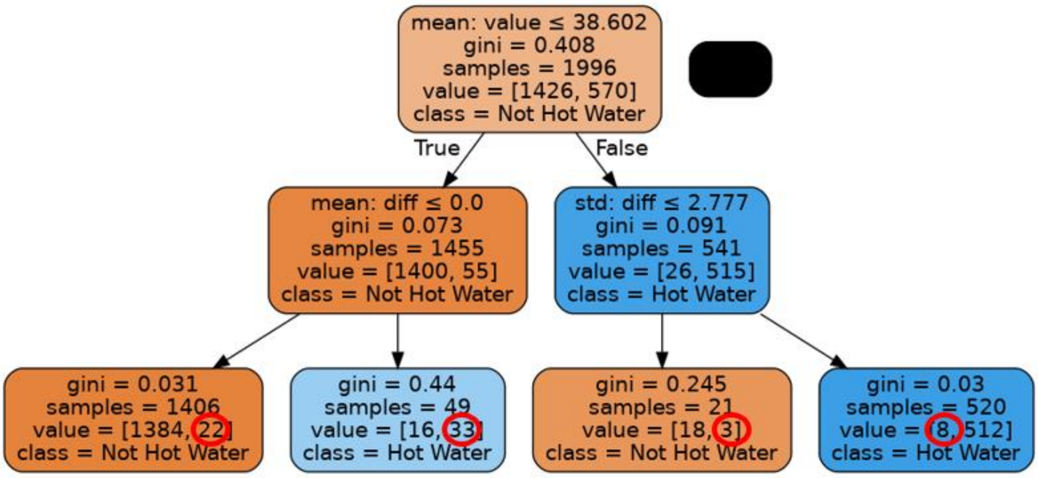

Figure 6.8: Non-cumulative data grouping decision tree (excluding “mean: count per day”). Red rings have been used to highlight number of sensors which have been classified by the tree as different from how it is labelled.

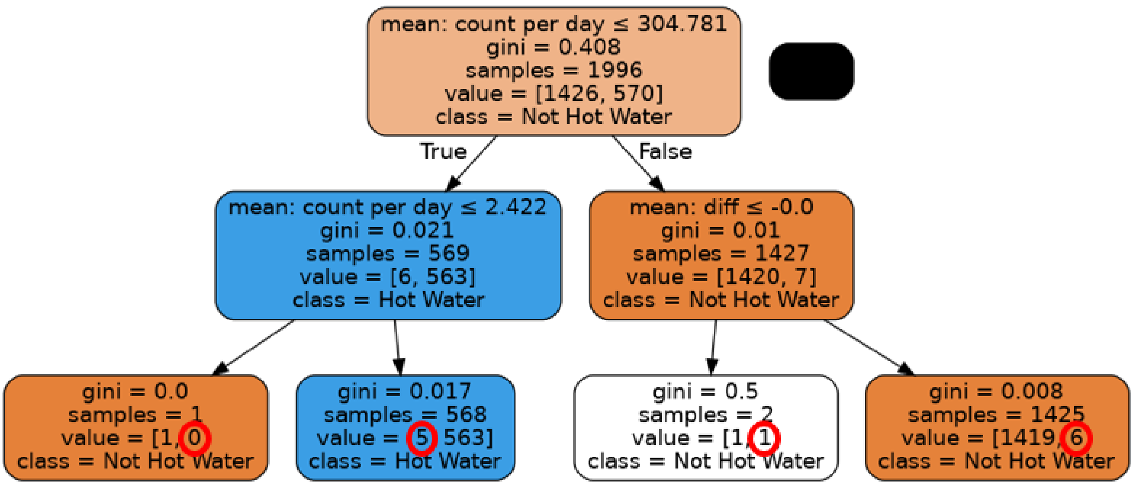

Figure 6.9: Non-cumulative data grouping decision tree (including “mean: count per day”). Red rings have been used to highlight number of sensors which have been classified by the tree as different from how it is labelled.

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.

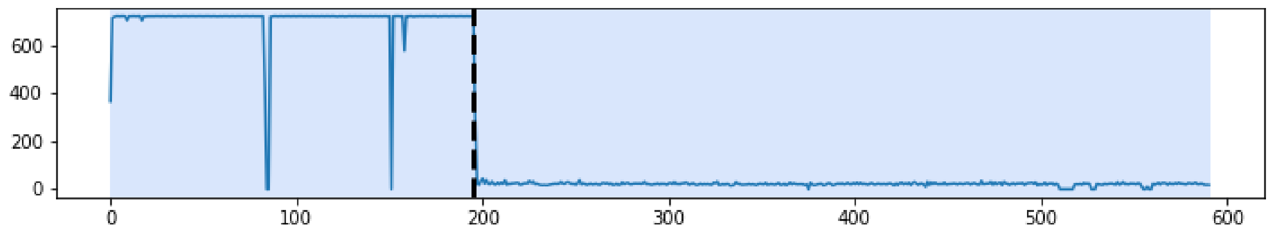

Figure 6.10: A graph of the change point detection used to identify when physical changes to the monitoring system were made.

The above process rectified most of the HWF and HPHF temperature swaps however, upon further analysis, additional erroneously logged data remained. This data was dealt with by performing a check of the cleansed 30-minute data to evaluate daily time spent in hot water (total number of hours per day) and daily time spent in heating mode throughout the year. The total daily energy consumed and energy output in each mode and the average temperature of the HWF and HPHF per day were also derived and inspected. The analysis of these non-cumulative metrics helped flagging a list of properties for which their hot water and heat pump heating temperature values were potentially erroneous.

A total of 29 properties with issues on how the flow temperature was tracked were identified. Following the automated reassignments, the raw and cleansed datasets were manually reviewed to recommend a flow temperature re-assignment. For properties EOH0737 and EOH0889, the flow temperatures warranted manual inspection however, upon inspection a good approach to cleanse the data couldn’t be determined so, the decision was made to leave the flow temperature as it was and avoid adding any 'features' to the data that could be misleading.

Following the manual checks, four types of temperature data cleansing were identified (note that some of these are closely aligned to those which have been defined earlier in this subsection, but are done at this stage as they were not captured via the automated process):

1. Swapping of the HPH and HW flow temperature values. Two cases were distinguished:
    a. Full data swap: HPHF temperature was erroneously labelled as HWF since the start of the data collection and vice versa. This affected eight properties (see Table 6.1).
    b. Partial data swap: mislabelling only occurring once for a specific period. Therefore, swapping only had to be implemented over those timestamps. This type of swapping was only found in one property.
    c. Allocating all observations to the HPHF temperature column: This was always affecting the data for a specific period (instead of for the whole dataset). Generally, over that time only one flow temperature data (in this case HWF) was tracked. At the end of that flagged period, both HPHF and HWF temperatures were measured. This affected 19 properties, but for 15 of those the periods were outside of the window selected, normally when data started to be collected.
    d. Dropping both HPHF and HWF temperature data: This was motivated by data quality concerns after the 2 min data was inspected. The complete removal of the flow temperature column was implemented for only for one property (EOH0590), which was already removed from the analysis because of other data quality issues.

Below the list of properties that undertook any of the described manual column reassignments.

Table 6.1: Temperature column reassignments resulting from manual checks of the data.

Property_ID	Column reassignment	Date Range
EOH0121	HWF and HPHF swap	Full data swap
EOH0457	HWF and HPHF swap	Full data swap
EOH0459	HWF and HPHF swap	Full data swap
EOH0603	HWF and HPHF swap	Full data swap
EOH2430	HWF and HPHF swap	Full data swap
EOH2722	HWF and HPHF swap	Full data swap
EOH3138	HWF and HPHF swap	Full data swap
EOH3186	Partial HWF and HPHF swap	15/06/2021 to 17/11/2021
EOH1669	HWF and HPHF swap back (following swap during automated cleansing)	Full data swap
EOH0067	Allocating HWF data to HPHF	26/01/2021 to 03/06/2021
EOH0082	Allocating HWF data to HPHF	04/03/2021 to 03/06/2021
EOH0279	Allocating HWF data to HPHF	26/10/2020 to 03/06/2021
EOH0346	Allocating HWF data to HPHF	21/04/2021 to 25/05/2021
EOH0516	Allocating HWF data to HPHF	16/02/2021 to 03/06/2021
EOH0526	Allocating HWF data to HPHF	01/10/2021 to 05/10/2021
EOH0546	Allocating HWF data to HPHF	01/11/2020 to 25/05/2021
EOH0690	Allocating HWF data to HPHF	19/02/2021 to 26/02/2021
EOH1400	Allocating HWF data to HPHF	09/02/2021 to 25/02/2021
EOH1406	Allocating HWF data to HPHF	02/03/2021 to 12/07/2021
EOH1588	Allocating HWF data to HPHF	18/03/2021 to 13/04/2021
EOH1629	Allocating HWF data to HPHF	29/07/2021 to 22/10/2021

Property_ID	Column reassignment	Date Range
EOH1826	Allocating HWF data to HPHF	02/03/2021 to 22/03/2021
EOH1852	Allocating HWF data to HPHF	14/05/2021 to 03/06/2021
EOH2061	Allocating HWF data to HPHF	12/05/2022 to 18/06/2022
EOH2101	Allocating HWF data to HPHF	01/11/2020 to 02/06/2021
EOH2406	Allocating HWF data to HPHF	06/03/2021 to 01/04/2021
EOH2799	Allocating HWF data to HPHF	17/11/2020 to 01/06/2021
EOH3107	Allocating HWF data to HPHF	14/01/2021 to 02/06/2021
EOH0590	HWF and HPHF drop	Full data

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 6.2.

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

Table 6.2: Accepted temperature ranges for each data column.

Data Column	Min Value (°C)	Max Value (°C)	Notes
Internal_Air_Temperature	2	40	Based on Temperature Variations in UK Heated Homes Study [28] with a 5°C variation at the top end and a lower limit of 2°C to remove temperatures which were constantly 0°C.
External_Air_Temperature	-27.2	40.3	Based on record UK temperatures [29].
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 [30]. Both have an extra +5°C 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°C all year around [31]. A 20°C variation has been allowed either side of this.
Brine_Return_Temperature	-10	30	See Brine_Flow_Temperature

As well as out-of-range temperatures, it was necessary to assess the feasibility of consecutive temperature readings. There were some instances in the raw data whereby the temperature data had consecutive equal (or near to equal) readings over multiple days. For the internal temperature data, this could be realistic however, for the flow and return temperatures and the external air temperature this is highly unfeasible. Temperature data was therefore removed if the standard deviation of the temperature for a given week was less than 0.5°C. This cleaning was completed for all temperatures except for internal air temperature.

6.2.7 Supplementary Data Cleansing

The supplementary data which was used to assist with the performance data analysis has undergone a rigorous quality checking and cleansing process. This is described within the Data Documentation Report [16] which is published alongside the dataset [18].

To ensure it was possible to use this data for analysis, the supplementary data should contain a consistent set of unique values. Table 6.3 provides the allowed variables for each column of supplementary data used at this stage of the performance data analysis.

Table 6.3: 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 was consistent with expectations, to perform the performance data analysis, it was also necessary to collate additional refrigerant data (which was collected by analysing the datasheets from the installed heat pumps) and design information 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 [18]. This cleansing is highlighted again as it may have some baring on the performance 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 6.4 below.

Table 6.4: 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 arose where the monitoring equipment did not operate 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:

- Assessing the percentage of data available in any given window.
- 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 energy output over a given period (for coldest day only).

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

Section 6.3.6 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 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 its 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 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 initially flagged for manual review, but after review were all included in the analysis.

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 6.5 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 6.5: 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 6.6 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 6.6: 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 6.7 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 6.7: 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	4
> 21 days	3	5

Table 6.8 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 6.8: 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 (particularly longer gaps) are scored more harshly than continuous data because since 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.

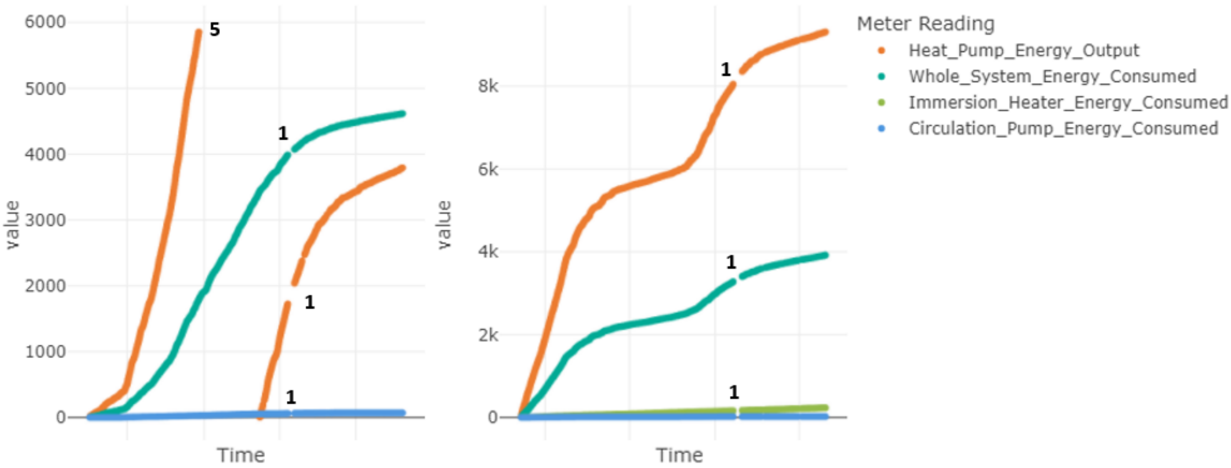

Figure 6.11: Two graphs showing unacceptable data (left) and acceptable data (right). The data shown on the left is rejected as it contains a max gap score of 5 due to meter reset following a large data gap.

6.3.2 Monthly Data Quality Scoring

As well as assigning quality scores to all gaps within the data, it was necessary to assess the quality of the data where gaps do not exist. There are significant variations in the performance 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 $COP_{(H2)}$ fell within the range of 0.9-6.5 and the energy used over the month was greater than 1kWh, a quality score of 0 was assigned to this month of data (indicating there are no quality issues). If the monthly $COP_{(H2)}$ was outside of the range of 0.9-6.5, a quality score of 3.3 was assigned to this month of data. If the monthly energy recorded across all cumulative sensors was less than 1kWh, a quality score of 3.2 was assigned to this month of data. These scores are shown in Table 6.9.

Table 6.9: 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 was 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 was 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 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. The exception to this is the majority of the hybrid heat pumps where the boiler's hot water provision is not metered. In these cases, it is expected that little to no energy consumption or output is recorded in the summer months.

As both of these issues may be subjective, they are scored between 3 and 4 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 could 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 was selected based on the data scoring (see Section 6.4), the system efficiency across that window was calculated using the analysis calculations described in Section 7. The data was excluded from the analysis if these calculated efficiencies were outside of the accepted ranges. The accepted efficiency ranges for each efficiency calculation are provided in Table 6.10.

Table 6.10: Accepted efficiency ranges for each calculation window, outside of which properties are excluded from the analysis.

Calculated Value	Timeframe	Accepted Range
SPF_{H4}	12 months	1.25 – 5.5[6]
$COP_{(H4)}$	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 its 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 the primary method used within the RHPP trial [32].

The SPF range used for this analysis was based on considering recent publications and data on heat pump performance as well as evaluating cases where the SPF was just inside or outside of the RHPP range (of 1.5 to 4.5). A manual check was undertaken on all of the properties which have SPF values between 1 and 1.5 and between 4.5 and 6. The majority of the properties between 1 and 1.25 and 5.5 and 6 had clear issues within the cumulative data and so the range of 1.25 to 5.5 was selected. Note that the number of homes close to the cut-offs was very small compared to the overall sample and therefore small changes to the cut-offs had no discernable impact on the headline SPF statistics.

Due to wider performance variations over shorter timeframes, the accepted daily $COP_{(H4)}$ ranges were wider than those 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 Energy Output – Acceptable Ranges

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

As a result, the data was filtered based on the heat pump energy output within the coldest day window. The energy use over the coldest periods was highly variable as it may be adjust based on the pre-conditioning of the property. It may also vary based on 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 was 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 was 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 204.6kWh for the coldest day.

[6] Note that the acceptable range has increased from 1.5 to 4.5 in the interim analysis following manual data quality checks of all cases where the SPF_{H4} falls between 1.25 and 1.5, and, 4.5 and 5.5.

6.3.5 Percentage Data Available – Acceptable Threshold

The final quality criteria used was to check the percentage of expected data available in any given annual window.

This check was necessary as any window may have multiple short or medium length 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 – see Section 6.3.1) however, the overall effect of the missing data is that confidence in the data is reduced.

As a result of this, a calculation window was not accepted for the SPF analysis if less than 70% of the expected Whole System Energy Consumed or Heat Pump Energy Output data readings were available. Where a property had no potential window with more than 70% of expected readings available, this property was deemed to have "No valid 1 year windows due to gaps" in the waterfall chart (Figure 6.12) in Section 6.3.6.

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

6.3.6 Data Quality Assessment Outcomes

Using the data quality assessment results, the best window of data was selected and certain properties could 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 1.25 to 5.5,[7]
- If the maximum data quality score in the SPF window is 4 or greater (including if there is less than 70% of the data being available in any possible window).

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.

[7] These SPF boundaries were chosen as initially the boundaries of 1.5 and 4.5 used in RHPP and the Energy Savings Trust trial were considered, and boundary cases were manually reviewed. Upon manual review, the properties exhibiting SPFs between 1.25 and 1.5 and, 4.5 and 5.5 were deemed to be showing realistic performance.

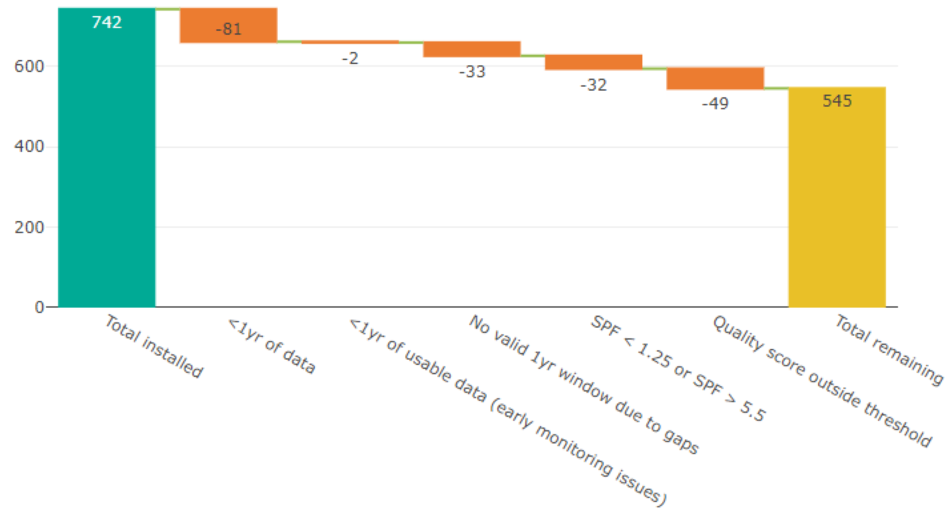

Figure 6.12: A graph showing the number of properties excluded from the SPF analysis for each reason as well as the number of properties remaining.

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.

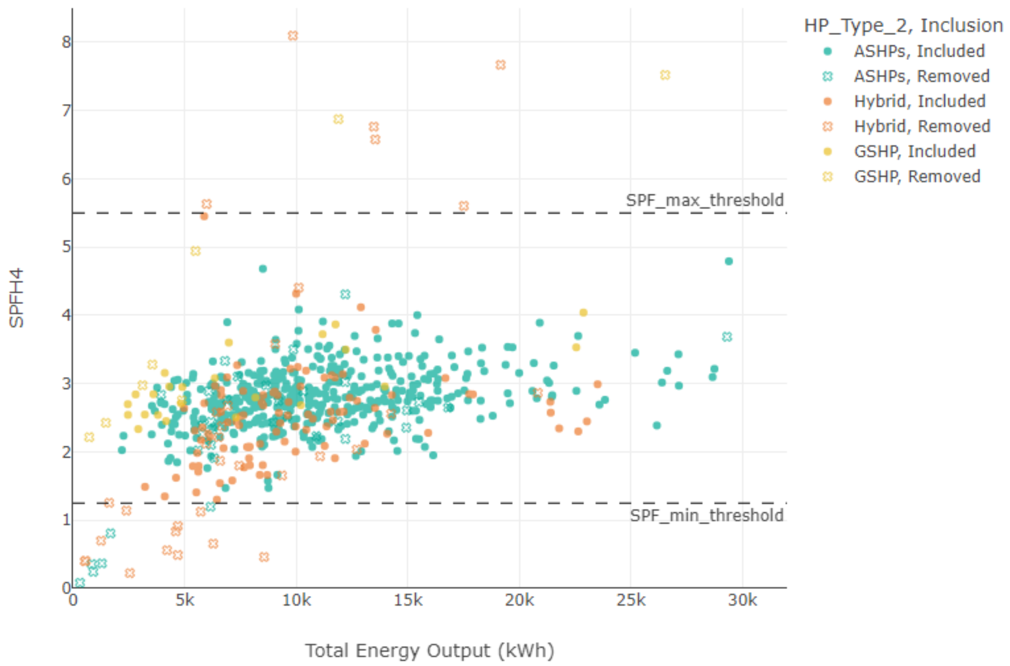

Figure 6.13: A scatter graph of SPF_{H2} against Total Energy Output for all properties with a 12 month data window, indicating where the SPF boundaries are and which properties were included in or excluded from the analysis.

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 6.11.

Table 6.11: 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
All properties	742
ASHP properties only	550
Sufficient data available	547
$COP_{(H4)}$ value inside of the range 0.75 to 7.5	524
Timestamps within winter months (Nov and Mar inc.)	513
Total heat pump energy output inside of 2 interquartile ranges (IQR) of Q1 and Q3.	510
Final Analysis Sample Size	510

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 were 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 process of selecting the analysis window is shown in Figure 6.14 and described below.

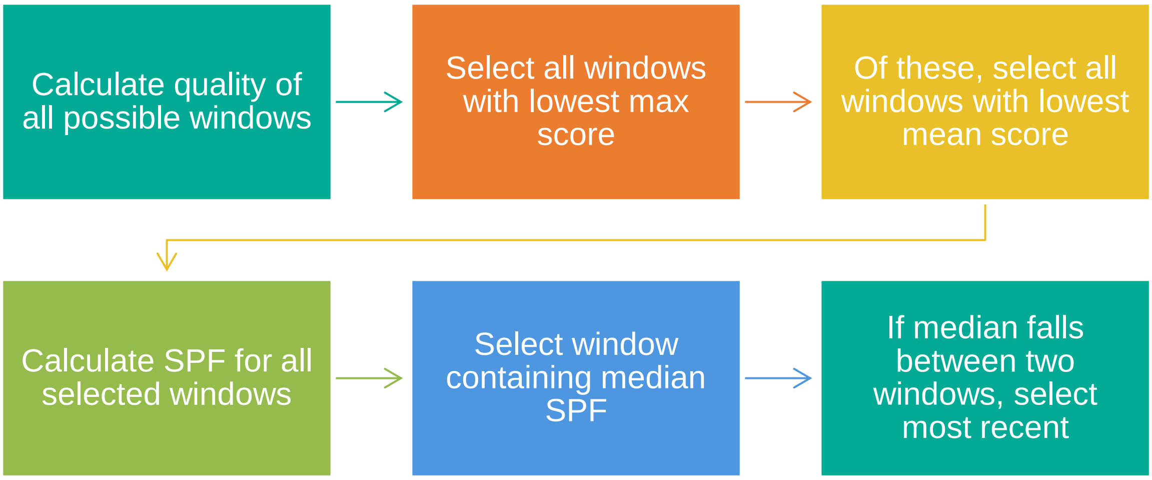

Figure 6.14: Flow chart showing 12-month window selection process.

All of the highest quality 12-month windows (based on lowest maximum data quality score and lowest mean data quality score) were then selected for each home and SPF values were calculated for each window. The window which contained the median SPF value was selected. [8] If two or more windows contained the median value, then the most recent of these was chosen.

[8] Note that the method was changed to select the median window rather than the most recent window (as used in the interim analysis) due to the existence of additional data and to reduce the potential for bias.

The maximum score within the window indicates whether the data is useable, so this is prioritised above the mean quality score.

6.4.2 Coldest Day Window Selection

To assess heat pump performance during the coldest day, it was necessary to find the coldest periods where the heat pump was 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 coldest day was 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 slight 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. This differs from the window selection method as the window selection method takes only the median result from the highest quality data windows.

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 [13].

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 mean variation across all homes is provided in Table 6.12.

Table 6.12: The mean 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}	-0.0018
SPF_{H3}	-0.0021
SPF_{H4}	-0.0019

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 were 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 two 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 two 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 four minutes, giving an average thermal output of 15kW (-50% impact).

As the maximum variation for any window is two 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 two 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 performance 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 545 analysed systems included in the analysis, 85 of them returned an erroneous circulation pump energy consumed value of 0kWh. The mean Circulation Pump Energy Consumed across all other systems was 135.7kWh. Taking this mean and applying it to the properties which returned a reading of 0kWh, the median SPF_{H2} across the trial increases by 0.02 and the median SPF_{H3} across the trial increases by 0.021.

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 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 through the monitoring period. Where it was possible to be confident in identifying the mislabelled data, the sensors have been relabelled to match the correct 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.

6.6.5 Back-up and immersion 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 dampened and the overall effect is likely minimal.

In a few instances, the low heat pump usage for hot water production suggests that the immersion heater may have been utilised whereas the immersion heater readings are either very low or zero. This error has not been verified but the potential for the error should be noted. Due to the monitoring system configuration, any errors of this fashion result in measured SPF_{H2} and SPF_{H3} being lower than the true values. As it is only an issue for a few properties, the overall effect has not been quantified.

7. Analysis Calculations

7.1 Assumptions

To perform SPF and COP calculations, certain assumptions were required. 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 were 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 gave 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.
- Defrost cycles are picked up as either negative differences between heat output readings or are performed using back up heaters, therefore energy used to defrost ASHPs is accounted for within the calculations.
- 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 were directly recorded by the meters and sensors in the heat pump monitoring system described in Section 4.1. There were, however, a few variables which needed 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 were derived based on the assumption listed in Section 7.1. The Heat_Pump_Energy_Consumed was 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 (electricity to heat conversion) efficiency percentage (i.e. an SPF of 2.90 means the heat pump operation over the year exhibited an electrical efficiency of 290%.)

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) [21]. Further clarification of the SPF boundaries was made during the Energy Saving's Trust Heat Pump Trial [22] [23] for systems which may include an immersion heater for hot water provision.

The SPF system boundaries used for the calculations herein were derived directly from these studies. Figure 7.1 shows these system boundaries for the EoH project monitoring system.

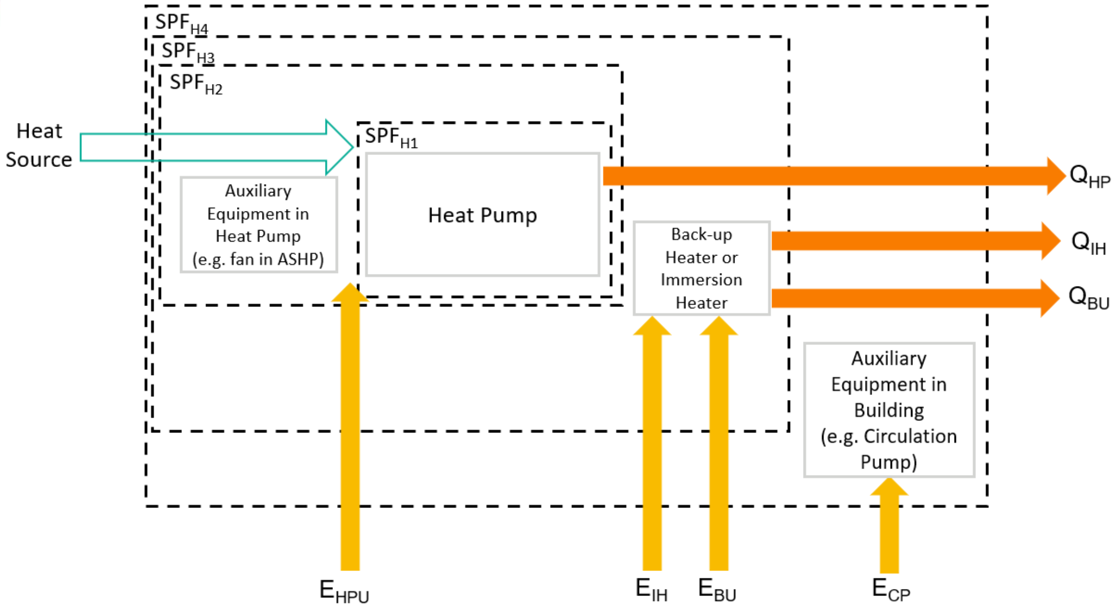

Figure 7.1: SPF system boundaries applied to the EoH monitoring system.

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”) were not separately monitored. As such, an SPF_{H1} values cannot be calculated using the data collected by this project.

Within a typical heart pump setup, the SPF_{H2} is the electricity to heat conversion efficiency of the heat pump unit, the SPF_{H3} is the efficiency of all heat generating equipment and the SPF_{H4} is the efficiency of the whole system including circulation pumps. Thus, the SPF_{H3} is the closest comparator to the in-situ efficiency of gas or oil boilers.

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 (electricity to heat conversion) 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 was used for any efficiency calculation which was 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 mean and median 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 was necessary to separate these systems out as Hybrid systems have different operating patterns compared with other heat pump systems (due to the existence of the gas boiler). 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} is excluded as it is equal to SPF_{H2})

Heat Pump Type	SPF Type	Sample Size	Median [IQR]	Mean [95% CI]
ASHP	SPF_{H2}	428	2.93 [2.67, 3.19]	2.95 [2.90, 2.99]
	SPF_{H3}	428	2.88 [2.62, 3.15]	2.89 [2.85, 2.94]
	SPF_{H4}	428	2.78 [2.55, 3.05]	2.81 [2.76, 2.85]
(Heat Pumps within) **Hybrid systems**	SPF_{H2}	94	2.68 [2.30, 3.03]	2.73 [2.58, 2.87]
	SPF_{H4}	94	2.50 [2.10, 2.84]	2.51 [2.37, 2.64]

Note that as the GSHP sample is limited and contains both shared loop and individual GSHPs, the GSHP results are provided separately in the appendices. It is not recommended that the EoH performance results be used as a reference for average GSHP SPF. The RB&M analysis of Ofgem heat pump data [8], published at the same time as this report, provides analysis on a sample of 286 GSHPs installed between 2017 and the end of 2022 and, as such, provides a more robust value which can be used as a reference for GSHP performance.

Note also that only the electrical components are considered when calculating SPF values for the Hybrid systems, (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.

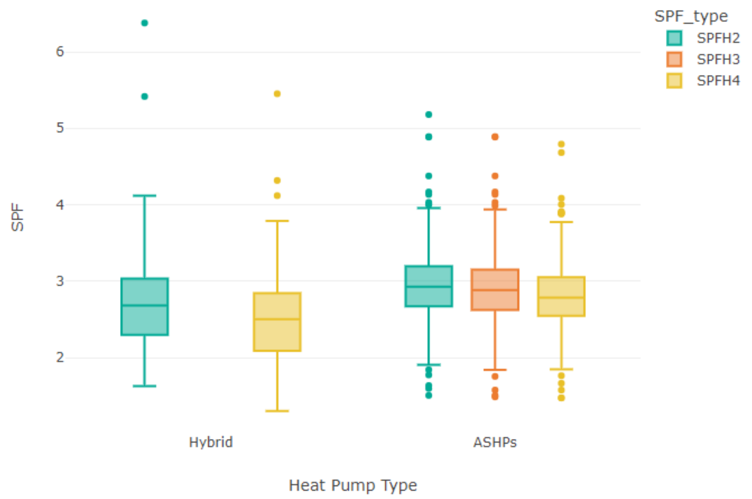

Figure 8.1: Q1 (top of each box), Q3 (bottom of each box) and median (within each box) SPF values for ASHPs and heat pumps within hybrid systems. Note that the upper and lower horizontal lines above and below each box are fences indicating the boundary for statistical outliers.

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 different heat pump systems. It can be seen that there was a greater probability of a higher SPF_{H2} and SPF_{H4} in ASHPs compared to heat pumps in hybrid systems.

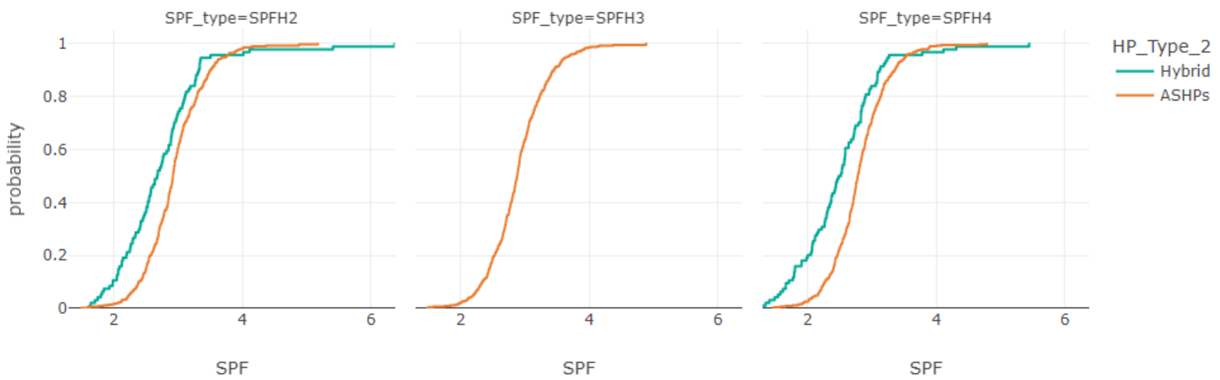

Figure 8.2: Empirical distribution of SPF for ASHPs and Hybrids, split by SPF type.

The most recent government 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 [32]. This monitoring programme included both ASHPs and GSHPs but did not include any Hybrid systems.

A comparison between the EoH SPF results and the RHPP SPF results for ASHPs 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 EoH ASHP performance against the RHPP scheme results.

SPF Value	EoH Sample	EoH Median SPF[9]	EoH SPF [Q1, Q3], IQR	RHPP Sample	RHPP Median SPF	RHPP SPF [Q1, Q3], IQR
SPF_{H2}	428	2.93	[2.67, 3.19], 0.52	292	2.65	[2.33, 2.95], 0.62
SPF_{H4}	428	2.78	[2.55, 3.05], 0.50	292	2.44	[2.15, 2.67], 0.52

It is clear reviewing the table that the median SPF for ASHP installations improved significantly between the RHPP (2017) and EOH (2023) trials. The median SPF_{H2} of ASHPs from EoH is 0.28 higher than that calculated through the RHPP trial and the median SPF_{H4} is 0.34 higher.

It should be noted that the EoH results are consistent with the results from analysis of Ofgem heat pump performance data, conducted by RB&M, which were published at the same time as these EoH findings [8]. The Ofgem data shows a median SPF_{H4} of 2.69 for ASHPs which increases to a median SPF_{H4} of 2.74 when only taking ASHPs installed in 2022 or later into account.

Despite the higher heat pump efficiency, the variance in SPF across installations remained similar to that observed through the RHPP scheme. The IQR for both EoH and RHPP ASHP installations (SPF_{H2} and SPF_{H4}) lay between 0.50 and 0.62. This represents a large variation in performance – 214 of the EoH installations had SPFs more than 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.

8.1.1 Comparison of Low and High Temperature ASHP

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 fact, only 4 of the HT ASHPs installed through the EoH project had a designed flow temperature[10] of 65°C or higher. Even in those cases where the design requires a 65°C flow temperature, the ASHPs weather compensation control mean that the heat pump rarely operates at these higher flow temperatures.

As such, many of the HT ASHPs installed through the project may have been operating in a similar manner and with similar flow temperatures to the LT ASHPs some of the time. 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.

[9] Interim EoH results: SPF_{H2} 2.94, SPF_{H4} 2.80.

[10] The theoretical flow temperature needed to overcome 99% or 99.6% of all external temperatures.

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}	245	2.93 [2.63, 3.25]	2.93 [2.87, 2.99]
	SPF_{H3}	245	2.87 [2.54, 3.16]	2.86 [2.80, 2.91]
	SPF_{H4}	245	2.75 [2.47, 3.04]	2.75 [2.70, 2.81]
HT ASHP	SPF_{H2}	183	2.92 [2.68, 3.16]	2.97 [2.89, 3.04]
	SPF_{H3}	183	2.92 [2.67, 3.13]	2.94 [2.87, 3.01]
	SPF_{H4}	183	2.85 [2.63, 3.06]	2.88 [2.81, 2.94]

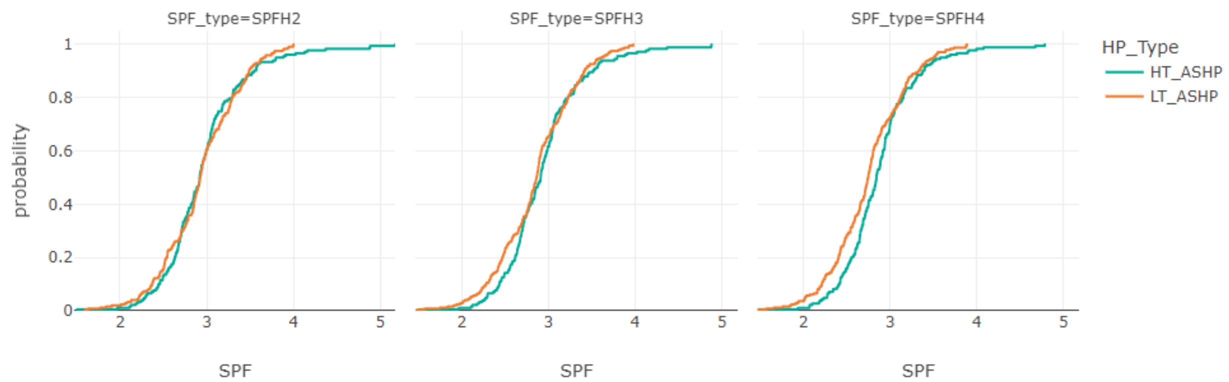

Figure 8.3: Empirical distribution of SPF for all HT and LT ASHPs, split by SPF type.

Reviewing these results, the HT ASHP units were observed to perform 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 were observed operate 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 Comparing ASHP SPF and 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 [33], 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	138
R290	3	165
R32	675	125

Figure 8.4 provides an indication of the median SPF_{H4} across 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.

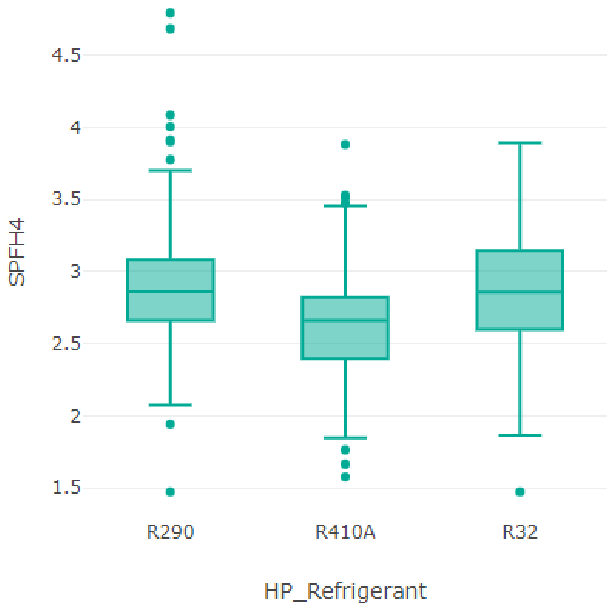

Figure 8.4: Q1, Q3 and median SPF_{H4} for all ASHPs broken down by refrigerant type.

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

Refrigerant	Median [IQR] SPF_{H4}	Mean [95% CI] SPF_{H4}
R290	2.86 [2.66, 3.08]	2.91 [2.84, 2.97]
R32	2.86 [2.60, 3.15]	2.87 [2.79, 2.94]
R410a	2.66 [2.40, 2.82]	2.63 [2.56, 2.70]

Considering no other factors, these results indicate a statistically significant relationship between the refrigerant used and the performance of the heat pumps. Notably that the more modern R32 and R290 units exhibited a significantly better performance than those using R410a. It should however be noted that other factors such as the efficiency of mechanical equipment and control strategy may have also impacted 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 and Table 8.6, it is also clear that the variance in the results for R290 was significantly lower than those for R32 and R410a. Table 8.6 below provides the number of each ASHP type which utilised each refrigerant type. It is evident that the HT ASHPs installed through this project mainly utilised R290 whilst the LT ASHPs mainly utilised 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	165	2.86 [2.66, 3.08]	2.91 [2.84, 2.97]
	R32	17	2.59 [2.42, 2.76]	2.58 [2.45, 2.72]
	R410a	1	3.00 [N/A]	3.00 [N/A]
LT ASHP	R32	108	2.90 [2.65, 3.19]	2.91 [2.83, 3.00]
	R410a	137	2.66 [2.40, 2.81]	2.63 [2.56, 2.69]

As so many of the HT ASHPs utilised what is observed as a more efficient refrigerant, the comparable 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 there is a large difference between the R32 HT and LT ASHP SPF results. However, the R32 HT ASHP sample is quite small, so conclusions should not be drawn from this observation with a great degree of certainty. In addition, there is only one HT ASHP which utilised the R410a refrigerant so the SPF result for this heat pump should not be used as a representative sample of R410a HT ASHPs.

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 worse than the others.

8.3 Performance by Flow Temperature

8.3.1 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, most heat pumps have in-built weather compensation controls which adjust the flow temperature based on the external temperature[11] 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 was first necessary to quantify the mean operating flow temperature.

The EoH heat pump monitoring systems (see Section 4.1) recorded a flow temperature reading every two 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 filtered out if trying to calculate a mean.

To calculate the mean flow temperature for each property, only the flow temperature readings when the heat pump was operational in heating mode for more than 10 minutes were considered (i.e. when the Heat Pump Energy Output was greater than zero for a minimum of 10 minutes previous and heat pump was in heating mode). The reason for excluding the first 10 minutes of data is because heat pumps take time to heat the water from its ambient condition to the desired flow temperature, as such, the flow temperatures could be skewed slightly downward, therefore the method aims to exclude the warming up period. The mean flow temperature across all ASHPs and heat pumps in hybrid systems was 39.7°C.

[11] 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.

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, whilst the relationship is weak, it is statistically significant.

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.

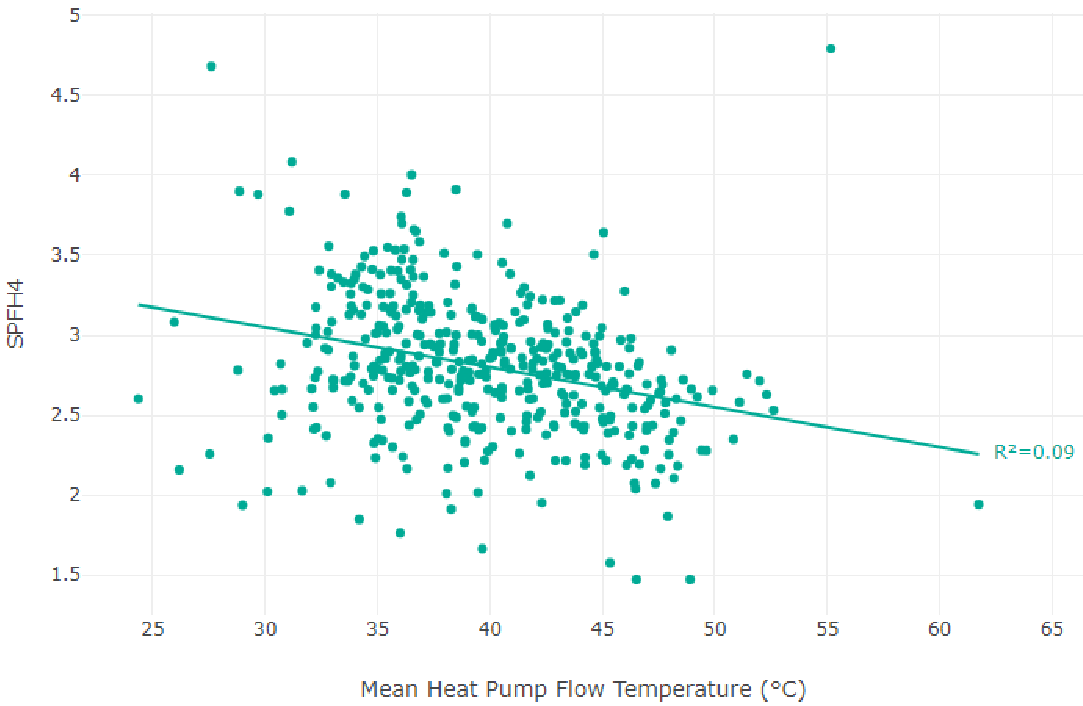

Figure 8.5: SPF_{H4} by mean heat pump flow temperature for all ASHPs. Note that flow temperatures when the heat pump was not outputting heat have been excluded from the mean.

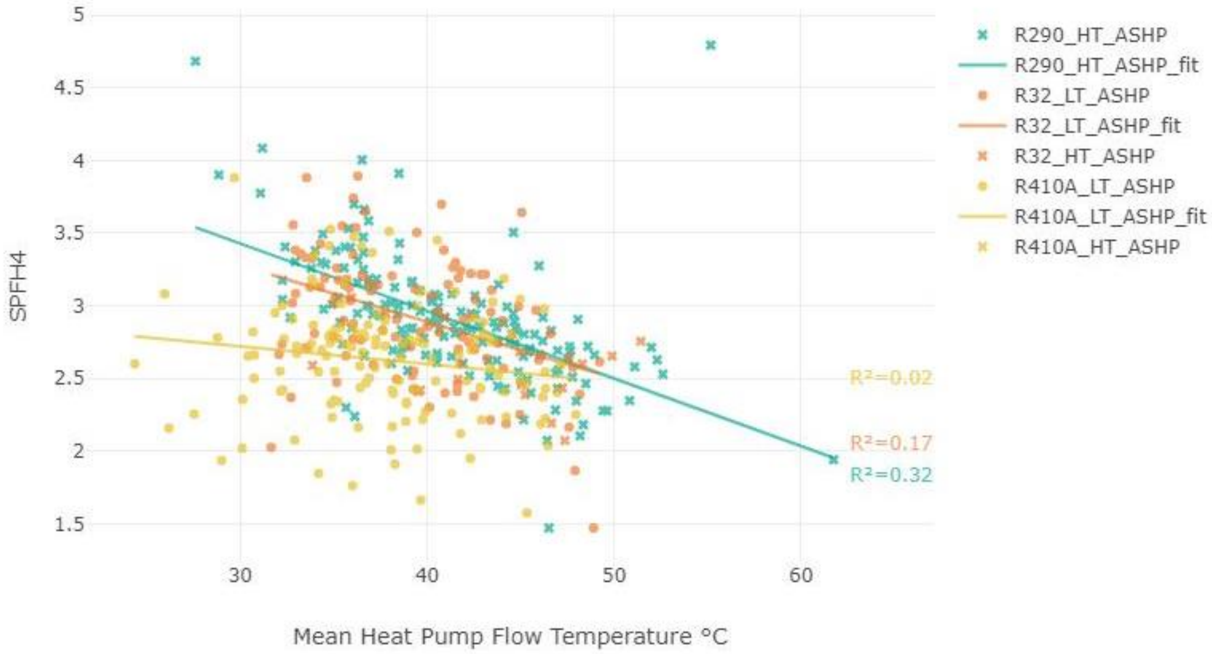

Figure 8.6: Scatter chart of mean heat pump flow temperature (°C) and SPF_{H4} by refrigerant and heat pump type. A line was not included for HT ASHPs with the R32 or R410a refrigerants as there are only 17 and 1 heat pumps in these categories respectively.

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 fell within each temperature range (25 to 35°C; 35 to 45°C and 45 to 55°C) and the mean SPF_{H4} across all of the heat pumps in these ranges.

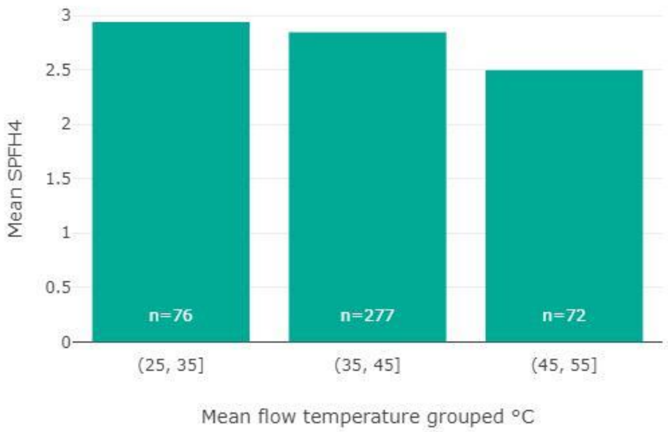

Figure 8.7: Histogram showing the mean SPF_{H4} by binned mean flow temperature (°C).[12]

[12] Note that one property had a flow temperature below 25°C and two properties had mean flow temperatures above 55°C, these have been left off of this chart.

8.3.2 Comparing High Temperature and Low Temperature Operation

It was noted in Section 8.1.2 that, based on pre-project definitions, HT ASHPs were observed to operate at a similar efficiency to LT ASHPs through this study. To assess reasons why this may have been the case, more analysis was undertaken. Section 8.2 indicates that most of the HT ASHPs were 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 HT ASHPs were less likely to have a very low mean flow temperature and more likely to have a higher mean flow temperature; however, there was a significant overlap in typical operating temperatures around 35°C to 45°C for both HT ASHPs and LT ASHPs.

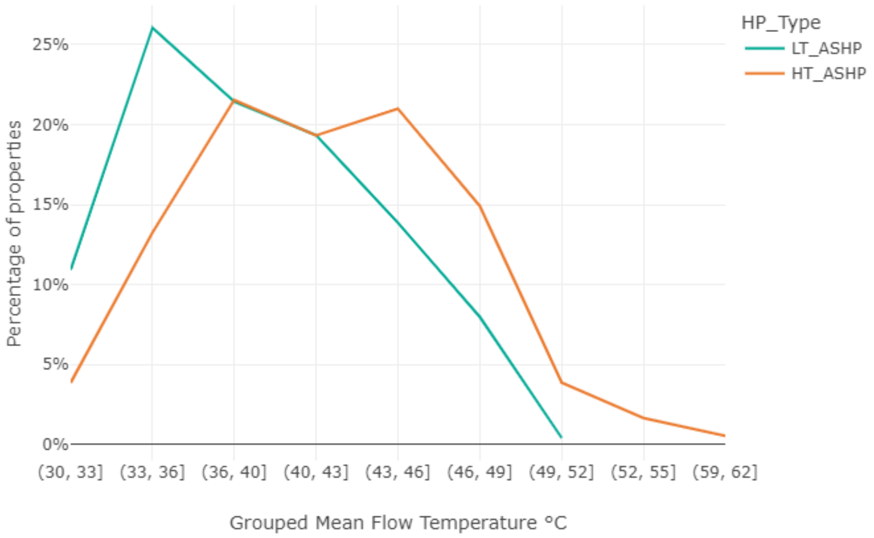

Figure 8.8: Frequency distribution of mean flow temperature by heat pump type.

Where HT operation was defined as a heat pump which operates above 65°C at any point over the 12-month period; 161 of the 183 HT ASHPs and 4 of the 245 LT ASHPs operated at a high temperature at any time during their analysed 12-month window.

Table 8.7: ASHP SPF values broken down by heat pumps which exhibited high flow temperatures at some point over the 12-month period compared with those that did not.

Heat Pump Type	SPF Type	Count	Median [IQR]	Mean [95% CI]
ASHPs which did not exhibit FT >65°C	SPF_{H2}	263	2.93 [2.61, 3.24]	2.93 [2.88, 2.99]
	SPF_{H4}	263	2.74 [2.47, 3.04]	2.76 [2.71, 2.82]
ASHPs which did exhibit FT >65°C	SPF_{H2}	165	2.93 [2.69, 3.18]	2.97 [2.90, 3.04]
	SPF_{H4}	165	2.85 [2.66, 3.07]	2.88 [2.81, 2.94]

The table does however still indicate the trend that the LT and HT ASHPs (by operation) have similar SPF. As such, it was necessary to assess how often the HT Operation ASHPs actually reach high temperatures.

Figure 8.9 shows that operating above 65°C is not a common occurrence. 139 of the 165 heat pumps operated above 65°C flow temperature less than 1% of the time and only 2 of the heat pumps operated above 65°C more than 5% of the time.

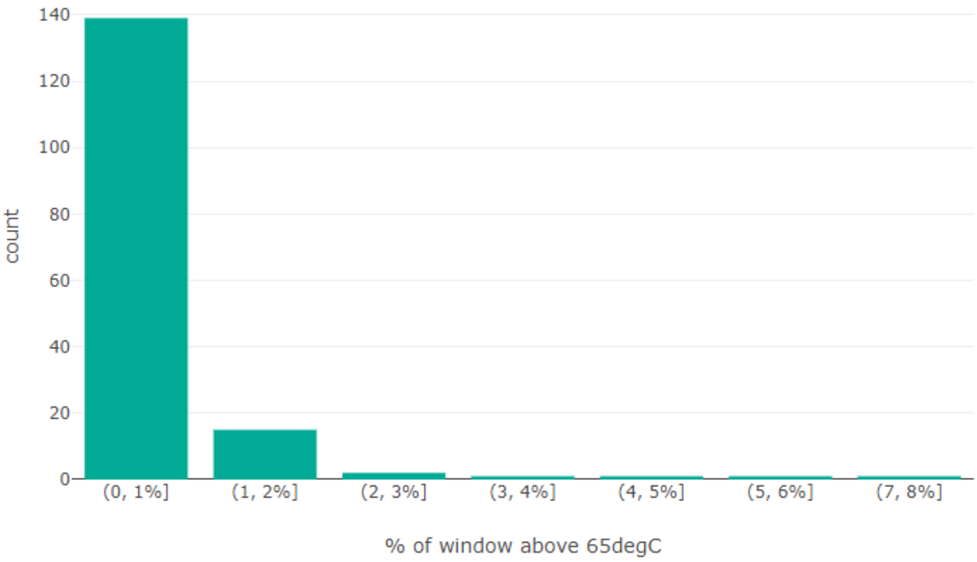

Figure 8.9: Percentage of heat pump operation above 65°C in the heat pumps observed to operate at high flow temperatures.

This is a result of two factors. The first is the design flow temperature which generally correlates to the expected building heat loss at a 99% external ambient weather condition. The second is the heat pump weather compensation controls were only demanding higher flow temperatures for a very small amount of the time to maintain good heat pump efficiencies (i.e. when at or below the designed external temperature). It may therefore be concluded that, most of the time, the HT ASHPs were 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 air source heat pumps in homes which are recommended for an installation by trained designers and installers.

A breakdown of ASHP SPF_{H4} by home type is provided in Table 8.8 below.

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

Home Type	Sample Size	Median [IQR] SPF_{H4}	Mean [95% CI] SPF_{H4}
Detached	203	2.84 [2.65, 3.14]	2.87 [2.82, 2.93]
Semi-Detached	127	2.73 [2.45, 2.95]	2.75 [2.67, 2.84]
End-Terrace	40	2.77 [2.53, 2.97]	2.76 [2.64, 2.87]
Mid-Terrace	49	2.71 [2.48, 2.98]	2.71 [2.58, 2.83]
Flat	9	2.59 [2.24, 3.33]	2.80 [2.27, 3.32]

In both the tabulated results and those shown in Figure 8.10 detached homes are observed to have a slightly higher SPF compared to the other housing types however, this increase was not large. The difference in SPF between all housing types was not statistically significant. The reasons for this are assessed at the end of this section.

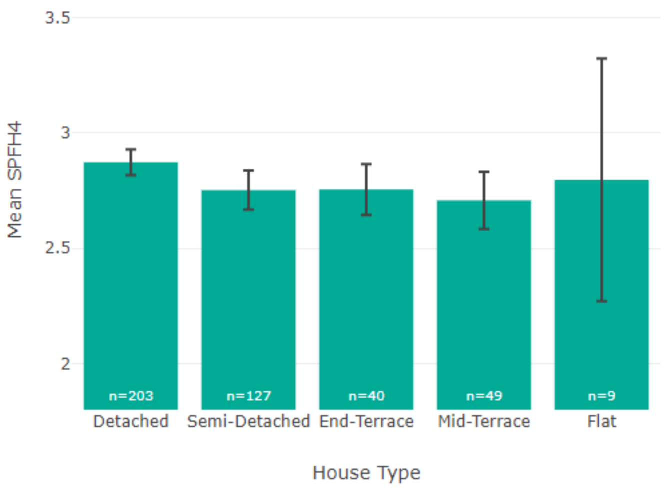

Figure 8.10: Mean SPF_{H4} of all ASHPs by house type with 95% CI.

Figure 8.11 indicates the mean heat energy output per day (over the 12-month analysis window) for all systems split by home type. This shows that detached homes demanded the most energy and, as expected, the energy demand reduced for semi-detached and end-terrace houses, mid-terrace houses and then flats.

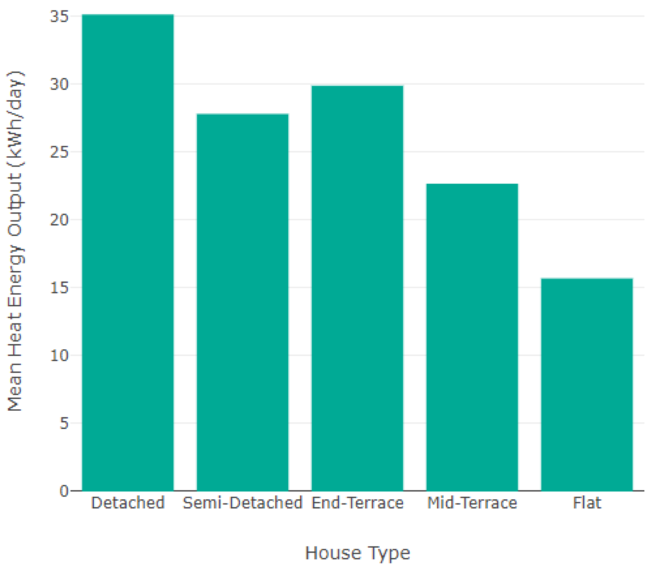

Figure 8.11: Mean heat energy output per day for each property form (including all ASHPs, GSHPs and Hybrids).

To assess the potential reason for the detached homes exhibiting a slightly higher SPF than the others, the breakdown of heat pump refrigerant type per house type was evaluated. Figure 8.12 shows the distribution of refrigerant by house type. The figure shows that a much lower proportion of the heat pumps using the R410a refrigerant were installed in detached homes compared with the other house types. As noted in Section 8.2, heat pumps using R410a were observed to operate with a lower SPF across the range of properties. This indicates that the detached homes were observed to have a higher median SPF due to having a higher proportion of higher performing heat pumps than the other home types.

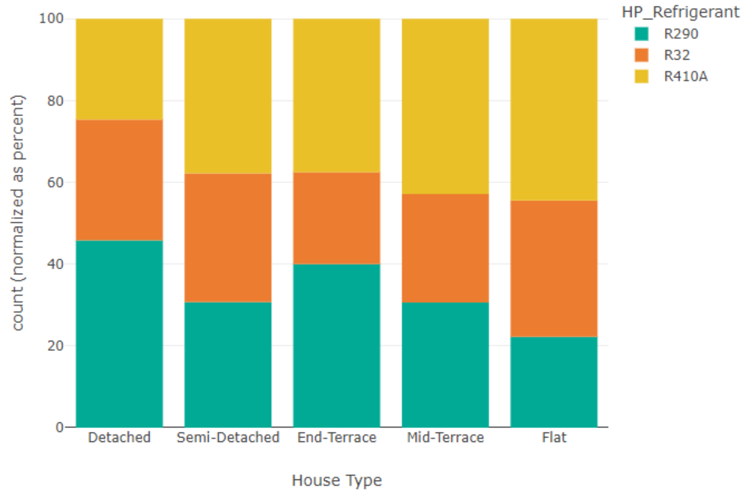

Figure 8.12: Breakdown of refrigerant type by house type.

Table 8.9 and Figure 8.13 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 was no statistically 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 for ASHP installations broken down by house age.

House Age	Sample Size	Median [IQR] SPF_{H4}	Mean [95% CI] SPF_{H4}
Pre-1919	35	2.90 [2.47, 3.15]	2.81 [2.62, 3.00]
1919-1944	50	2.84 [2.58, 3.10]	2.83 [2.72, 2.95]
1945-1964	96	2.81 [2.48, 3.10]	2.81 [2.70, 2.91]
1965-1980	92	2.74 [2.55, 3.05]	2.80 [2.71, 2.89]
1981-1990	45	2.74 [2.60, 2.98]	2.77 [2.67, 2.87]
1991-2000	40	2.80 [2.64, 3.03]	2.84 [2.72, 2.96]
2001+	70	2.77 [2.53, 3.01]	2.79 [2.70, 2.89]

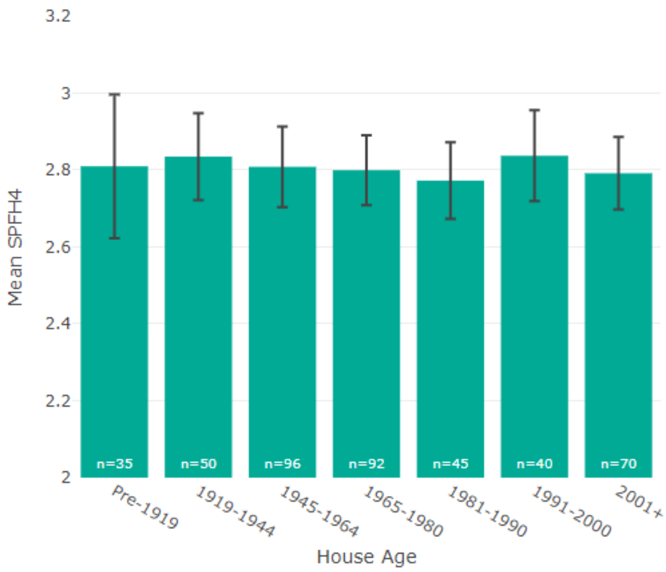

Figure 8.13: Mean ASHP SPF_{H4} by house age with 95% CI.

9. Hybrid Heat Pump System Operation

When assessing hybrid heat pump operation using the data from this project, it is necessary to reiterate that the domestic hot water provision was not metered and that any observed 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 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.

Additionally, most (139) of those with a separate boiler had a new boiler installed as part of a whole hybrid solution whereas a few (11) utilised a pre-existing boiler. The full breakdown and analysed sample is provided in Table 9.1 below.

Table 9.1: Breakdown of hybrid sample.

Hybrid system configuration	Full sample size	SPF analysis sample size
Integrated hybrid	5	5
Separate heat pump and new boiler	139	79
Separate heat pump and existing boiler	11	10

As the sample size for the integrated systems and separate systems with existing boilers is very small, more granular analysis into each system type has not been included in this report and all hybrids have been treated as one system type. This is because the small sample would produce a mean or median result with a low level of certainty and because the overall hybrid result is not significantly skewed by a small number of different systems.

The Hybrid systems installed through this project were installed to operate cost-optimally, with the heat pump providing the base space heating load (down to a certain external temperature) and the boiler providing the space heating load below the temperature at which they are designed to switch over. The designed setpoint at which the boiler took over the space heating was different for each home and generally corresponded to a certain external temperature. However, a portion of the hybrids installed through this project experienced control issues which meant that they may have utilised their boilers a higher proportion of the time than was designed and may have utilised the heat pumps at times which were different to what the design intended.

9.1 Heat Pump to Boiler Operating Ratio

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 9.2 and Figure 9.1.

Table 9.2: 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%)
94	45.0%	40.4%	29.7%	55.5%

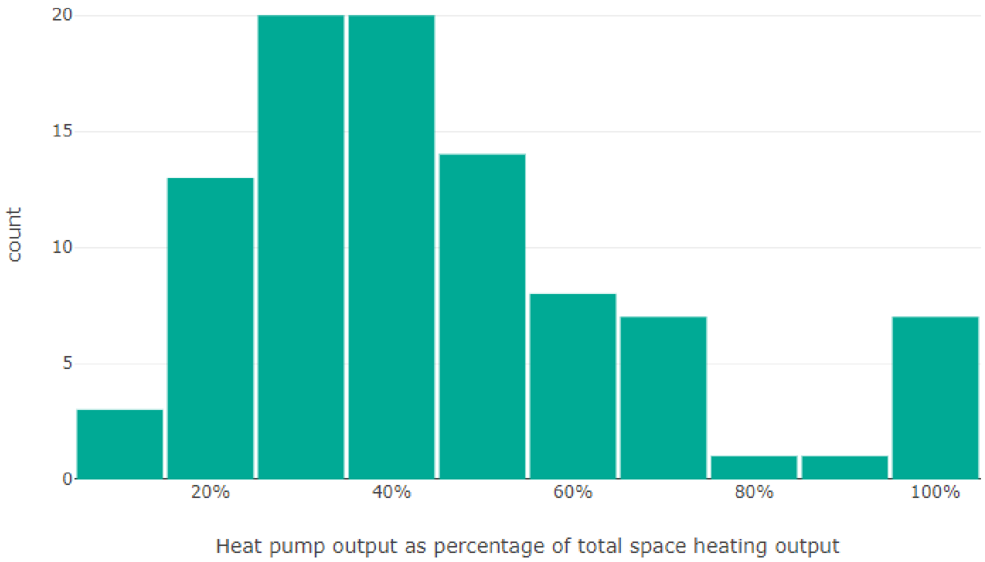

Figure 9.1: Frequency distribution of heat pump energy output as a percentage of total energy output in Hybrid systems.

9.2 System Efficiency

Section 8.1 indicates the mean and median SPF observed through this project for heat pumps within hybrid systems. For ease, this result is shown in Table 9.3 below. This result does not present a full picture of system efficiency as it does not account for boiler performance.

Table 9.3: The mean and median SPF for heat pumps within hybrid systems.

SPF	Sample	Median [IQR]	Mean [95% CI]
SPF_{H2}	94	2.68 [2.30, 3.03]	2.73 [2.58, 2.87]
SPF_{H4}	94	2.50 [2.10, 2.84]	2.51 [2.37, 2.64]

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 did not monitor hot water production, nor did 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 need to be assumed.

Using the space heating proportion and SPF_{H4} results from this project, Table 9.4 provides a matrix of estimated whole system efficiencies (COP_{Hybrid}) for hybrid systems (noting that all of the domestic hot water production was provided by the boilers) 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 (median) 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 Efficiency 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 9.4: Hybrid system efficiency matrix with assumed boiler efficiency across the top, hot water production percentage down the left and therefore estimated hybrid system efficiency (COPHybrid) in the middle (blue cells).

COP_{Hybrid}		Boiler Efficiency (%)								
		76%	**78%**	**80%**	**82%**	**84%**	**86%**	**88%**	**90%**	**92%**
Hot Water Production (%)	**10%**	142%	143%	144%	145%	147%	148%	149%	150%	152%
	12%	140%	141%	143%	144%	145%	146%	148%	149%	150%
	14%	139%	140%	141%	143%	144%	145%	146%	148%	149%
	16%	137%	139%	140%	141%	142%	144%	145%	146%	148%
	18%	136%	137%	138%	140%	141%	142%	144%	145%	146%
	20%	134%	136%	137%	138%	140%	141%	142%	144%	145%

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.

It might be expected that a low heat pump utilisation results in the heat pump producing lower flow temperatures on average and should therefore result in a higher SPF. However, low utilisation could also indicate a hybrid system which has been installed in a less efficient property. In this scenario, the heat pump may need to output slightly higher flow temperatures than in a more efficient property resulting in a lower SPF. Equally, a low heat pump utilisation may be the result of control issues or operating a heat pump intermittently which may negatively impact upon SPF.

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.

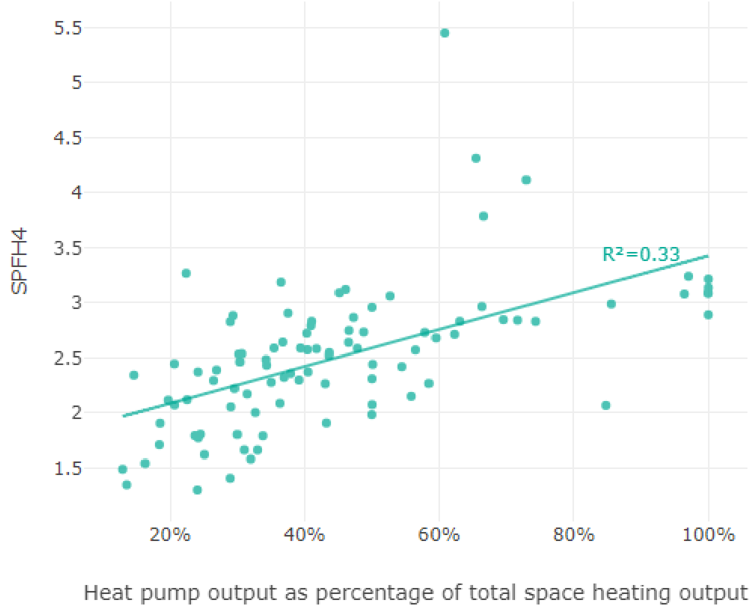

Figure 9.2: SPF_{H4} of heat pumps in hybrid systems by heat pump output percentage.

It should also be noted that as a result of the hybrid systems cost-optimal control strategy, the less efficient homes with greater heat losses will likely have a lower setpoint at which the boiler takes over the space heating load. They are therefore likely to experience a higher boiler percentage operation and a slightly lower SPF result.

10. COP Temperature Dependency

To determine the impact of large-scale rollout of heat pumps on the wider energy system, it is necessary to consider the variation in COP (and therefore power draw) of heat pumps over different 30-minute periods. It is also necessary to consider how these factors vary during the coldest periods of the year. The following subsections consider the impact of varying flow temperatures and external temperatures on COP both by considering the mean flow and external temperature over 30-minute periods and by considering the COP over the coldest days of the year.

10.1 External Temperature Impact on COP

The heat demands of buildings are highest when it is coldest outside. These periods are also commonly the periods where heat pumps operate least efficiently as the heat source (typically external air) has less energy which can be extracted, and the heat emitters often need higher temperature water to overcome the heat loss of the building. It is important in assessing the energy system impact of large-scale rollout of heat pumps to evaluate how they operate when it's coldest outside.

Considering only a singular 30-minute period, the resultant power draw and COP may be subject to significant noise as any given property will be subject to variable conditions such as preheating, use of other heating assets (such as an oven or fire) or open windows. As such, it was necessary to aggregate all 30-minute periods across all heat pumps which were subject to a given external temperature. Similar flow temperature-based analysis is provided in Section 10.3.

To perform this analysis, each external temperature in the 30-minute dataset was taken and filtered for periods when the heat pump was operational. Then these external temperatures were rounded to the nearest 1°C. The median COP across all heat pumps for each 1°C interval was calculated based on the different heat pump types.

Figure 10.1 indicates the median $COP_{(H4)}$ against the bucketed (1°C interval) external temperature across all ASHPs.

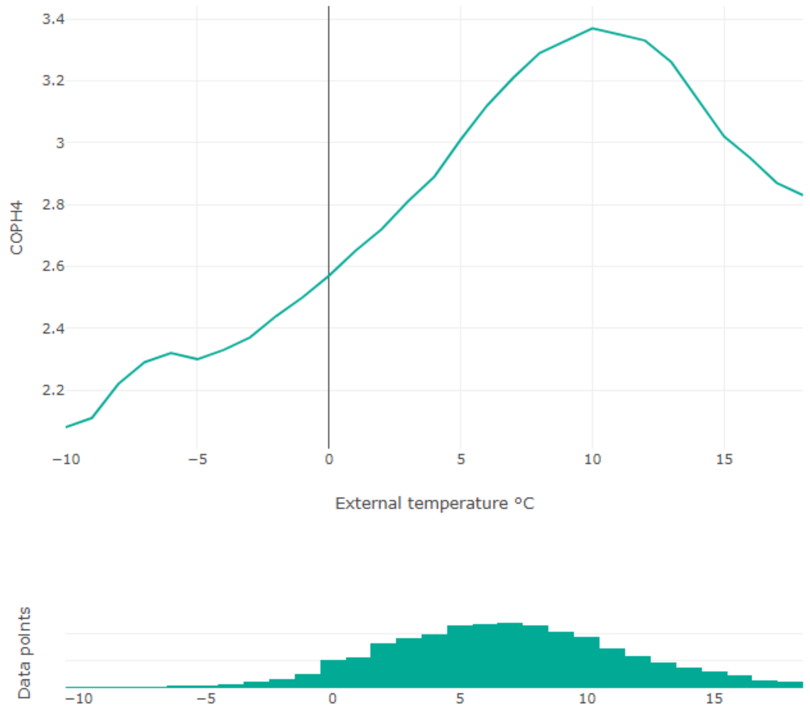

Figure 10.1: (Above) 30-minute mean external temperature plotted against median $COP_{(H4)}$ across all ASHPs across and all periods. (Below) The spread of datapoints across each temperature interval.

The graph shows a significant increase in COP as the external temperature increased up 10°C ($COP_{(H4)}$ = 3.37) when many of the heat pumps were using more energy for hot water production than heating. As the external temperature after this point rose, the COP decreased but it should be noted that, due to switching from heating to hot water mode, the energy consumed after this point also decreased. The sample size at the lower extreme of the external temperatures is very small however, the decrease in COP (alongside external temperature) continued to this point where the COP was 2.08 as the external temperature decreased to -10°C.

All of the UK external design conditions (in the MCS Heat Pump Standard Design [34] Guide) are between 0°C and -6°C.[13] This is because these are the temperatures which are exceeded 99% to 99.6% of the time in the UK. Noting these design temperatures, the median COP, heat pump energy output and heat pump energy input across all of the heat pumps between these points was evaluated and is shown in Table 10.1.

[13] 99% temperature for Plymouth is -0.2°C and 99.6% temperature for Glasgow is -5.9°C. All other temperatures fall between these two. Most design conditions lie around -3.0°C and -5.0°C.

Table 10.1: The median 30-minute COP(H4), 30-minute Heat Pump Energy Output and 30-minute System Energy Input across all ASHPs given each rounded external temperature.

Rounded external temperature	Sample	Median $COP_{(H2)}$	Median $COP_{(H4)}$	Median Heat Pump Energy Output (kWh)	Median Whole System Energy Consumed (kWh)[14]	Max Whole System Energy Consumed (kWh)[15]
0°C	100478	2.67	2.57	1.45	0.59	4.37
-1°C	51895	2.60	2.50	1.60	0.67	4.37
-2°C	35653	2.54	2.44	1.68	0.72	4.36
-3°C	23578	2.48	2.37	1.76	0.79	4.25
-4°C	14787	2.43	2.33	1.85	0.84	3.92
-5°C	7440	2.39	2.30	1.85	0.84	4.19
-6°C	4816	2.39	2.32	1.88	0.86	4.36

Figure 10.2 and Table 10.2 show the same statistic but with for all GSHPs.

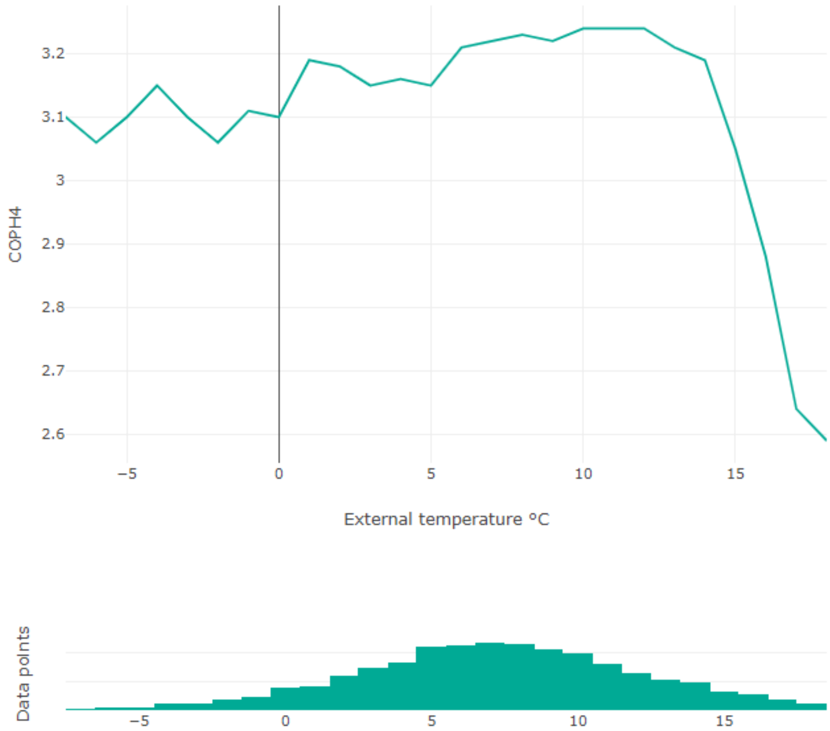

Figure 10.2: (Above) 30-minute mean external temperature plotted against median COP(H4) across all GSHPs across and all periods.[16] (Below) The spread of datapoints across each temperature interval.

[14] Whilst the median values appear low, this is due to averaging over several thousand 30-minute periods. Peak power demands should not be interpolated from these values, the peak power draw of a heat pump is often closer to its highest possible power draw.
[15] The maximum value is the max from one 30-minute period from one property (i.e. non-diversified). It is provided to demonstrate variance of a potential peak from the median. The difference between GSHP and ASHP should not be analysed as they are likely to represent different heat pump sizes.
[16] At the lower extreme of the GSHP plot the sample size was very low and so a narrower filter has been applied to the x-axis on this plot.

Table 10.2: The median 30-minute COP(H4), 30-minute Heat Pump Energy Output and 30-minute System Energy Input across all GSHPs given each rounded external temperature.

Rounded external temperature	Sample	Median $COP_{(H2)}$	Median $COP_{(H4)}$	Median Heat Pump Energy Output (kWh)	Median Whole System Energy Consumed (kWh)[17]	Max Whole System Energy Consumed (kWh)[18]
0°C	3857	3.31	3.10	1.05	0.35	3.06
-1°C	2230	3.30	3.11	1.18	0.38	3.10
-2°C	1879	3.28	3.06	1.13	0.38	3.08
-3°C	1278	3.30	3.10	1.08	0.36	3.04
-4°C	991	3.35	3.15	1.07	0.35	3.10
-5°C	462	3.33	3.10	1.24	0.41	3.10
-6°C	252	3.30	3.06	1.30	0.44	3.09

Noting that the GSHP sample size was much smaller than that of ASHPs, comparing the two sets of results indicates that, as may be expected, the GSHP COP was much less temperature dependent than that for ASHPs. This relationship is demonstrated in Figure 10.3.

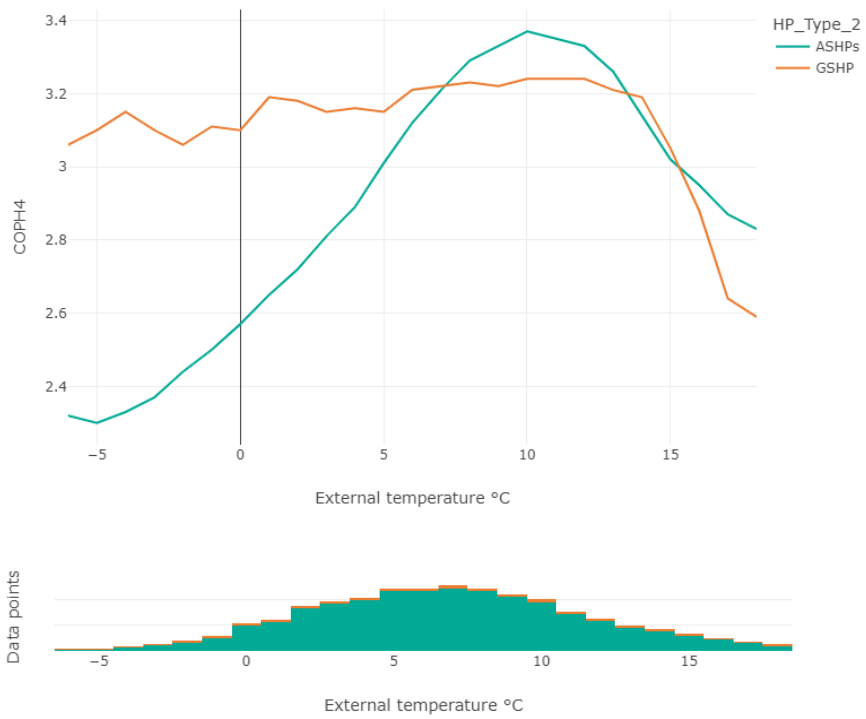

Figure 10.3: (Above) 30-minute mean external temperature plotted against median COP(H4) across all ASHPs and GSHPs, across and all periods. (Below) The spread of datapoints across each temperature interval.

[17] Whilst the median values appear low, this is due to averaging over several hundred 30-minute periods. Peak power demands should not be interpolated from these values, the peak power draw of a heat pump is often closer to its highest possible power draw.
[18] The maximum value is the max from one 30-minute period from one property (i.e. non-diversified). It is provided to demonstrate variance of a potential peak from the median. The difference between GSHP and ASHP should not be analysed as they are likely to represent different heat pump sizes.

This is because the energy available in the GSHPs heat source (geothermal energy) does not fluctuate as much as the external air as changes in weather are experienced. The COP still decreased slightly, most likely as a result of the increasing flow temperature as the external temperature reduced, however the impact was much lower.

Figure 10.4 indicates the median $COP_{(H4)}$ against the external temperature across all ASHPs broken down per refrigerant.

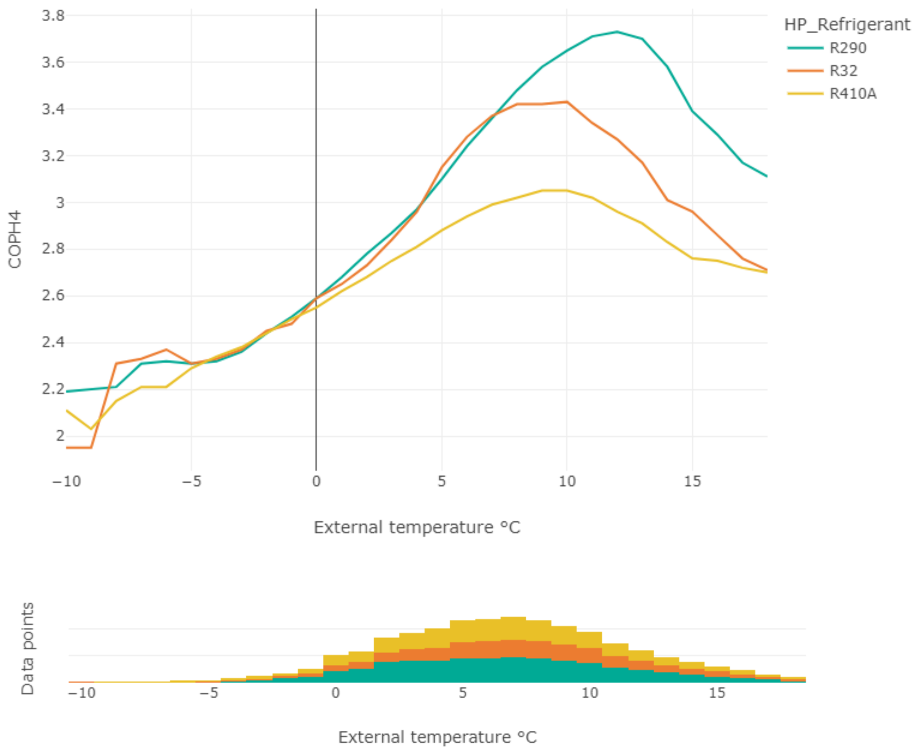

Figure 10.4: (Above) 30-minute mean external temperature plotted against median $COP_{(H4)}$ across all ASHPs across and all periods, split by refrigerant. (Below) The spread of datapoints across each temperature interval.

This figure shows that all of the heat pumps operated with a similar efficiency between -7°C and 3°C external temperature. Below -7°C, the sample sizes for all categories are small, hence the data became spikier. Above 3°C, the performance of both R32 and R290 heat pumps continued to rise at a steep gradient whereas R410a heat pumps performed with a lower efficiency. As most of the UK heating season is above 3°C external temperature, this shows that the more modern R32 and R290 heat pumps were better optimised for UK conditions however, that the (very) cold weather COP across all of the ASHPs was consistent.

10.2 Coldest Day Analysis

10.2.1 Window Selection

Another method to analyse air source heat pump performance during colder periods, is 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 10.3 (selected based on mean external temperature).

Table 10.3: The 10 most common coldest days, including how many homes they were the coldest day for (count), 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 10.5.

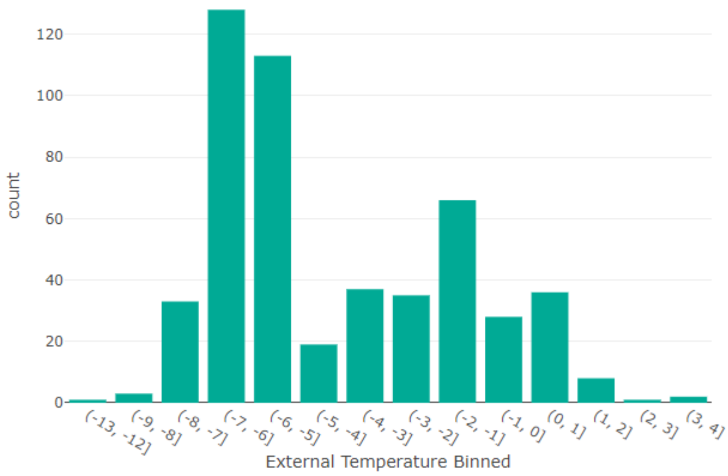

Figure 10.5: Distribution of mean external temperature in the coldest day analysis window.

10.2.2 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 10.4. Figure 10.6 indicates the $COP_{(H4)}$ variation against the mean difference between internal and external temperatures on the coldest day.

Table 10.4: Median and mean COPs for the coldest day across all ASHPs.[19]

Sample Size	Median [IQR] $COP_{(H4)}$	Mean [95% CI] $COP_{(H4)}$	Mean external temp. (°C)
510	2.27 [2.04, 2.49]	2.27 [2.23, 2.30]	-4.15

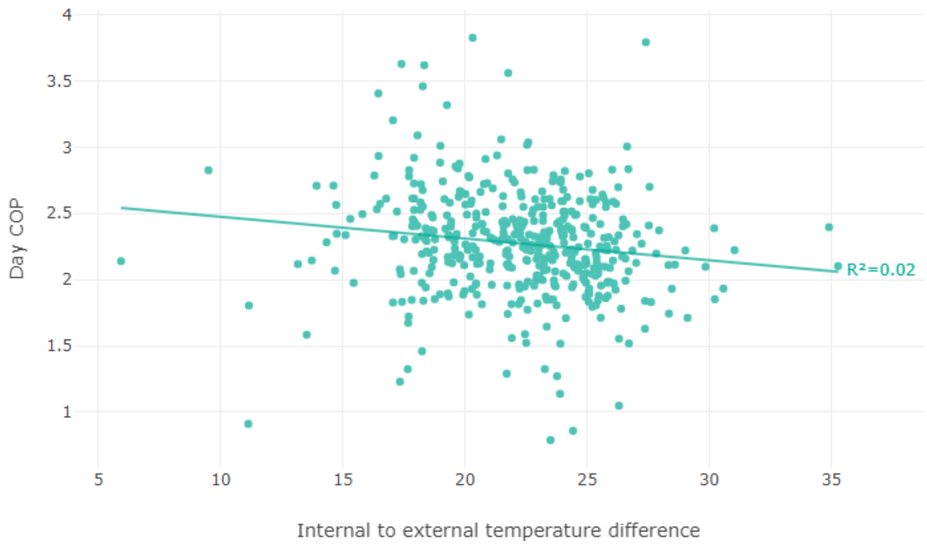

Figure 10.6: Scatter graph indicating the $COP_{(H4)}$ against the difference between internal and external temperature.

Reviewing this figure, there is a lot of variation in the $COP_{(H4)}$ values, especially where there is a mean temperature difference of 15 to 25°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 external factors can impact upon heat pump performance. These may include the pre-conditioning of the property leading up to the analysis window, the heating setpoint during the window (which may be impacted by participant occupancy) as well as any excessive heat gains or losses during the window such as the opening of windows or the use of an oven or any supplementary heating which has not been monitored (such as log fires).

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.

[19] Note that the median and mean COP are lower than observed through the interim analysis when they were both 2.44. This is likely due to a lower mean external temperature (during the coldest days) as this has reduced from -0.4°C in the interim analysis to -4.15°C in this final analysis.

10.3 Flow Temperature Impact on COP

The following subsection provides similar analysis to Section 10.1 however, it is based on the variance in flow temperature of the heat pumps, rather than external temperature. The flow temperature and external temperature are intrinsically linked as, as external temperature decreases the resultant heat loss of a building increases and therefore flow temperatures must increase to provide the required heat energy into each room given radiator sizes are fixed.

To perform this analysis, each flow temperature in the 30-minute dataset was taken and filtered for only when the heat pump was operational. Then this flow temperature was rounded to the nearest 1°C. The median COP across all heat pumps for each 1°C interval was calculated based on the different heat pump types.

Figure 10.7 indicates the median $COP_{(H2)}$ against the rounded (1°C interval) flow temperature across all ASHPs and GSHPs.

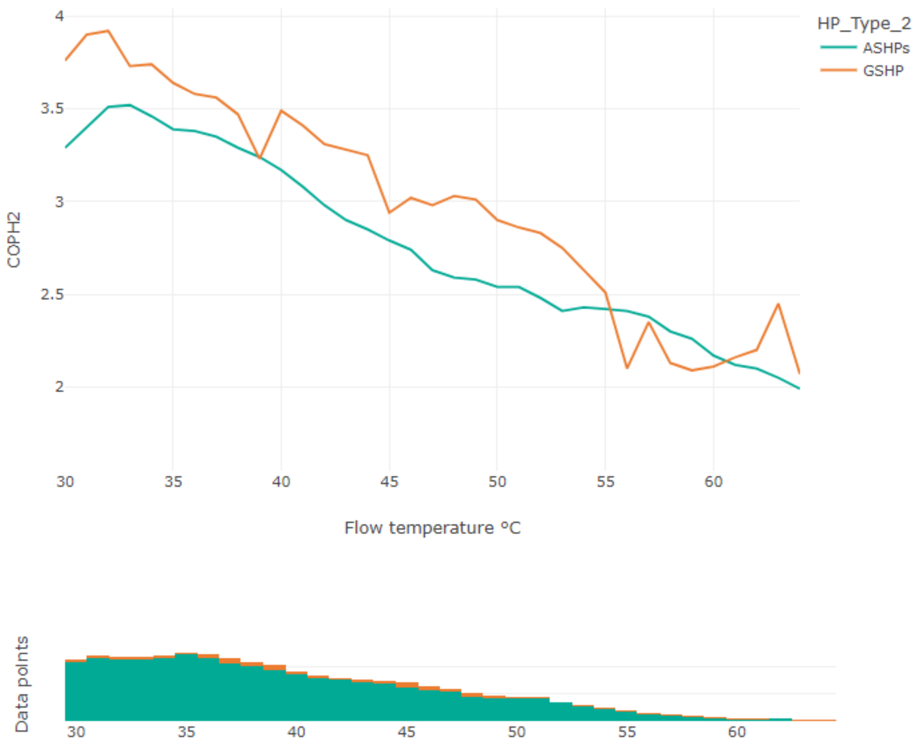

Figure 10.7: (Above) Rounded flow temperature for all ASHPs and GSHPs across each 30-minute period plotted against COP for that period. (Below) The spread of datapoints across each temperature interval.

Figure 10.8 indicates the median $COP_{(H2)}$ against the flow temperature across all ASHPs broken down per refrigerant.

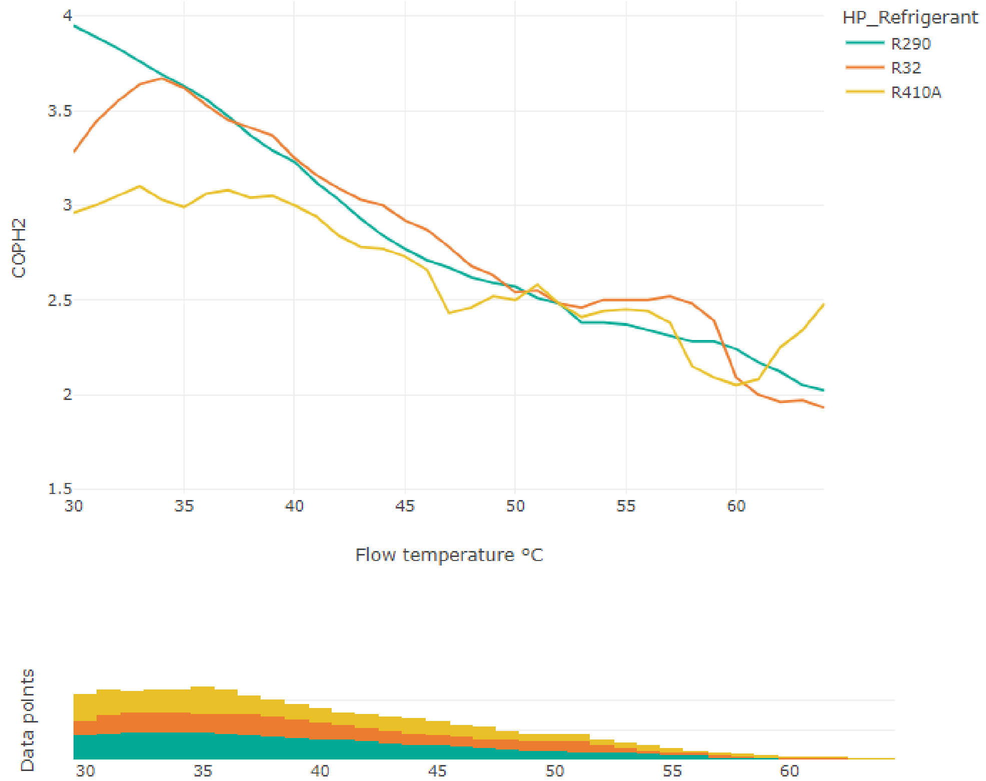

Figure 10.8: (Above) Rounded flow temperature for all ASHPs (split by refrigerant) across each 30-minute period plotted against COP for that period. (Below) The spread of datapoints across each temperature interval.

Note that any spikiness in the graphs is generally due to low sample size for the specific flow temperatures, particularly at the higher extremity for GSHPs and R410a ASHPs.

Reviewing the figures, it is clear that as flow temperatures increase, the COP decreases for all heat pumps. This reiterates that from an efficiency perspective, the temperatures which a heat pump typically operates at are more important than its maximum achievable temperature.

The result also indicates that the overall energy consumption and peak power demands of heat pumps which regularly operate at higher temperatures will be greater. Heat pump systems should therefore be designed and set up to operate at low flow temperatures for as much of the time as possible, regardless of their maximum temperature. It is worth noting that in some cases systems may need to be designed to consistently operate at higher temperatures to reduce disruption (from changing pipework and radiators) or to enable faster decarbonisation of less efficient homes. When assessing these cases the overall costs and benefits to both the consumer and the wider system need to be considered.

11. Comparing Designed and Actual Performance

This section compares the SPF with the MCS listed Seasonal Coefficient of Performance (SCOP)[20] values. For this comparison the SPF_{H2} value is used as this represents the same system boundary as the SCOP.

For a property to be included in this part of the analysis it was required to have a SPF which met the criteria to be included in the SPF analysis (see Section 6.3.6) and have a SCOP listed on the MCS installations database. Note that all 'as designed' SCOP values have been obtained from the MCS installations database and are provided in the supplementary dataset [18]. Table 11.1 indicates the number of properties with a useable SPF, the number of properties with a useable SCOP and the number of properties with both which were then used for this analysis.

Table 11.1: The sample size for the designed and actual performance comparison analysis.

Sample Description	Sample size	Percentage of EoH sample
Full sample	742	100%
Properties included in the SPF analysis: SPF_{H2}	545	73.7%
Properties with MCS design information: 'as designed' SCOP	645	87.3%
Properties included in this analysis, with calculated SPF_{H2} and with available 'as designed' SCOP	483	65.4%

For each of the 483 properties, both the difference and the relative difference (%) between the SPF_{H2} value and the 'as designed' SCOP have been calculated using the below two equations.

$$Difference = SPF_{H2} - SCOP; \qquad Relative\ Difference = \frac{SPF_{H2} - SCOP}{SCOP}$$

For 92% of the properties considered, the SPF_{H2} was lower than the SCOP. The mean difference between the two was -0.66, meaning the SPFH2 was 18% lower than the SCOP. A comparison of the differences between SCOP and SPF_{H2} is provided in Table 11.2 and Figure 11.1 below.

Table 11.2: The mean and median difference between SPF_{H2} and SCOP.

	Mean [95%CI]	Median [IQR]
Difference	-0.66 [-0.71, -0.61]	-0.69 [-0.97, -0.36]
Relative (%) Difference	-17.9 [-19.3, -16.5]	-19.4 [-26.9, -9.8]

[20] The SCOP value is the designed approximation of the true energy efficiency of a technology over an entire year (based on lab tested efficiency results) and as such is used alongside SPF to compare designed and in-situ performance.

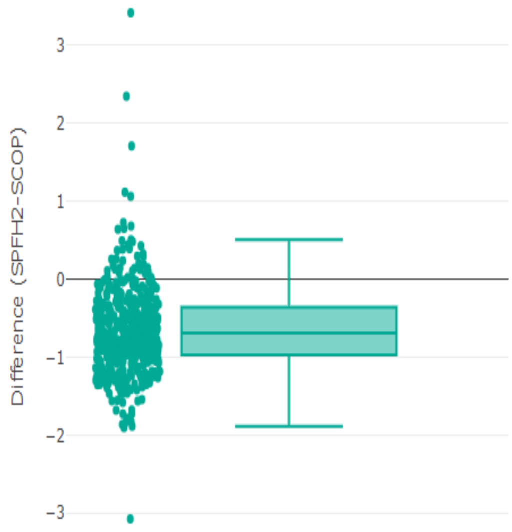

Figure 11.1: Box plot showing the distribution of the difference between SPF_{H2} and SCOP for all analysed properties.

Reviewing the results, whilst this study has found that for many homes the real-world performance of heat pumps is good, it is clear that on average the design process resulted in an overestimation of heat pump efficiencies at the design stage.

To evaluate whether this difference was spread across all heat pump types or mainly down to one type of heat pump, the difference between designed SCOP and SPF_{H2} was considered for ASHPs and heat pumps in hybrid systems independently. GSHPs were not included as the sample which had both a SCOP and a useable SPF was too small. The results are presented in Table 11.3.

Table 11.3: The difference and relative difference between SCOP and SPF_{H2} split by heat pump type.

		Difference		**Relative (%) Difference**	
Heat Pump	**Sample Size**	**Mean [95% CI]**	**Median [IQR]**	**Mean [95% CI]**	**Median [IQR]**
ASHP	413	-0.70 [-0.75, -0.65]	-0.72 [-1.0, -0.37]	-18.9 [-20.2, -17.7]	-19.9 [-27.4, -10.7]
Hybrid	69	-0.39 [-0.58, -0.21]	-0.5 [-0.78, -0.1]	-12.0 [-17.9, -6.1]	-16.22 [-23.9, -3.6]

To further evaluate whether the difference was apparent across each heat pump type, Table 11.4 shows the difference in between SCOP and SPF for heat pumps containing each of the three refrigerants used in the ASHPs installed through the EoH project.

Table 11.4: The difference and relative difference between SCOP and SPFH2 split by ASHP refrigerant type.

		Difference		**Relative (%) Difference**	
Heat Pump	**Sample Size**	**Mean [95% CI]**	**Median [IQR]**	**Mean [95% CI]**	**Median [IQR]**
R410a	136	-0.66 [-0.74, -0.59]	-0.65 [-0.93, -0.38]	-18.94 [-20.94, -16.93]	-19.14 [-26.43, -11.18]
R32	176	-0.53 [-0.63, -0.44]	-0.59 [-0.9, -0.26]	-14.71 [-17.54, -11.89]	-16.81 [-25.31, -7.53]
R290	171	-0.78 [-0.86, -0.69]	-0.81 [-1.12, -0.47]	-20.25 [-22.33, -18.17]	-21.74 [-28.58, -13.25]

It is clear when reviewing the results that the difference of SCOP at the design stage (compared to SPF_{H2} results) was apparent across all other heat pump types.

As the spread of results was quite wide across all heat pump types, any correlation between the SPF_{H2} and SCOP was explored to understand whether the SCOP was routinely higher by a similar amount across the sample or whether the differences were more random. The scatter plot shown in Figure 11.2 plots each SPF_{H2} result against the properties designed SCOP. To assess if there was any relation between the two variables compared, an Ordinary Least Square (OLS) regression model was implemented, this is shown in grey. In red, an y=x line is shown to help visualise and interpret the results.

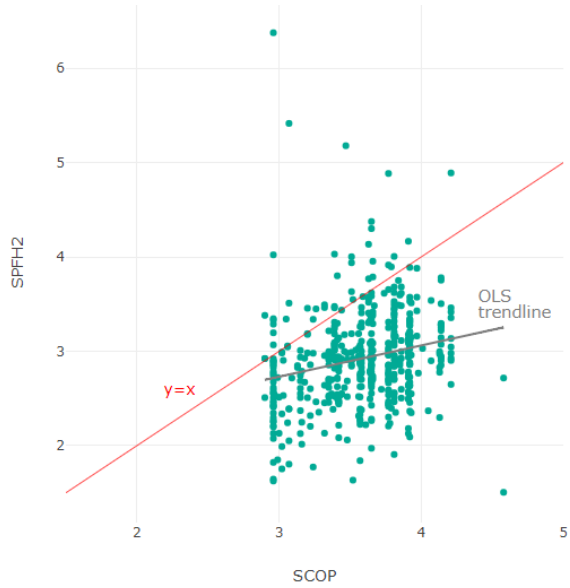

Figure 11.2: Scatter plot showing the SPF_{H2} vs SCOP for the full analysed sample.

As indicated before, most of the data points fall below the y=x red line, i.e., SPF_{H2} was lower than 'as designed' SCOP. The R^2 of the OLS regression model is 0.05 (p-value = 0.00), which confirms that there was little to no correlation between the 'as designed' SCOP and derived SPF_{H2}.

There are two conclusions which can be drawn from this. Firstly, the 'as designed' SCOPs appear to consistently overestimate performance which indicates there is an issue with the 'as designed' SCOP calculations that needs addressing so consumers are given a realistic picture of the performance they should expect.

Just as importantly, the lack of correlation suggests that the current method for estimating 'as designed' SCOP fails to predict whether an individual heat pump installation will perform well compared to others.

Both of these conclusions may be the result of the common method to select the SCOP which generally consists of making a selection based on lab-test results and the designed flow temperature (this is indicated by the vertical lines on the scatter showing identical SCOPs for multiple properties). This method for calculating or selecting 'as designed' SCOPs appears to be consistently missing key factors that influence performance.

There are a examples of a few heat pumps installed through this project and others installed through other projects where the real-world performance is comparable to or better than the as-designed SCOP. This shows that achieving the SCOP calculated at design stage is not impossible given the correct conditions. It is likely that utilising SCOPs which were derived from lab test results does not account for variations which occur during the installation process or the heat pump operation.

Overall, the results suggest that additional review of the SCOP selection method could be conducted to evaluate whether there might be a more robust method to calculate expected SCOP at the design stage, providing a more realistic estimate for consumers.

Note that whilst in theory systemic monitoring issues that resulted in under-reporting SPF could account for some of this performance gap, both the rigorous data quality checks and the fact the performance gap has been observed in previous studies renders this unlikely to be a major factor. Equally, whilst this result is assumed to be due to the simplified SCOP selection used in most designs, the project analysis did not directly evaluate the accuracy of the designs or the quality of all installations and so contribution of installation quality to the performance gap compared to design accuracy cannot be quantified.

12. Conclusions

The Electrification of Heat Demonstration Project has found that Air Source Heat Pump (ASHP) Seasonal Performance Factors (SPFs) have improved by around 0.3 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 12.1. The analysis indicates that some of this improvement was 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 12.1: Median ASHP SPFs.

SPF Type	Sample Size	Median [IQR]
SPF_{H2}	428	2.93 [2.67, 3.19]
SPF_{H3}	428	2.88 [2.62, 3.15]
SPF_{H4}	428	2.78 [2.55, 3.05]

The heat pumps in hybrid systems had a median SPF_{H2} of 2.68 which is lower than ASHPs. They were used to meet between 30% and 56% of the space heating demand in half of installations with a median proportion of space heating demand met by the heat pump across all hybrid installations of 40%. Heat pumps in hybrid systems were also found to be less efficient the smaller the proportion of heating demand they met. It should be noted that these hybrid systems were commissioned to operate cost optimally and may have exhibited different results if they had been commissioned differently.

The improvement in SPF may suggest that the design (and installation) of heat pump systems has improved over the period between the two studies. However, the EoH project has also found that variation in performance between heat pump installations remains high. Some of the reasons for this variation relate to the efficiency of heat pump units as noted above but, using the data collected through the EoH project, reasons for this variation were difficult to quantify with high certainty. The variation in performance does however suggest that progress may still be required to improve the quality and consistency of heat pump designs and installations. More research should therefore be conducted to evaluate the impact of low-quality design and installation and identify measures to improve the consistency; ultimately supporting a large-scale rollout of heat pumps in existing homes and deliver positive energy, carbon, and consumer outcomes.

The results indicate a performance gap between the SCOPs which were calculated at the design stage and the real-world SPF results. In addition, there was no correlation found between designed SCOPs and SPFs so, a higher SCOP at design stage did not necessarily translate into higher real-world performance. SCOPs are based upon lab test results however; they are provided to indicate the performance a consumer may expect. Therefore, the results indicate that a review should be conducted (including further research into the current methods for calculating building heat loss, designing heating systems and estimating efficiencies). This should aim to evaluate how and why designs consistently produce unrealistic estimates for many consumers.

Heat pump COP varied based on external temperature though the impact of this was smaller across the GSHP sample. At more moderate temperatures during the heating season, the ASHPs exhibited high COPs (e.g. the median 30-minute $COP_{(H4)}$ across all ASHPs when external temperatures were 10°C was 3.37). As temperatures cooled to the common GB design conditions of -3°C and -5°C, the 30-minute $COP_{(H4)}$ across all ASHPs reduced to 2.37 (at -3°C) and 2.30 (at -5°C).

All types of heat pump exhibited lower efficiencies when generating higher flow temperatures however, high temperature ASHPs did not perform worse than low temperature ASHPs. This is likely due to the fact that for most of the time they operated at similar temperatures as low temperature ASHPs and, when doing so, the modern high temperature heat pumps (using the R290 refrigerant) tended to operate with a higher COP than many (R410a) LT ASHPs. Figure 10.8 in Section 10.3 indicates this result.

Combining these two results, the comparable SPF means that HT ASHPs may be used (without a significant negative impact on consumers) to avoid deeper retrofit in cases where the difficulty or economics make energy efficiency measures less achievable. However, to reduce the peak electricity demand from heat pumps (and associated impact on the whole energy system), designers and installers should still aim to design systems which operate at lower temperatures most of the time where possible. Systems should only be designed to use higher temperatures where they're cost-effective and/or unavoidable or, as a backup when they are needed (in particularly cold periods).

13. Appendix 1 – GSHP Performance Results

As noted in the main body of the report, the GSHP sample is limited and contains both shared loop and individual GSHPs. As a result of the shared loops, the sample is less diverse. One of the impacts of this is that behaviours resulting in different performance could be amplified by being adopted by a larger proportion of the participants. An example is, if a small number of participants decided to utilise their immersion heaters rather than heat pump for Domestic Hot Water production, this behaviour is more likely to be copied by more participants and, the small sample size means this behaviour is seen across a larger proportion of the sample, thus skewing the results more significantly than if there were a larger, more diverse sample.

As a result of this potential skewing, there is a lack of certainty in the representativeness of the results. **It is therefore not recommended that these results be used as a reference for mean or median GSHP SPF.**

The RB&M analysis of Ofgem heat pump data [8], published at the same time as this report, provides analysis on a sample of 286 GSHPs installed between 2017 and the end of 2022 and, as such, provides a more robust value which can be used as a reference for GSHP performance.

Table 13.1 provides a breakdown of the median and mean SPF values for all GSHPs. Table 13.2 provides a breakdown of the median and mean SPF values based on GSHP configuration (Shared ground loop and individual GSHPs).

Table 13.1: Median and mean SPF values for all GSHPs.

Heat Pump Type	SPF Type	Sample Size	Median [IQR]	Mean [95% CI]
GSHP	SPF_{H2}	23	3.29 [2.93, 3.75]	3.43 [3.13, 3.72]
	SPF_{H3}	23	3.16 [2.72, 3.43]	3.18 [2.98, 3.39]
	SPF_{H4}	23	2.85 [2.62, 3.33]	2.99 [2.78, 3.21]

Table 13.2: Median and mean SPF values for individual and shared ground loop GSHPs separately.

Heat Pump Type	SPF Type	Sample Size	Median [IQR]	Mean [95% CI]
Shared Ground Loop GSHP	SPF_{H2}	16	3.18 [2.78, 3.32]	3.21 [2.90, 3.52]
	SPF_{H3}	16	3.14 [2.65, 3.21]	3.02 [2.85, 3.19]
	SPF_{H4}	16	2.75 [2.55, 2.95]	2.80 [2.63, 2.96]
Individual GSHP	SPF_{H2}	7	3.91 [3.67, 4.32]	3.92 [3.29, 4.55]
	SPF_{H3}	7	3.73 [3.30, 3.92]	3.55 [3.03, 4.07]
	SPF_{H4}	7	3.53 [3.23, 3.80]	3.45 [2.95, 3.95]

Figure 13.1 shows a graphical representation of the median SPFs and IQR for GSHPs. Reviewing this image, the variation and low confidence in the GSHP result is demonstrated by the wider box and uneven distribution above and below the median.

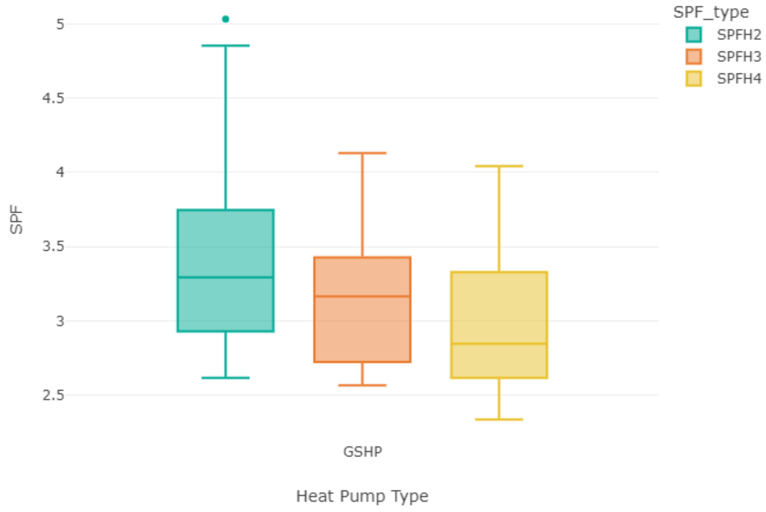

Figure 13.1: Q1, Q3 and median SPF values for GSHPs.

A comparison between the EoH SPF results and the RHPP SPF results for GSHPs is provided in Table 13.3. Note that no adjustment has been made for weather variations within the analysis windows.

Table 13.3: A comparison of the EoH GSHP performance against the RHPP scheme results.

SPF Value	EoH Sample	EoH Median SPF	EoH SPF [Q1, Q3], IQR	RHPP Sample	RHPP Median SPF	RHPP SPF [Q1, Q3], IQR
SPF_{H2}	23	3.29	[2.93, 3.75], 0.82	92	2.81	[2.63, 3.14], 0.51
SPF_{H4}	23	2.85	[2.72, 3.43], 0.71	92	2.71	[2.48, 3.02], 0.54

Reviewing the table, the median SPF_{H2} across GSHPs installed through the EoH programme was much higher than the RHPP GSHPs. It should again be noted however that the EoH sample is much smaller which reduces certainty in this result. The increased IQR in the EoH results is representative of the lower certainty created by a smaller sample size.

The results also show that a much larger difference between SPF_{H2} and SPF_{H4} was observed across the EoH GSHPs compared to the RHPP GSHPs. As the difference between the SPF boundaries on RHPP was so much smaller, this indicates that the large SPF difference observed through EoH may have been an anomaly (likely due to small sample size) rather than being representative of typical GSHP performance.

14. Appendix 2 - References

[1] Energy Systems Catapult Ltd., “Electrification of Heat Demonstration Project: Raw Heat Pump Performance Data,” UK Data Archive, 2020-2023. [Online]. Available: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=9049.

[2] Energy Systems Catapult Ltd., “Electrification of Heat Demonstration Project: Cleansed 2-Minute Interval Heat Pump Performance Data,” UK Data Archive, 2020-2023. [Online]. Available: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=9050.

[3] Energy Systems Catapult Ltd., “Electrification of Heat Demonstration Project: Cleansed 30-Minute Interval Heat Pump Performance Data,” UK Data Archive, 2020-2023. [Online]. Available: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=9209.

[4] Energy Systems Catapult Ltd., “Electrification of Heat Demonstration Project: Cleansed Daily Heat Pump Performance Data,” UK Data Archive, 2020-2023. [Online]. Available: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=9210.

[5] Energy Systems Catapult Ltd., “ESC Data Science Github - EoH Analysis Code,” 2023. [Online]. Available: https://github.com/ES-Catapult/electrification_of_heat.

[6] Energy Systems Catapult Ltd., “DESNZ Electrification of Heat Demonstration Project - Insights from Heat Pump Performance Data,” 2024.

[7] Energy Systems Catapult Ltd., “BEIS Electrifiation of Heat Demonstration Project - Interim Insights from Heat Pump Performance Data,” 2023.

[8] RB&M, “In-Situ Heat Pump Performance Analysis of Ofgem Data 2017-2022,” Department for Energy Security and Net Zero, 2024.

[9] J. Love, A. Summerfield, P. Biddulph, J. Wingfield, C. Martin, C. Gleeson and R. Lowe, “Investigating Variations in Performance of Heat Pumps Installed Via the Renewable Heat Premium Payment (RHPP) Scheme,” UCL Energy Institute, London, 2017.

[10] Energy Systems Catapult Ltd., “BEIS Electrifiation of Heat Demonstration Project - Interim Heat Pump Performance Data Analysis Report,” 2023.

[11] Energy Systems Catapult Ltd., “Electrification of Heat Demonstration Project - Heat Pump Installation Statistics Report,” 2022.

[12] LCP Delta, “BEIS Electrification of Heat Demonstration Project - Home Surveys and Installation Report,” 2022.

[13] Energy Systems Catapult Ltd., “Electrification of Heat Demonstration Project: Heat Pump Performance Summary Data,” USmart, 2020-2023. [Online]. Available: https://usmart.io/org/esc/discovery/discovery-view-detail/6a5e5753-aaff-455e-8b3b-8ee282010261.

[14] Electrification of Heat Project Database, “Energy Systems Catapult - USmart,” USmart, 2019 - 2023. [Online]. Available:

https://usmart.io/org/esc/discovery?order=statistic.viewCount&tags=DESNZ%20EoH%20Project&limit=20&offset=0.

[15] LCP Delta, "BEIS Electrification of Heat Demonstration Project - Participant Recruitment Report," 2022.

[16] Energy Systems Catapult Ltd., "Electrification of Heat Demonstration Project Data Documentation Report: Recruitment, Survey, Design, and Installation Data," 2022.

[17] BEIS Electrification of Heat Project - Heat Pump Installation Statistics, "Energy Systems Catapult - USmart," 2021. [Online]. Available: https://usmart.io/org/esc/discovery/discovery-view-detail/d506e975-cb39-47d7-99e0-e99939a2c4bf.

[18] BEIS Electrification of Heat Project - Property, Design and Installation Information Database, "Energy Systems Catapult - USmart," 2022. [Online]. Available: https://usmart.io/org/esc/dataset/view-edit?datasetGUID=5325ef18-9cd1-493c-beae-e278d8998400.

[19] Energy Systems Catapult Ltd., "Electrification of Heat Demonstration Project - Heat Pump Optimisation Report," 2024.

[20] BEIS, "Electrification of Heat Demonstration Project Delivery Contractor - Invitation to Tender: 2174/12/2019," 19th December 2019.

[21] R. N. Andreas Zottl, "D4.2. /D 2.4. Concept for evaluation of SPF, Version 2.2, defined methodology for calculation of the seasonal performance factor and a definition which devices of the system have to be included in this calculation," SEPEMO, 31st May 2012.

[22] D. P. Dunbabin and C. Wickins, "Detailed analysis from the first phase of the Energy Saving Trust's heat pump field trial," Dept of Energy & Climate Change, March 2012.

[23] D. P. Dunbabin and et al, "Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial," Dept of Energy & Climate Change, May 2013.

[24] Ofgem, "Domestic Renewable Heat Incentive - Essential Guide to Metering and Monitoring Service Packages (MMSP) v5.0," ofgem, January 2018.

[25] Dept of Energy and Climate Change, "Metering and Monitoring Service Packages Technical Supplement - Outline of Metering and Monitoring Service Package requirements for the domestic Renewable Heat Incentive," 12th July 2013.

[26] MCS, "MCS Domestic RHI Metering Guidance v1.1," Dept of Energy and Climate Change, 2013.

[27] Energy Systems Catapult Ltd, "ESC Data Science Github - Spikiness," 2022. [Online]. Available: https://github.com/esc-data-science/spikiness.

[28] A. Morton, "Temperature Variations in UK Heated Homes," Loughborough University, 2012.

[29] Met Office, "UK Climate Extremes," [Online]. Available: https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-extremes.

[30] Vaillant, *aroTherm plus Operating Installation and Maintenance Instructions.*

[31] Ground Source Heat Pump Association, "What is Ground Source Energy?," [Online]. Available: https://gshp.org.uk/gshps/what-are-gshps/.

[32] Robert Lowe et al, "Final report on analysis of Heat Pump Data from the Renewable Heat Premium Payment (RHPP) scheme," March 2017.

[33] UK Government, *The Fluorinated Greenhouse Gases Regulations,* 2015.

[34] MCS, "MCS Heat Pump Design Standard 3005-1," 2021.

.

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

Electrification of Heat Demonstration Project

Department for Energy Security & Net Zero

Report produced in 2024

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