Department for Energy Security & Net Zero

Electrification of Heat Demonstration Project

Insights from Heat Pump Performance Data

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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 (Usually 95%)
COP	Coefficient of Performance
DC	Delivery Contractor
DESNZ	Department for Energy Security and Net Zero
EoH	Electrification of Heat Demonstration Project
GSHP	Ground Source Heat Pump (Ground to water heat pump)
HT	High Temperature
Hybrid	Gas-Electric Hybrid Heat Pump System
IQR	Interquartile Range
LT	Low Temperature
MC	Management Contractor
RHPP	Renewable Heat Premium Payment scheme
SCOP	Seasonal Coefficient of Performance
SPF	Seasonal Performance Factor

1. Introduction

1.1 Project Introduction

The Electrification of Heat demonstration project (EoH) was funded by the Department for Energy Security and Net Zero (DESNZ) – (previously the 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 led by Energy Systems Catapult Ltd. (the Catapult) 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 the 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 across a range of housing archetypes.

1.2 Project Stages

Figure 1.1 below shows a flow chart of the key project stages. The mass recruitment began in June 2020 and final heat pump system was installed in November 2021. The monitoring stage began upon completion of the first installation (in September 2020) and, for most of the installations ran through until September 2023.

Figure 1.1: Flow chart of key project stages.

The data used to form the insights in this paper was collected from the date of the first installation (September 2020) up to and including the end of the monitoring period on September 28th 2023.

1.3 Document Purpose

This document highlights the insights from the heat pump performance data analysis. 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].

For full details on the process and data analysis, please see the Data Analysis Report [6].

2. Data Analysis Calculations

Prior to conducting any analysis calculations, the data was cleansed, and quality checks were performed. An overview of the cleansing and quality checking process is provided within Appendix 2 of this report.

The insights in this report are largely drawn by investigating the Seasonal Performance Factors (SPFs) and various Coefficients of Performance (COPs) of the heat pumps.

SPFs are a measure of the heat pumps 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.

The SPF calculations and heat pump system boundaries are provided below, for more details on assumptions and calculation methodology, please refer to Section 7 of the Performance Data Analysis Report [6].

Table 2.1: Data items and symbols associated with the SPF 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}	$Q_{IH} = E_{IH}$

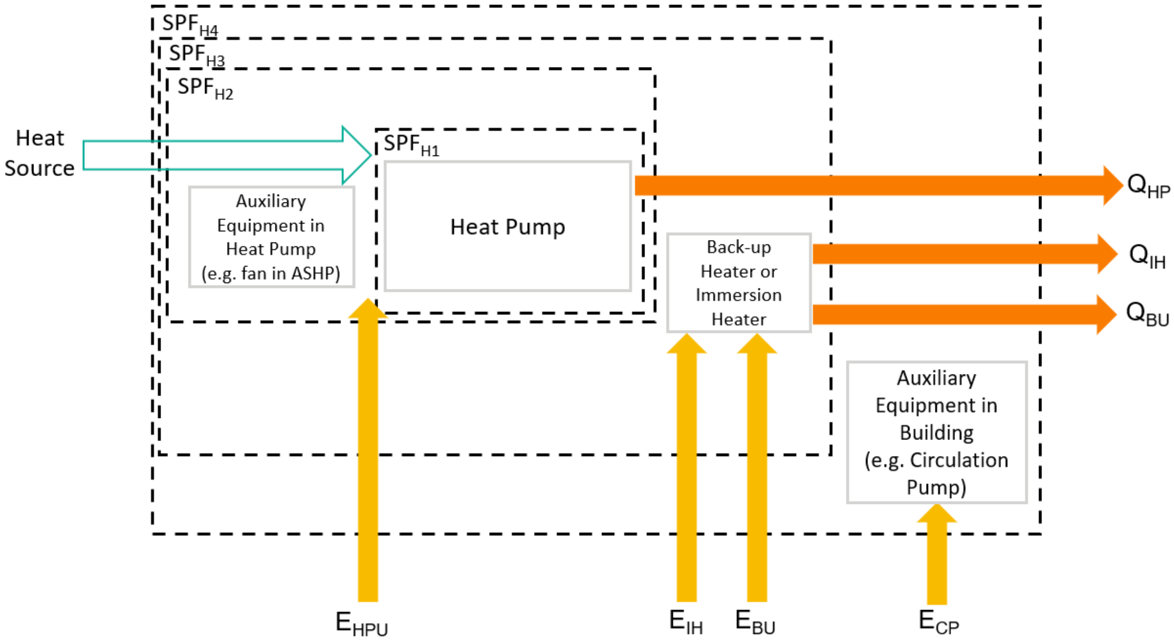

Figure 2.1: SPF system boundaries, as defined in the SEPEMO project [7]. Applied to the EoH monitoring system.

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

An SPF value was generated for each property over its selected 12-month data window. These values were then evaluated, and key correlations and variations have been reported upon. An overview of this analysis is provided in Section 3.

All COP results provided in this report are denoted with a (H2) or (H4) based on which of the SPF boundaries is used. In addition, the time interval for all COP results is provided and, where necessary start and end dates and times are provided in the summary data set [8].

3. Data Insights

This section provides an overview of the results and some key insights from the data analysis. It should be noted that these results are based on a set of analysis requirements which was prioritised by DESNZ and the project team. The project datasets [1, 2, 3, 4, 9] provide the potential for much more analysis and as such are available (open-source) on the UK Data Archive and USmart. The analysis code used to conduct this analysis is also available open-source on Github [5].

For more information on the analysis process, full analysis results and further conclusions, please refer to the Performance Data Analysis Report [6].

3.1 Seasonal Performance Factor

Table 3.1 provides a breakdown of the median and mean SPF values for all ASHPs and heat pumps within hybrid systems separately. These results remain consistent with those published at the interim stage of the project [10] and the results from analysis of Ofgem data, conducted by RB&M, which were published at the same time as these EoH findings [11]. 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 3.1.

Table 3.1: 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 also that only the electrical components are considered when calculating SPF values for the Hybrid systems, (i.e. the boiler is excluded).

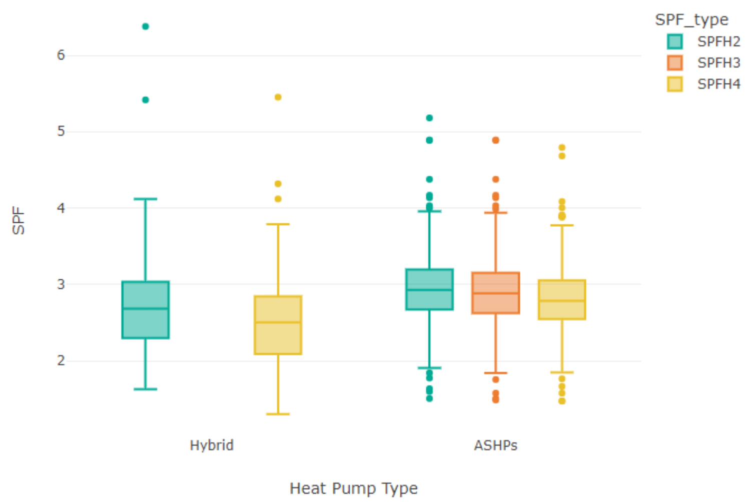

Figure 3.1: Box plot showing Q1, Q3 and median SPF values for ASHPs and heat pumps within hybrid systems.

Whilst median ASHP SPF has improved significantly since the RHPP trial (when the median ASHP SPF_{H4} was 2.44), variance in SPF across installations remains high (the IQR for SPF results in both trials were between 0.50 and 0.62). Whilst some of this variation is explained in the following sections, some of it is likely related to the consistency of design, installation, and operation of the heat pumps.

GSHPs were installed in a small number of properties (38) through the EoH project so 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 EoH results are used as a reference for median GSHP SPF. As such, the EoH GSHP performance results are provided in the annex of this report. The Ofgem heat pump data analysis [11] provides more robust SPF values which may be used as a reference.

Table 3.2 provides a comparison of SPF split by High Temperature (HT) and Low Temperature (LT) ASHPs based on the pre-project definitions. The pre-project definition of a HT ASHP is an ASHP which can achieve flow temperatures greater than 65°C[1].

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[2] 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.

Table 3.2: 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]

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 operated 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.

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[1] Based on heat pump design. Please note that LT ASHPs may also be capable of operating above 65°C in certain conditions but are classified as low temperature by the manufacturers.
[2] The theoretical flow temperature needed to overcome 99% or 99.6% of all external temperatures.

3.2 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.

The ASHPs installed through this project utilised three refrigerants. Figure 3.2 provides an indication of the median SPF_{H4} for all ASHPs broken down by refrigerant type as well as an indication of the IQR. Table 3.3 provides the median and mean SPF_{H4} values for each refrigerant type and whether they were used in HT or LT ASHPs.

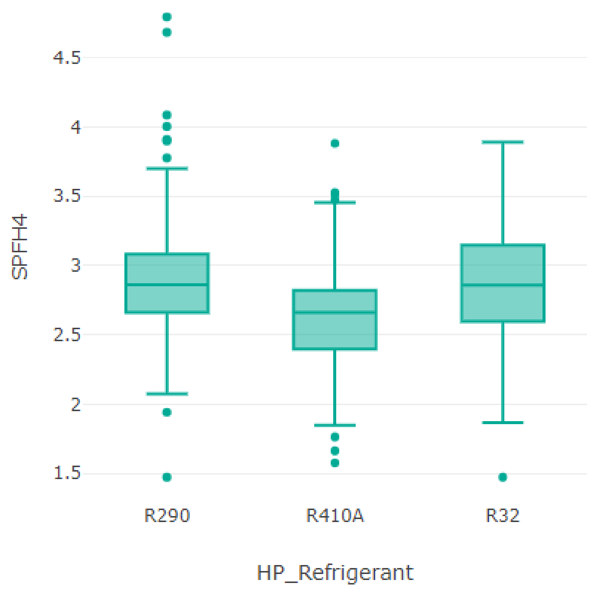

Figure 3.2: Q1, Q3 and median SPF_{H4} for all ASHPs broken down by refrigerant type.

Table 3.3: 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]

Considering no other factors, these results suggest that differing refrigerants by heat pump type may contribute to the differences in heat pump efficiency. However, other factors such as the efficiency of mechanical equipment and control strategy may also impact the SPF observed.

It is also evident that the HT ASHPs installed through this project mainly utilised R290 whilst all LT ASHPs utilised R410a or R32. The difference in performance seen between HT ASHPs and LT ASHPs may therefore be partially attributed to the choice of refrigerant.

3.3 SPF by Operating Temperature

The operating flow temperature of a heat pump has a direct impact on the heat pump efficiency. For this reason, heat pumps have in-built weather compensation controls which adjust the flow temperature based on the external temperature[3] 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. across all ASHPs and heat pumps in hybrid systems, the mean operating flow temperature was 39.7°C.

Through this study, it has been observed that when considered in isolation, the heat pumps which operate with a higher mean flow temperature generally have a lower SPF. Figure 3.3 shows this relationship for all ASHPs.

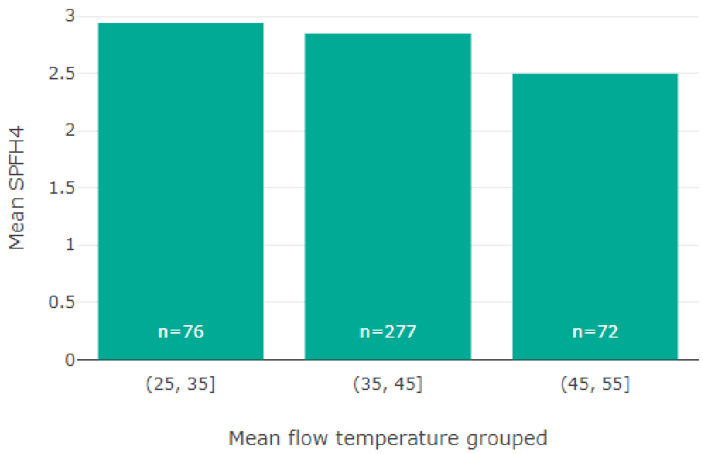

Figure 3.3: Histogram showing the mean SPF_{H4} by binned mean flow temperature (°C).[4]

It was noted in Section 3.1 that based on pre-project definitions, HT ASHPs have been observed to operate at a similar efficiency to LT ASHPs through this study, however this may be down to the actual operating temperature and control strategy. In practice, in many cases HT and LT ASHPs may be operating at similar temperatures.

Figure 3.4 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 large overlap in typical operating temperatures around 35°C to 45°C for both HT ASHPs and LT ASHPs.

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[3] 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.

[4] 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.

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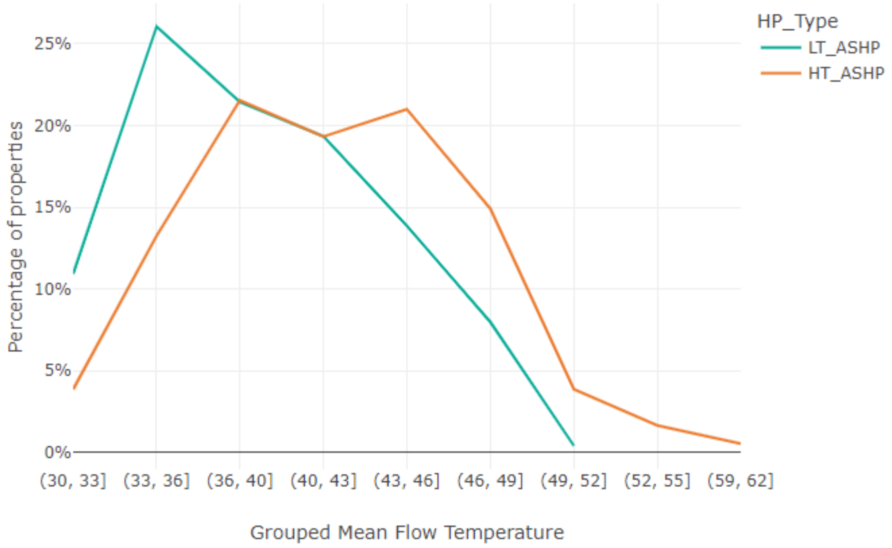

Figure 3.4: Frequency distribution of mean flow temperature by heat pump type.

Defining HT operation as when a heat pump operates above 65°C at any point over the 12-month analysis 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 3.4 indicates that the LT and HT ASHPs (by operation) exhibited a similar SPF. However, 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 so it may be concluded that a large proportion of this result is due to the weather compensation control and refrigerant performance. This is backed up by the analysis conducted in Section 3.6.

Table 3.4: 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]

3.4 SPF by Property Type

It should 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 the following results may not be representative of the UK housing stock. Nonetheless, this analysis still provides valuable insight into the performance of heat pumps in homes which are recommended for an installation by trained designers and installers.

Figure 3.5 and Figure 3.6 show the SPF_{H4} by house type and house age respectively. Whilst there are minor variations in the performance between different house types and age, there were no statistically significant variations in the performance of heat pumps based upon house type and age.

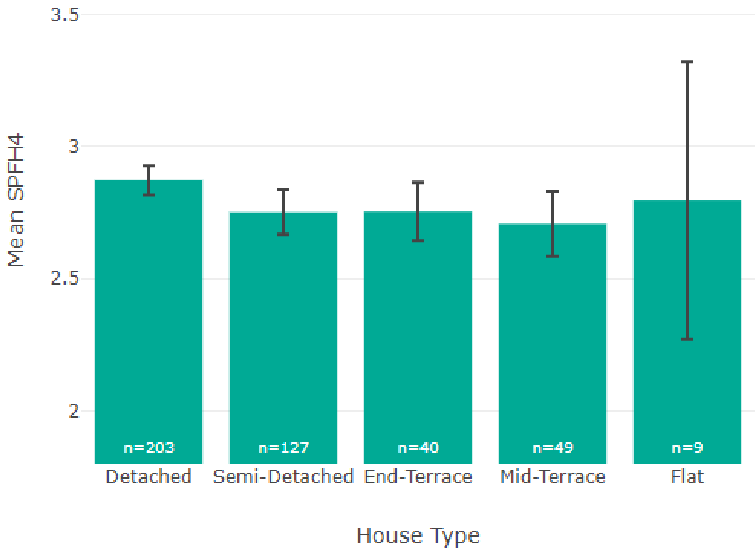

Figure 3.5: Mean SPF$_{H4}$ of all ASHPs by house type with 95% CI.

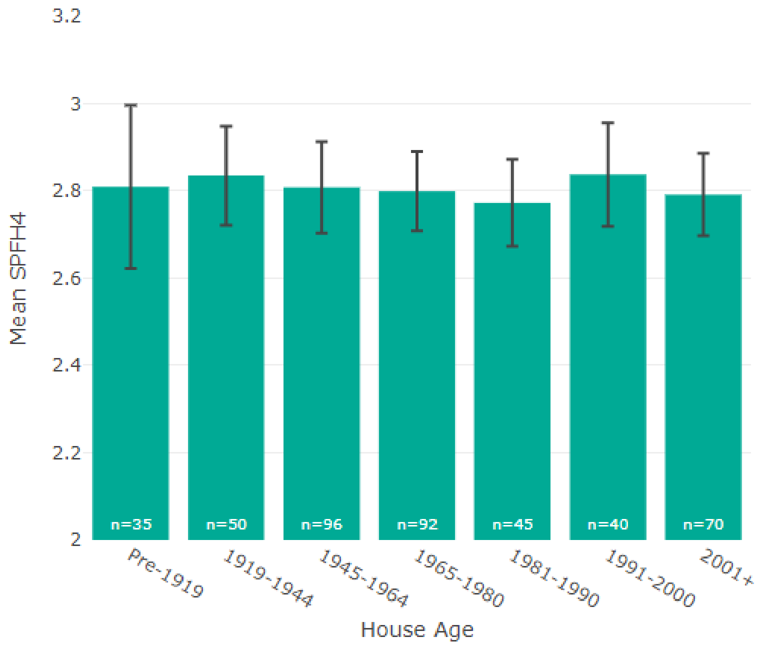

Figure 3.6: Mean ASHP SPF$_{H4}$ by house age with 95% CI.

3.5 Hybrid Heat Pump System Operation

When assessing hybrid system operation using the data from this project, it is necessary to reiterate that the domestic hot water provision was not metered and that any proportions of heat pump to gas boiler operation are those for space heating only. It should also be noted that there were two types of hybrid system 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. Some of these systems used existing boilers whereas most had new boilers installed as part of the project.

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 3.5 and Figure 3.7.

Table 3.5: 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%

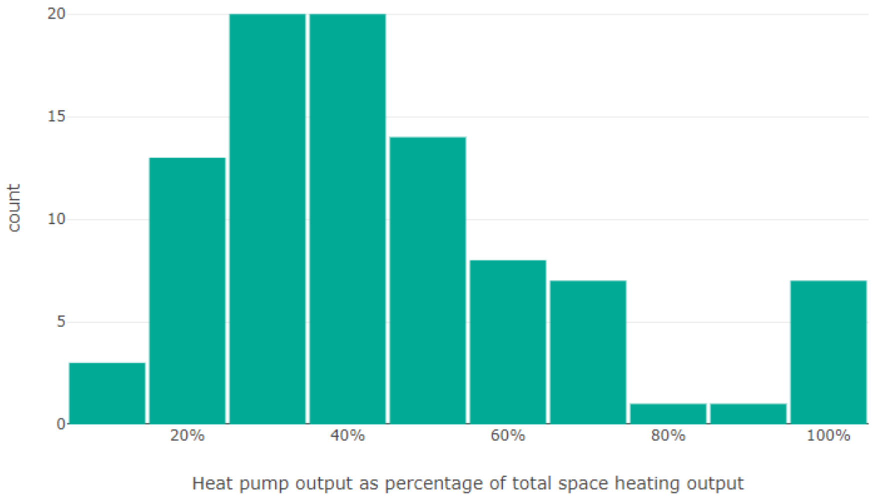

Figure 3.7: Frequency distribution of heat pump energy output as a percentage of total energy output in Hybrid systems.

The data indicates a statistically significant relationship between proportion of heat pump use in Hybrid systems and SPF, with systems that have a higher heat pump usage tending towards higher SPFs.

This result may be because intermittent heat pump operation is less efficient. It should also be noted that when designing and commissioning the hybrid systems, the systems are generally cost-optimised, so the gas boiler is only used for space heating when external temperatures are sufficiently low to warrant higher flow temperatures. The SPF result therefore may be slightly skewed as the hybrid systems shown to use the heat pump less may be installed in less efficient homes with greater heat losses.

3.6 COP Temperature Dependency

As already noted in Section 3.3 heat pump efficiency varies based on the flow temperature of the heat pump. Heat pump efficiency also varies based on the temperature of the heat source (for ASHPs, the external air temperature). By evaluating the flow temperature and external temperature over each 30-minute period, analysis was conducted to evaluate the significance of this reduction in efficiency over shorter time frames; the results are presented in this section,

Initially, focussing on the external temperature; Figure 3.8 shows the change in $COP_{(H4)}$ across all of the ASHPs as the external temperature varied. The ASHP peak in $COP_{(H4)}$ occurred when the external temperature was 10°C ($COP_{(H4)}$ = 3.37). Above 10°C, the COP (and energy use) decreased due to the proportion of the heat which was used for space heating (compared to less efficient hot water production) decreasing.

Most importantly when evaluating the impact of a large-scale heat pump roll out, the $COP_{(H4)}$ of ASHPs reduced as the external temperature also reduced. This is a known impact of reducing external temperatures, but the data provides the ability to quantify this effect.

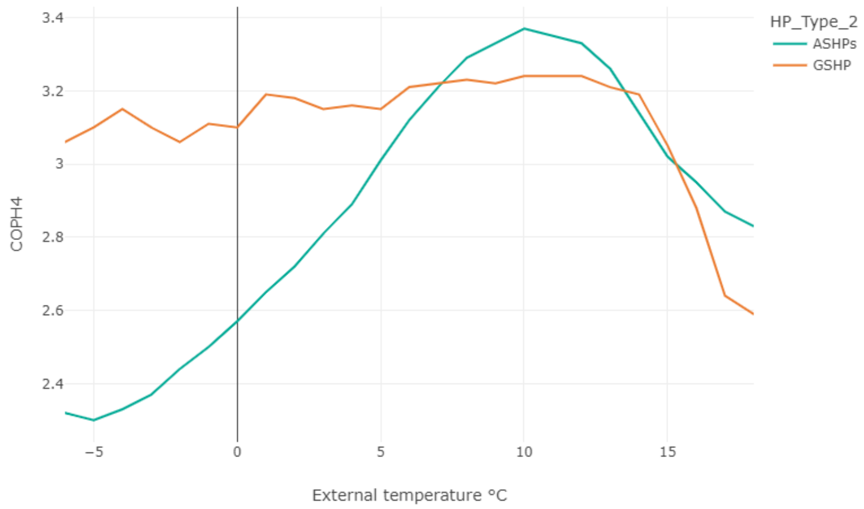

Figure 3.8: 30-minute mean external temperature plotted against median $COP_{(H4)}$ across all ASHPs and GSHPs, across all periods.

Considering the common GB design conditions of around -3°C and -5°C, the 30-minute $COP_{(H4)}$ reduced to 2.37 (at -3°C external temperature) and 2.30 (at -5°C external temperature) respectively. The impact of external temperature on COP was much less severe for GSHPs where the median $COP_{(H4)}$ at -5°C was 3.10 (note that the sample size for GSHPs was much smaller than that for the ASHPs).

The COP of all types of heat pump also decreased as the flow temperature increased. 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.

3.7 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 the SPF shows real-world 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 difference in operational heat pump efficiencies and those provided to the participants 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, indicating 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 used in the EoH project, failed to predict whether a given heat pump installation would perform well compared to others.

There are examples of a few heat pumps installed through this project 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.

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.

4. 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 4.1. 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 4.1: 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.

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 aim to design most heat pump systems to operate at lower peak flow temperatures 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).

5. Appendices

5.1 Appendix 1 - Heat Pump Installation Details

5.1.1 Heat Pump Equipment

In total, the EoH project completed 742 domestic heat pump installations across Great Britain. These installations can be separated into four heat pump types: Low Temperature Air Source Heat Pump (LT ASHP), High Temperature Air Source Heat Pump (HT ASHP) (capable of producing flow temperatures >65°C), Ground Source Heat Pump (GSHP), Gas-Electric Hybrid Heat Pump System (Hybrid).

Table 5.1 provides the installation statistics based on heat pump type.

Table 5.1: Installation statistics by heat pump type.

Group	Installations (%)	Installations (No.)
LT ASHP	41.2%	306
HT ASHP	32.8%	243
GSHP	5.1%	38
Hybrid[5]	20.9%	155

The heat pumps were also installed in a range of home types and ages, this was discussed further in Section 3.4 and all installation statistics are presented in the Installation Statistics Report [12] and USmart datasets [9]. Note that, as mentioned in Section 1.1, all of the heat pumps were installed in three geographical areas around the UK, therefore there may be some geographical bias in the analysis results.

5.1.2 Monitoring Equipment

Whilst the configuration of the monitoring system for each heat pump type and model varied, Figure 5.1, Figure 5.2 and, Figure 5.3 show the typical monitoring system configuration for an ASHP, GSHP and hybrid installation respectively. The monitoring system consisted of a maximum of five electricity meters, two heat meters and one internal temperature sensor. The five electricity meters / sensors recorded the following:

1. The whole heat pump system energy consumed.
2. Back-up heater energy consumed.
3. Circulation pump energy consumed.
4. Position of the control (diverter) valve (to inform hot water or heating mode).
5. Immersion heater energy consumed.

All installations had at least one heat meter which recorded the heat pump unit heat output. For hybrid systems, there was a second heat meter which recorded the boiler heat output. For GSHP installations, there were temperature sensors recording the brine temperatures going into

[5] Hybrid refers to both hybrid systems with a heat pump and boiler in separate units and integrated systems (which contain the heat pump and boiler in the same unit). The systems can be further broken down by those properties which installed heat pumps alongside existing boilers and those which had new boilers and heat pumps installed.

and out of the heat pump. All installations also had an internal temperature sensor to record room temperature. The external temperatures were collected from the local weather station.

The electricity and heat meters recorded cumulative data, so the readings should increase over time. All temperature sensors recorded an instantaneous reading at a given moment in time.

For more information on the monitoring equipment and configurations, please refer to the Heat Pump Performance Data Analysis Report [6].

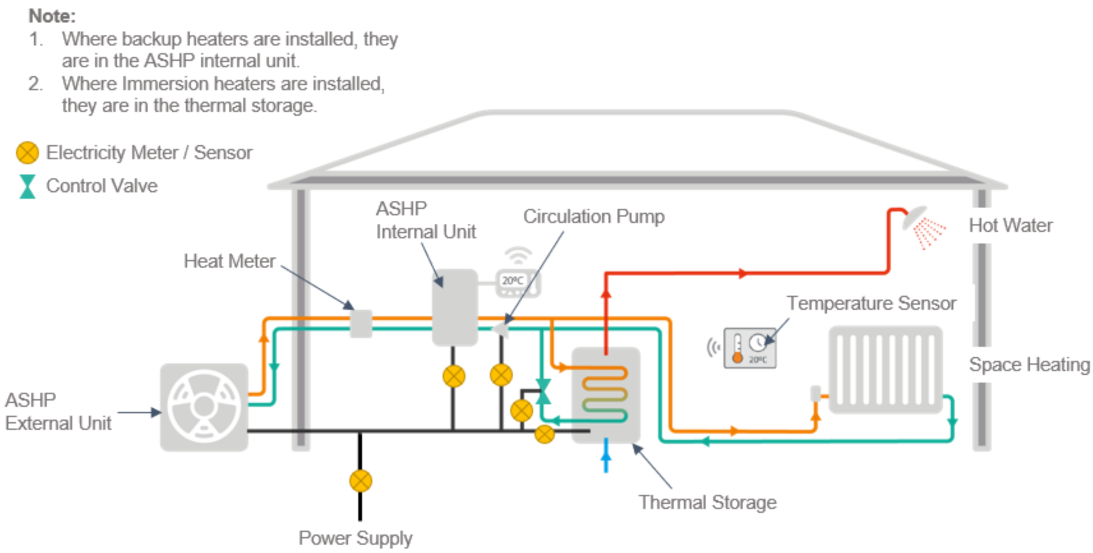

Figure 5.1: Typical arrangement of sensors in ASHP monitoring solution.

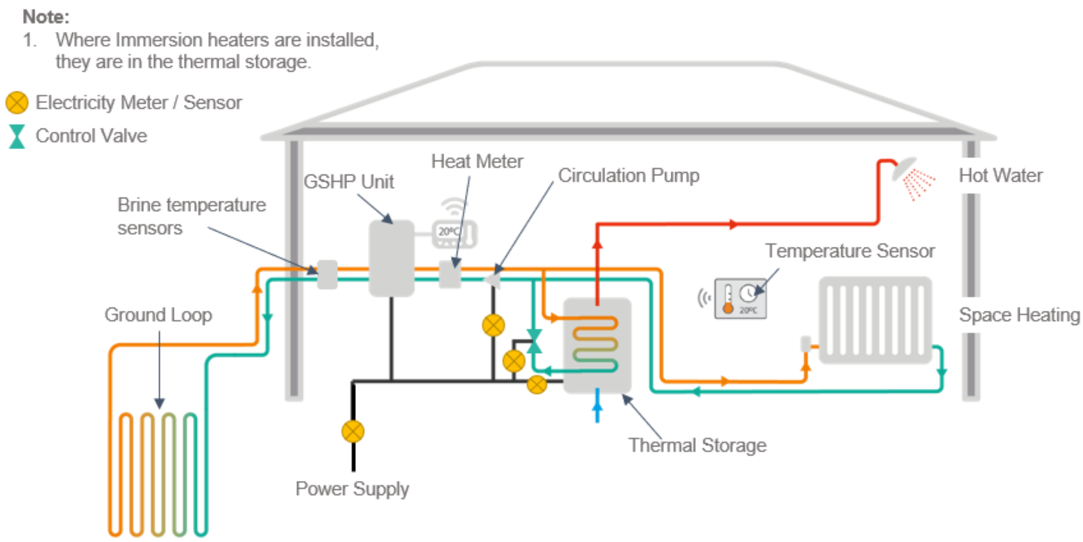

Figure 5.2: Typical arrangement of sensors in GSHP monitoring solution.

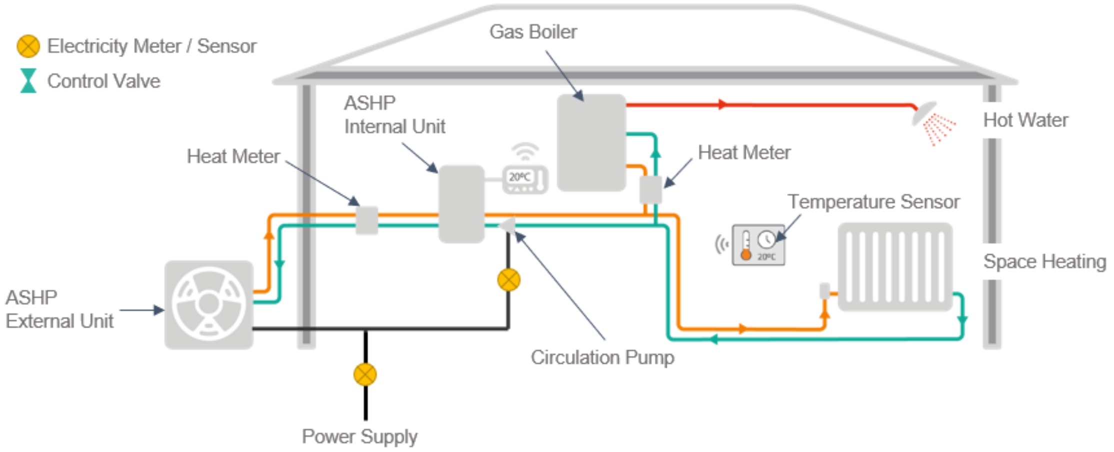

Figure 5.3: Typical arrangement of sensors in hybrid heat pump monitoring solution.

5.2 Appendix 2 – Data Quality Checks and Cleaning Process

Prior to conducting any analysis, rigorous data quality checks and small amounts of data cleansing were performed. This appendix provides a brief overview of the quality checking and cleaning process. For a more thorough description of this procedure, please refer to the Performance Data Analysis Report [6].

The code which was used to cleanse and assess the quality of the data has been published open source.

5.2.1 Data Cleansing

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 Performance Data Analysis Report [6].

- 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.

5.2.2 Data Quality

Following cleansing, quality checks were performed on the data and analysis windows were selected. The quality checks resulted in a data quality score for each possible one-year analysis window for each property, based on various quality metrics as outlined below.

Quality issues in the data arose where the monitoring equipment didn't 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).

Where gaps in any of the cumulative data arose, they were scored between 1 and 5 depending on the length of the gap and what happens before and after the gap period. Higher scoring gaps indicate worse data quality. In addition, each month of data was scored based on what happens in that month. If the monthly data was as expected, it was given a score of 0 and if it was not as expected it was scored between 3 and 4 and flagged for a manual check. A full breakdown of the data scoring and rationale is provided in the Performance Data Analysis Report [6].

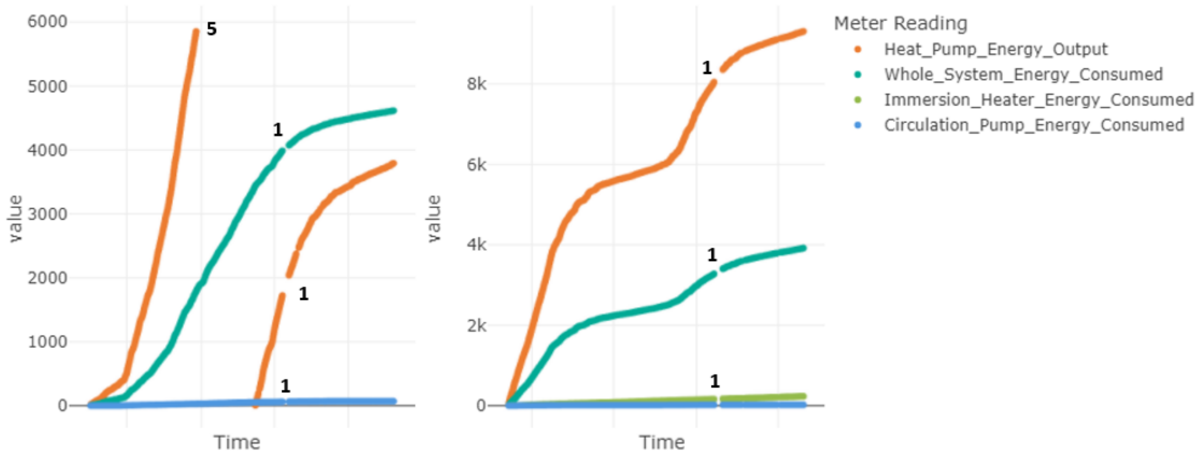

Figure 5.4: Two graphs showing unacceptable data (left) and acceptable data (right). The data shown on the left is rejected as it contains a max gap score of 5 due to meter reset following a large data gap.

Following data scoring, all possible 12-month windows were assessed and the window which was taken forward for analysis was selected based on the criteria shown in Figure 5.5.

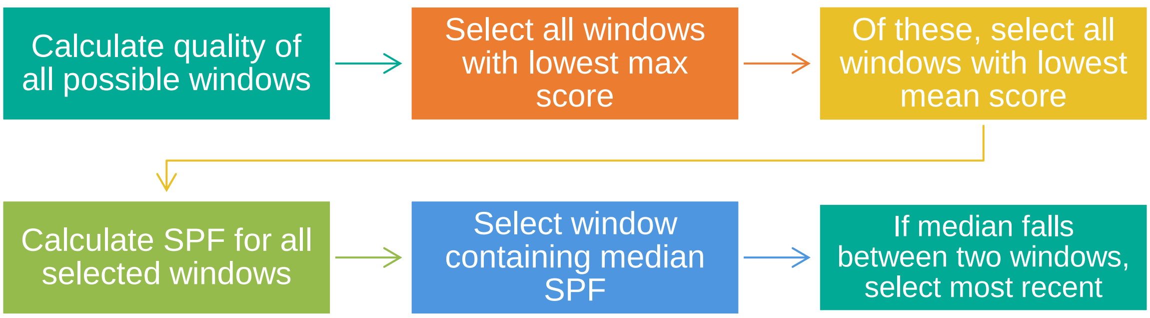

Figure 5.5: Flow chart showing 12-month window selection process.

SPF values were then calculated for the chosen window and the property was either included in the SPF analysis or was excluded for one of the following reasons:

- 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,
- 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).

The graph shown in Figure 5.6 indicates the sample of properties which were included in the SPF analysis and reasons why other properties were excluded.

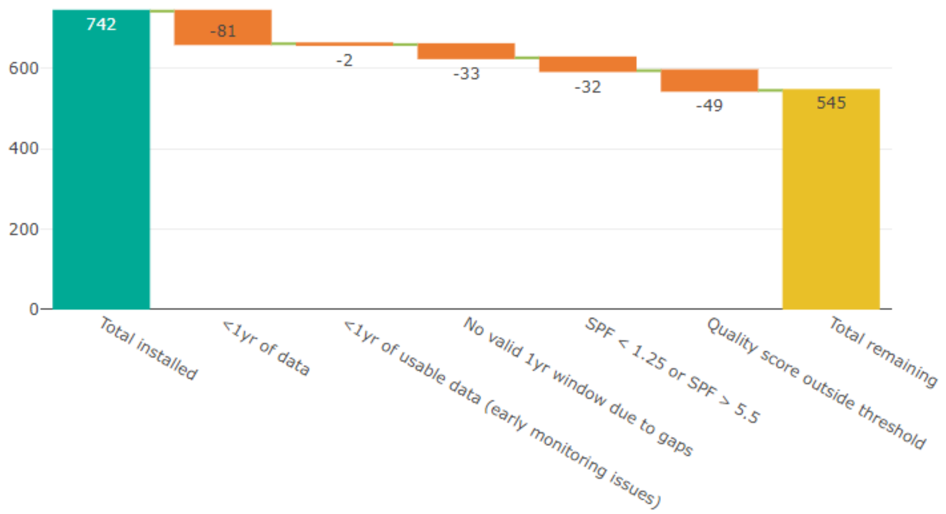

Figure 5.6: A graph showing the number of properties excluded from the SPF analysis for each reason as well as the number of properties remaining.

5.3 Appendix 3 – 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 also geographically localised, meaning that behaviours resulting in different performance can be exemplified by being adopted by a larger proportion of the participants. One example of this is if a small number of participants decided to utilise their immersion heaters rather than heat pump for DHW production, this behaviour is more likely to be copied by more participants (due to locality) 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, geographically diverse sample.

Following data checks, the analysed sample of GSHPs installed through the EoH project was very small and included both shared loop (n=16) and individual (n=7) GSHPs. As a result, the GSHP results are provided separately to those of ASHPs and Hybrid systems.

Due to the small sample size is 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 [11], 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.

The GSHP SPF results are provided in Table 5.2.

Table 5.2: 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]

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.

6. References

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