UCL **ENERGY** INSTITUTE

ANALYSIS OF DATA FROM HEAT PUMPS INSTALLED VIA THE RENEWABLE HEAT PREMIUM PAYMENT (RHPP) SCHEME

Case Studies Report from the RHPP Heat Pump Monitoring Campaign

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Nomenclature

PERFORMANCE EFFICIENCY NOMENCLATURE

COP	Heat pump (HP) coefficient of performance
SPF_{Hn}	HP seasonal performance factor for heating at SEPEMO boundary Hn

MONITORED VARIABLES

Eb	Electricity for whole system boost only
Edhw	Electricity for domestic hot water (DHW) - typically an immersion heater
Ehp	Electricity for the HP unit (may include a booster heater and circulation pump)
Esp	Electricity for boost to space heating (SH) only
Fhp	Flow rate of water from HP (may be SH only)
Fhw	Flow rate of water to DHW cylinder (if separately monitored)
Hhp	Heat from HP (may be SH only)
Hhw	Heat to DHW cylinder (if separately monitored)
Tco	Temperature of water leaving the condenser
Tin	For ASHP: Temperature of refrigerant leaving the evaporator For GSHP: Temperature of ground loop water into the HP
Tsf	Flow temperature of water to SH
Twf	Flow temperature of water to cylinder

(Note that external temperature, Tex, was not measured directly. Data from a publicly available database were used in the analysis.)

RHPP ENERGY AND POWER UNITS

Energy	J	Joule	SI unit of energy
Energy	kWh	3.6 MJ	Customary unit of energy for residential energy use
Energy	MWh, GWh	3.6 GJ, 3.6 TJ	
Power	W	Watt, J/s	SI unit of power and heat flow
Power	Wh/2 minutes	30 W	Base unit of energy for monitored data in RHPP trial, limit of resolution of power – note that power and heat have been recorded at 2 minute intervals
Power	kWh/year	3.6 MJ/year 0.11416 W	Customary unit for rate of residential energy use
Power	kW	1000 W	Typical unit for measurement of heating system ratings

KEY ACRONYMS AND ABBREVIATIONS

DECC	Department of Energy and Climate Change (became part of the Department of Business, Energy and Industrial Strategy on 14th July 2016)
EST	Energy Saving Trust
Preliminary Assessment	Preliminary assessment of the RHPP data performed by DECC (Wickins, 2014)
RAPID-HPC	Research and Analysis on Performance and Installation Data – HP Consortium
RHPP	Renewable Heat Premium Payment Scheme
MCS	Microgeneration Certification Scheme - a nationally recognised quality assurance scheme, supported by the DECC. MCS certifies microgeneration technologies used to produce electricity and heat from renewable sources.
MIS	Microgeneration installation standards. MIS 3005 set out requirements for MCS contractors undertaking the supply, design, installation, set to work, commissioning and handover of microgeneration HP systems.
SEPEMO	SEasonal PErformance factor and MOnitoring

Context

The RHPP policy provided subsidies for private householders, Registered Social Landlords and communities to install renewable heat measures in residential properties. Eligible measures included air and ground-source heat pumps, biomass boilers and solar thermal panels.

Around 14,000 heat pumps were installed via this scheme. BEIS[1] funded a detailed monitoring campaign, which covered 700 heat pumps (around 5% of the total). The aim of this monitoring campaign was to provide data to enable an assessment of the efficiencies of the heat pumps and to gain greater insight into their performance. The RHPP scheme was administered by the Energy Savings Trust (EST) who engaged the Buildings Research Establishment (BRE) to run the meter installation and data collection phases of the monitoring program. They collected data from 31 October 2013 to 31 March 2015.

RHPP heat pumps were installed between 2009 and 2014. Since the start of the RHPP Scheme, the installation requirements set by MCS standards and processes have been updated.

BEIS contracted RAPID-HPC to analyse this data. The data provided to RAPID-HPC included physical monitoring data, and metadata describing the features of the heat pump installations and the dwellings in which they were installed.

The work of RAPID-HPC consisted of cleaning the data, selection of sites and data for analysis, analysis, and the development of conclusions and interpretations. The monitoring data and contextual information provided to RAPID-HPC are imperfect and the analyses presented in this report should be considered with this in mind. Discussion of the data limitations is provided in the reports and is essential to the conclusions and interpretations presented. This report does not assess the degree to which the heat pumps assessed are representative of the general sample of domestic heat pumps in the UK. Therefore these results should not be assumed to be representative of any sample of heat pumps other than that described.

[1] The Department of Energy and Climate Change (DECC) merged with the Department for Business, Innovation and Skills (BIS) in July 2016, to create the new Department for Business, Energy & Industrial Strategy (BEIS)

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Executive Summary

Background to this report

The Renewable Heat Premium payment scheme subsidised the installation of heat pumps and biomass boilers in domestic properties. The scheme ran from 2011 to 2014. BEIS, formerly DECC[2], funded a detailed monitoring campaign to collect data on the performance of just under 700 domestic heat pumps installed via the Scheme. Heat and electricity data were collected between 2013 and 2015. These data, together with metadata on the monitoring schematics, heat pump types, heat emitter types, installation certificates and energy performance certificates for the properties were provided to RAPID-HPC for analysis.

This report forms part of a series and concerns detailed analysis of technical and social data from 21 case studies across the UK. A combined team consisting of an architect and an engineer, with support from a social scientist from RAPID-HPC visited each of these properties to inspect the heat pump installation and monitoring equipment and to interview householders to determine the factors influencing their level of satisfaction.

This report presents the analysis, concentrating on five main areas:

a) Assessment of quality of the heat pump installation

b) Consumer views of heat pumps : examination of users' strategies for operation and degree of satisfaction

c) Cross-checking of user experience with monitored performance

d) Performance of the heat pumps (calculated from measured heat and electricity data)

e) Determination of factors influencing performance.

The quality of heat pump installations

During a sub-sample of 10 site visits, the quality of system plumbing and pipe insulation was assessed. Three heat pump systems were found to be poorly planned/insulated, one was classed as "intermediate"

[2] The Department of Energy and Climate Change (DECC) merged with the Department for Business, Innovation and Skills (BIS) in July 2016, to create the new Department for Business, Energy & Industrial Strategy (BEIS)

and the remainder were "of good quality". It was not possible to carry out in depth analysis of radiator sizing and heat demand.

Consumer views of heat pump systems

The team interviewed householders to establish their strategies for operating their heat pump, their estimated bills, the degree of comfort, how the heat pump compared with their previous fuel and whether they had experienced any problems with their heat pump.

The case studies revealed the complexity of the notion of satisfaction, which included the level of thermal comfort felt, running costs, ease of use, environmental impact, technical integrity, noise levels and controllability of the system. In eighteen out of twenty-one cases, occupants were satisfied or very satisfied with their heat pumps and preferred them to their previous heating system.

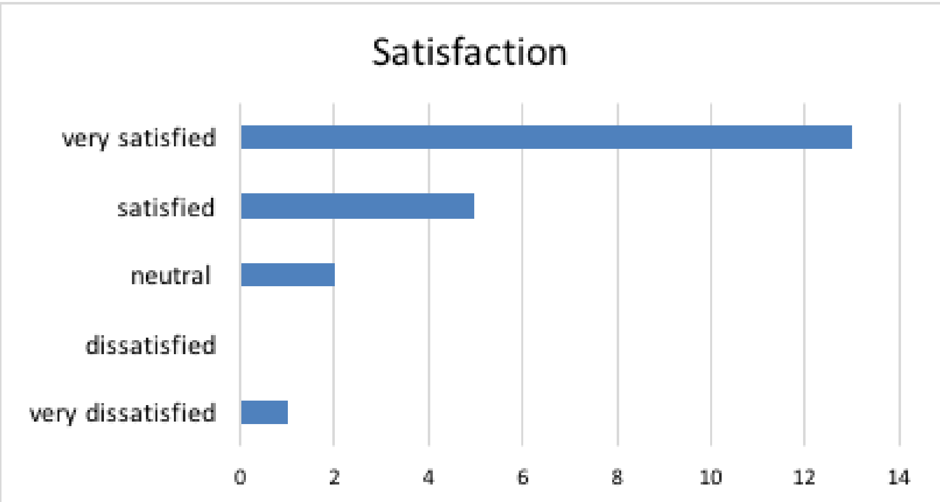

Figure 0-1. Levels of satisfaction reported across the 21 case studies.

Reasons stated for satisfaction varied from household to household and any given household's overall satisfaction level was generally a synthesis of several different factors (for example, cost and constant heat (CS20) or maintenance and environmental benefits (CS14)). One social housing case stood out; the occupants were dissatisfied for a variety of reasons that did not seem to correlate with the apparently good performance of the heat pump during the last year of monitoring.

Satisfaction with the training material provided was a little lower, with 17 of the 21 households stating that they were satisfied or very satisfied with the training material provided.

Consumers' strategies for control

Householders were asked about their strategies for control of their heat pump, including what their thermostat settings were; whether they had zonal control or radiator TRVs; whether they operated the system 24/7 or for shorter periods; whether they used night setback temperatures; how much domestic hot water they used and whether they used secondary heating (for example log fires or electric heaters).

The results indicated a wide spread of patterns of use. For example, thermostat set points generally ranged from 18 to 23 degrees C (with one exception for a householder with health problems). The social housing tenants were asked to control their heat pump by the thermostat only, while several private householders experimented with operational strategies.

Faults

Despite the high levels of householder satisfaction, at least 10 out of the 21 cases had experienced some problem since installation. A few were major, such as a suspected compressor fault[3], while others were more minor, such as antifreeze problems, condensation dripping from external ASHP units, blockages, a "faulty motherboard" and unintentional use of resistance heating, resulting in excessively high electricity bills.

Despite significant disruptions (HPs in three out of the seven RSL cases suffered a breakdown, with heating systems out of action for periods of up to two months), six out of seven RSL households were satisfied with their new heating systems. Responses from the RSL occupants show the need for RSLs to have access to competent personnel to deal with troubleshooting.

Cross-checking of site data with monitored data

The site visits identified a number of errors in the metadata, including inaccurate entries in the MCS certificates, inaccuracies in information about emitters and inaccuracies in EPCs. Unfortunately problems with metadata cannot be detected solely from statistical analysis of the larger dataset. This finding emphasises the importance of ensuring that resources are available for site visits in field trials.

Interview data were cross-checked against the monitored heat and electricity data. In one case, a householder stated that the heat pump settings had reset after a power cut and that subsequently bills had increased. Examination of the data indicated that the domestic hot water immersion had been used excessively during this period.

In another case, the householder was adamant that the performance was good, despite the apparent poor performance of the heat pump. Detailed examination of the heat and electricity data indicated that there had been a monitoring error during this period.

[3] The householder stated that "the HP burnt out due to a faulty generator."

As a result of detailed examination of the heat and electricity data and cross checking with interview data, three of the twenty-one estimates of seasonal performance factor (SPFH4) were revised upwards.

These examples demonstrate the value of combining social and technical information.

Calculated performance of heat pumps and factors impacting performance

The distribution of SPFH4 in the 21 case study sites is shown in Figure 0.1 and shows a large range of performance. All seven heat pumps installed at RSL sites (ASHP and GSHP) had representative SPFH4s of 2.3 or above. Four of six ASHPs in the private sector had a representative SPFH4 of 2.5 or above. Two of the sites with GSHPs had an estimated SPFH4 of less than 2; both were in the private sector. The remaining five of the GSHPs had representative SPFH4s between 3 and 4.6.

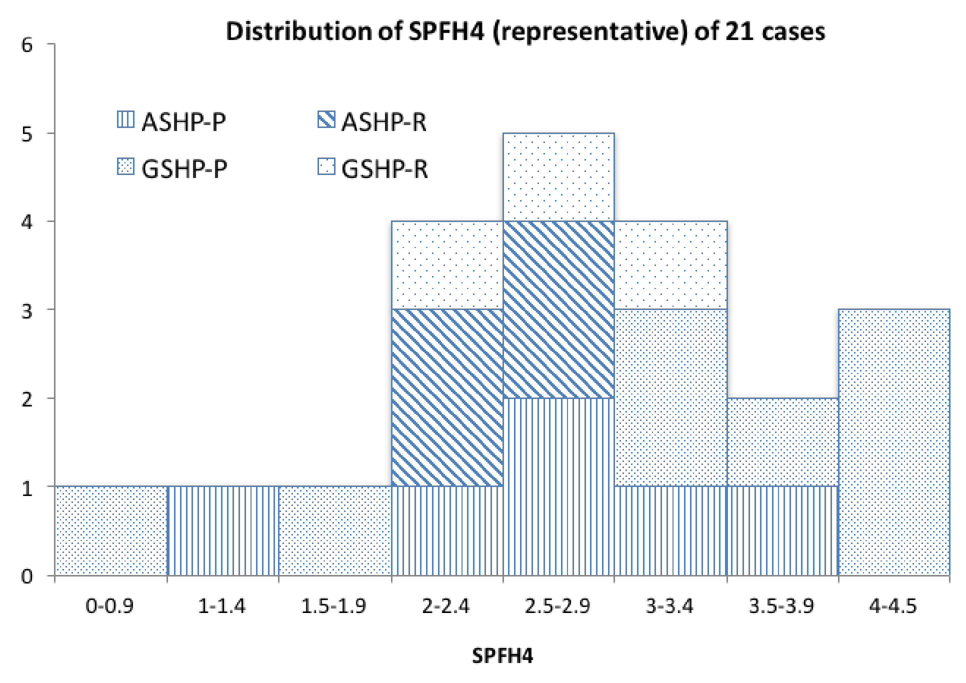

Figure 0-2. Distribution of representative SPFH4 by heat pump type and tenure.

Factors influencing performance

The study indicated that a range of social and technical factors influence performance, including:

- Low load factor (which can be caused either by mis-sizing the heat pump, or by using supplementary sources of heat);
- Excessive use of electric resistance heating (particularly domestic hot water or internal boost being switched on unnecessarily);

- In one case, location of the heat pump far from the house to minimise noise issues, resulting in a loss of heat in the pipe between the heat pump and the house.

These issues, though at first sight physical in nature, are the result of both physical factors (e.g. system design, installation, the way controls are set up) and social factors (e.g. how householders chose to control heat pumps).

Experience on a number of sites suggests that follow up visits by technically competent personnel might help to ensure that initial teething issues are resolved and that performance is maintained over the long term.

Technical Summary

Context

The Renewable Heat Premium Payment (RHPP) Heat Pump Field Trial is the largest and most recent study of field performance of domestic heat pumps in the UK. BEIS, formerly DECC[4], funded a detailed monitoring campaign to collect data on the performance of just under 700 domestic heat pumps installed via the RHPP Scheme, which ran from 2011 to 2014. BEIS contracted the RAPID-HPC to analyse this data. The data provided to RAPID-HPC included physical monitoring data, and metadata describing the features of the heat pump installations and the dwelling in which they were installed.

Late in 2015, RAPID-HPC were commissioned to undertake a detailed field study of 21[5] RHPP installations to complement and address a series of issues arising from the statistical analysis of the physical monitoring and metadata. This report presents the data, analysis and conclusions from this study[6].

Aims and objectives

The overall aim of this study was to improve the understanding of performance of and users' satisfaction with domestic heat pumps. This aim was pursued through the following objectives:

- To collect and analyse information on the immediate physical context in which the heat pumps and physical monitoring systems operated;
- To investigate the quality of monitoring data and heating systems on a case-by-case basis;
- To analyse the physical and social data collected in each case and corroborate with the monitored data and metadata available;
- To carry out case analysis and cross-case comparison to support development of hypotheses to explain performance variation;

[4] The Department of Energy and Climate Change (DECC) merged with the Department for Business, Innovation and Skills (BIS) in July 2016, to create the new Department for Business, Energy & Industrial Strategy (BEIS)
[5] The study was designed to cover 20 case studies, but a pilot study was also added.
[6] The present report is accompanied by two parallel reports, the abbreviated titles of which are *RHPP Performance Variations Report* (RAPID-HPC, 2017a), and *RHPP MCS Compliance Report* (RAPID-HPC, 2017b).

Methodology

This study has utilised the multiple case study method for collecting both quantitative and qualitative, technical and social data from 21 cases of heat pump installations in residential dwellings across different geographical areas in the UK.

The RAPID-HPC team undertook the following work:

- Site visits were carried out for 21 domestic heat pump installations. Configurations of heat pump systems (for example, radiator sizes, insulation levels, thermostat settings etc.) were observed and recorded for comparison and analysis.

- Householders of the 21 sites were interviewed to explore their strategies for operating the heat pumps (e.g. 24/7 operation, timed operation etc) and any usage of supplementary sources of heating, such as log fires or stoves.

- Factors influencing householders' choice of their heat pump and satisfaction were also investigated. This include conditions perceived pre- and post installation such as comfort level, energy bills; and other factors that might also influence householders' adaptive behaviours such as previous heating system, information provided by installers, and availability of support in rectification of faults.

Finally, the available data were analysed to explore possible reasons for performance variations. To allow closer scrutiny, much of this analysis was performed on a sub-sample of ten installations. This sub-sample was subsequently extended by the inclusion of six additional RSL dwellings to enable a fuller analysis of heat pumps in social housing.

Sites/households selected for study

A total of twenty-one sites was initially selected for investigation based on the preliminary and unpublished dataset derived from the statistical study of variation performance (RHPP *Performance Variations Report*). Seven (CS02-CS08) of 21 sites were under the ownership of Registered Social Landlords (RSLs) and fourteen (CS01, CS09-CS21) were owner-occupied properties. Of the RSL-owned sites, 4 ASHPs and 3 GSHPs were installed; and 6 ASHPs and 8 GSHPs were installed amongst the owner occupied sites. Detailed information of the technical specification of all sites can be found in Appendix E. The table below shows the 21 case study sites broken down by tenure and heat pump type.

Table 0-1. Cases by heat pump type and tenure

	RSL	Private housing
ASHP	CS02, 06, 07, 08	CS01, 09, 10, 11, 20, 21
GSHP	CS03, 04, 05	CS12, 13, 14, 15, 16, 17, 18, 19

As noted above, a sub-sample of ten cases was selected for case and cross-case comparison based on performance (i.e. primary unpublished SPFH4 scores of 5 well performed and 5 poorly performed cases). These dwellings initially comprised: CS07, CS09, CS12, CS13, CS14, CS15, CS16, CS18, CS19, CS20. However, when it transpired that CS07 was the only social house selected in the ten cases, and could not be logically compared with dwellings with the nine other cases that have very different contextual and physical factors, the six RSL dwellings, CS02, CS03, CS04, CS05, CS06, CS08 from the 21 samples were then included.

Results

Complexities in data collection

Metadata inconsistencies

For each site in the trial, the metadata (entries of the heat pump's type, size and numbers of heat emitters on MCS certificate as well as data from EPCs) includes a schematic which indicates the number and location of the sensors used for remote physical monitoring. However, it has been found that amongst the 21 sites, the schematics of 2 sites (i.e. CS10 and CS20) were not available and furthermore, site observations showed that 7 out of the remaining 19 sites had incorrect schematics[7]. Examples of problems in the metadata include:

- Inaccurate entries in the MCS certificates. In one case (CS03), information for solar panels had been entered instead of HP details. In another case (CS10), two HPs were identified (14 and 8.5kW) but only one was listed in the MCS certificate, identified as 22.5kW.

[7] As part of the process, RAPID-HPC compared the heat pump types and capacities from the MCS certificates to the metadata supplied across all 21 cases. The metadata published in April 2016 includes the capacities from the MCS certificates as a separate column. Similarly, in a few cases, RAPID-HPC's analysis concluded that some of the schematics listed in the metadata were incorrect and alternative schematics are suggested in a separate column in the published metadata.

- Inaccuracies in the metadata regarding heat distribution systems: a towel radiator in two cases (CS09 & 18 see Table E.10), and hydronic fan convectors linked to HPs in three other cases (CS06, 07, & 08 Tabel E.7) were omitted. Three other cases with hybrid heat distribution systems were listed as having either radiators or underfloor heating only.
- An incorrect heat pump type was recorded in the EPC for one case.

The issue of metadata can sometimes go beyond inconsistency. In one of the sites (CS20) the schematic was unavailable, and DHW was also not recorded in monitoring data. As a result, researchers did not know how domestic hot water was heated. However, it became clear during a visit to this site that domestic hot water was supplied by a combination of a solar thermal collector and a separate, unmetered immersion heater, rather than by the heat pump.

Comparison of metadata has revealed some inconsistencies and issues between site observations and metadata supplied to RAPID-HPC, which could not have been detected solely from statistical analysis. Although these findings cannot easily be generalised to the whole of the dataset, it seems likely that there will have been mistakes/omissions in metadata entries for other sites.

Sensor Installation

Variation in sensor installation – It was found that the installation quality of the monitoring equipment varied throughout the sample. For example, in CS12, two auxiliary temperature sensors were observed, one incorrectly fitted with insulation material between the sensor and the pipe, and one properly positioned and fitted in the same house. In case CS20, the position of the heat meter, located near the HP but with a long pipe run into the house, was likely to result in overestimation of the water temperature provided to the radiators. Case CS10 was observed to have two HPs, only one of which was heat metered[8]. The fact that two HPs were installed was not recorded in the RHPP metering database or MCS certificate.

Changes in sensor status - it was also found that some monitoring systems experienced changes in status over the course of the project. As an example, in CS09, the occupants reported that there had been a flat battery in the monitoring system which had been replaced in the period between September 2013 and September 2014. Examination of the data for this HP showed an unexplained reduction in mass flow (F_{HP}) through the heat meter over most of the period for which SPF had originally been calculated. This reduction began with a slow decline and finished with a slow recovery to the original flow rate, a pattern which does not appear to be consistent with a "flat battery" explanation. The reduction in mass flow

[8] The manufacturer's technical documentation confirms that the combination of two heat pumps in this way is an option offered by the product range. RAPID-HPC has been unable to determine which of the two heat pumps was metered. The occupants stated that both were used.

varies across the period in question, but it is large enough to explain much of the reduction in SPF observed across this period.

GSHP systems of CS13 and CS18, were both flagged as potentially having metering issues due to heat output with no electricity input for short periods. Despite this, most of the data appears plausible.

Monitoring Problems

Of a sub-sample of ten cases, eight were initially suspected of having monitoring system issues. A combination of revised algorithms for automatic selection of monitoring data, and visual inspection of data led the following appraisal of these sites:

- heat metering problems were identified in two cases - CS13 and CS18 – but were judged to be sufficiently limited not to affect analysis;
- in CS20, a problem with an unexplained schematic was resolved during the site visit, allowing all of the monitoring data to be used for this site;
- metering issues were initially suspected in CS16 due to a low SPF, but this appears to be better explained by the low load factor of the heating system, which in turn arises from the occupants' lifestyle and decisions about how to heat their house;
- metering issues were one of a number of problems that affected CS07 – these appeared to be resolved following reinstallation of the faulty external unit;
- CS09 exhibited a persistent but unexplained reduction in mass flow in the primary heating circuit, as recorded by the heat meter flow sensor – this affected the estimate of SPF based on the *preliminary and unpublished* dataset, but did not affect the estimate of SPF based on the B2 dataset;
- metering issues due to poor installation of sensors were suspected in CS15, but according to the occupants' account, were eventually fixed by the installer, allowing some of the data to be used;
- potentially serious and unresolved problems with the monitoring system were suspected in CS12.

The overall conclusion is that monitoring data could support useful analysis in nine out of ten sites in the sub-sample. Further information on quality of monitoring data is provided in the accompanying RHPP *Performance Variations Report.*

Complexities of interviews

On-site observations and interviews also proved demanding and complex. The limited time allocated for site visits meant that it was difficult to gather sufficient physical and social data. The task of collecting photographic data both of the heat pump systems and dwellings could be be made harder by weather, the timing of the site visit (available daylight) and the internal space and level of lighting in the dwelling. Dwellings and external units could be photographed in daytime, but thermal imaging is better done at night. In some cases, accessing cylinders and controls was difficult, e.g. when these were located in limited spaces such as attics or small cupboards.

As expected, occupants were a valuable source of information. But human memoires fade, and occupants' sometimes struggled to recall detail of events related to installation, commissioning, and operation that might have happened several years before, particularly with respect to precise timing of events. More importantly, occupants' interpretations of events was not generally expressed in precise technical language. Some statements may have involved misconceptions about occupants' heating systems, or may in turn have been misinterpreted by the research team.

Complexity of heat pump system design

In general, the visiting team was able to observe the outcome of the physical installation but could not determine at first hand whether the systems had been correctly installed. Similarly, the complexity of dwellings, heating systems, and monitoring systems made a complete survey of all three impossible in the time available on site. Even with remotely monitored physical data, and from monitoring system photographs supplied by BRE, it was not always possible to provide a definitive answer with regard to whether sensors were correctly installed. An unambiguous assessment of radiator sizing could not be delivered for most sites (see *RHPP MCS Compliance Report*). An attempt was made to classify installations on the basis of a visual evaluation of quality of planning and insulation of pipework associated with the heat pump. The pattern within the sub-sample of ten installations, is shown in the Table below:

Table 0-2. Visual evaluation of quality of planning and insulation of pipework

Evaluation	Cases
Poor insulation and planning	CS07, CS09, CS12
Intermediate insulation and planning	CS20
Good insulation and planning	CS13, CS14, CS15, CS16, CS18, CS19

Revision of estimates of heat pump performance

Previous sections have indicated some of the difficulties of complex monitoring design, metering errors and anomalies in the metadata.

RAPID-HPC undertook a detailed analysis of the time traces of heat and electricity recordings for 6 sites. In cases where it was suspected that the initial, unpublished estimates of SPF were affected by spurious data, metering errors or other faults, alternative periods of data were selected and estimates of SPF were revised. In total, there were 4 sites for which representative SPFH4 changed by ±0.5 or more with respect to SPFs based on the preliminary and unpublished dataset: CS07, CS09, CS15 & CS21.

Heat pump performance

The distribution of SPFH4 in the 21 case study sites is shown in Figure 0.1. All seven heat pumps installed at RSL sites (ASHP and GSHP) had representative SPFH4s of 2.3 or above and four were above 2.5. Four of six ASHPs in the private sector had a representative SPFH4 of 2.5 or above. Two of the sites with GSHPs (CS12 & CS16) had an estimated SPFH4 < 2; both were in the private sector. The remaining five of the GSHPs had representative SPFH4s between 3 and 4.6.

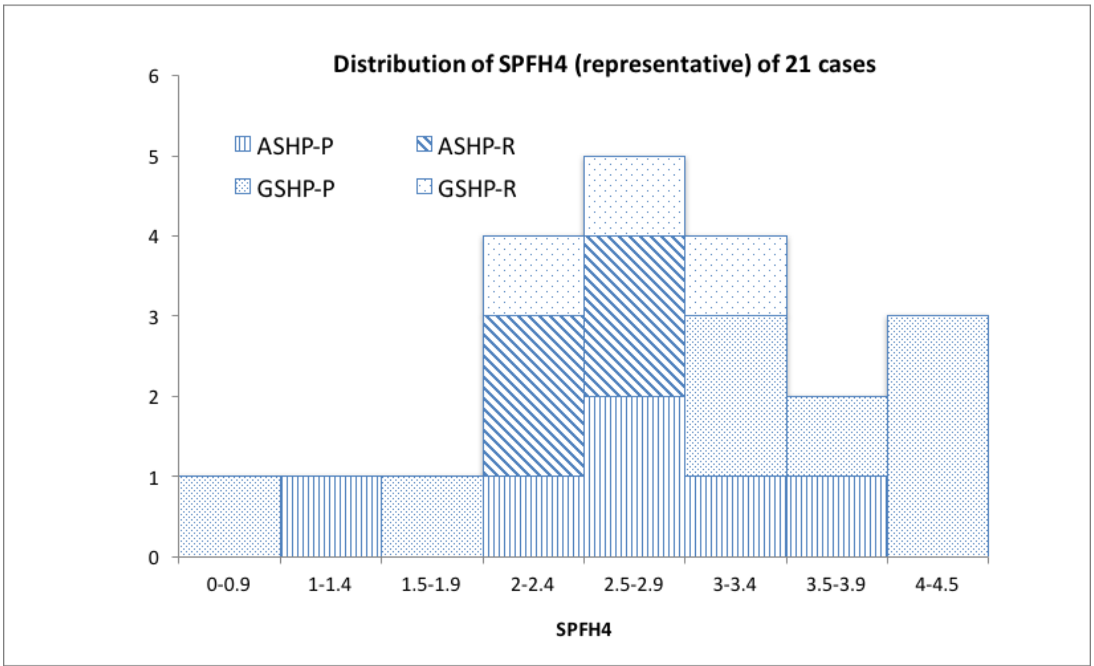

Figure 0-1. Distribution of representative SPFH4 by heat pump type and tenure.

With respect to the understanding of possible reasons for variations in HP performance, the following results emerged:

- It appears that SPFs may be significantly negatively impacted if HP's operate at low load factors– this corroborates a similar, tentative conclusion, reported in the *RHPP MCS Compliance Report*.
- In several cases, heat pump performance is likely to have changed significantly through the course of the project, under the influence of changes in control settings (immersion heaters or internal booster heaters being switched on), or due to failure of key components such as external units of ASHPs.
- Issues around noise and visual intrusion can result in decisions to site HPs significant distances dwellings. It is important to ensure that householders appreciate the potential loss of performance consequent on such a decision, and if it is unavoidable, to ensure that pipework to remotely sited external units is insulated to a high standard.
- Occupants' choices of heating control strategies can make a significant difference to the performance of HP systems. This is best illustrated by CS16, where it is likely that a significant part of the space heat demand of the house was met by a combination of an electric Aga and two wood burning stoves, resulting in a low load factor, and low SPF. This suggests a need for technical advice to householders that emphasising that:
    - a heat pump is likely to produce heat at around a third the price of other on-peak electric heating systems;
    - electric resistance heating and other sources of heat can easily displace heat from the heat pump, at the same time, increasing heating costs;
    - heat pump performance may then decline because of the lower load, increasing heating costs still further.
- Experience on a number of sites suggests that follow up visits by technically competent personnel might help to ensure that initial teething issues were resolved and that performance was maintained over the long term. It should be noted that a similar observation was made in the RHPP *Performance Variations Report*.

The role of electric resistance heating is, unsurprisingly, a theme that runs throughout this analysis. It appears that 12 out of the 21 cases had internal boost heaters, and that the onset of resistance heating could be triggered both by physical and social factors (See Section 4.5. and 5.5. for details). Specifically, automated or integrated resistance heater units, and the unexpected and in some cases, undetected switching on of booster or immersion heaters can increase the proportion of heat supplied by resistance heating. Resistance heating was particularly problematic where occupants were unaware of the presence of such systems or lacked knowledge of their potential effects. Some heat pumps have "safe" or "protected" modes, in which the compressor is unable to run. An external assessor has suggested that these may be triggered by power outages. The occupant of CS08 suggested that this may have happened to their system.

Moreover, even in well performing HPs, there is evidence of electric resistance heating at work. For example, although none of the seven social housing cases were assessed as poor performers, four appeared to exhibit significant resistance heating for most of the monitoring period, despite relatively predictable heat demands due to simple built forms and demographics. The implication of this may be that even better performance could be achieved with improved control of boost and immersion heating, underpinned by improved commissioning. Manufacturers might wish to consider how control systems might be designed to alert occupants to the operation of immersion heaters and integrated boosters, so that they can either make appropriate adjustments themselves, or seek advice.

Performance and EPC rating

There is no evidence from this study that heat pump performance was affected by the EPC rating. The sample size was too small and there are numerous confounding factors. This does not mean that the efficiency of the dwelling, as reflected in the EPC rating, is unimportant. Finding space for the large low-temperature radiators that would be needed in poorly insulated dwellings is likely to be problematic.

Observed faults with heat pumps in case studies

At least 10 (four RSL and 6 privately owned) out of the 21 cases had experienced some major problem since installation, such that the occupants could not easily resolve it themselves. In at least four cases, the occupants had experienced more than one issue. Note that for CS07 and CS16, there were ongoing issues with the HP at the time of the visit. Overall, the main technical issues as described by occupants (Section 4.7, and summarised in table on following page figure 0.2) relate to faulty HPs or faulty sub-system, installation and antifreeze problems, condensation dripping from external ASHP units, blockages, a "faulty motherboard" and unintentional use of resistance heating resulting in excessively high electricity bills[9]. Response to faults was sometimes slow, most noticeably in social housing, where the occupant in CS08 had to move in with relatives for a period of around 2 months in the spring of 2013.

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[9] IEA HPT Annex 36 "Investigating the effect of quality of installation and maintenance on heat pumps", May 2015,. concluded that the reported error was not always the real issue, but it was easy for the service provider to change, thus sometimes leading to larger servicing costs http://heatpumpingtechnologies.org/annex36/ .

Table 0-3. Summary of faults

Issue	Leakage		Faulty HP or sub-system						Installation		Condensate		Block-age	Resistance heater	
	Cracked tube *Leakage from ground loop*		*HP burnt out due to faulty generator* *HP burnt out due to faulty air inlet fan in external unit* *Faulty motherboard* *Faulty pump, sensor/miscommunication between sensor and controller* *Faulty air inlet fan in external unit* *HP broke down after a big surge in voltage*						*Air in ground loops* *Specific zone wouldn't heat up due to manifold floor valves installed back to front*		*Missing drip-tray causing excessive spillage* *Missing drip-tray causing slippery damp patch*		*Tank and rad blockage causing water flow problem*	*Booster left on by plumber or maintenance team*	
CS	04	14	06	07	08	12	21	17	13	01	08	06	06	12	08
RSL/Private	RSL	P	RSL	RSL	RSL	P	P	P	P	P	RSL	RSL	RSL	P	RSL
HP type	GSHP	GSHP	ASHP	ASHP	ASHP	GSHP	GSHP	GSHP	GSHP	ASHP	ASHP	ASHP	ASHP	GSHP	ASHP
Fixed?	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✖	✔	✔	✔

Occupants' experiences and perceptions

Occupants' strategies for controlling systems and fixing problems

Occupants' strategies for controlling their systems, and dealing with problems varied widely. Two of the case study households included physicists, who were able to engage technically and conceptually at a level that other occupants were not. One of these, the occupant of CS19, decided in the period immediately following installation, to experiment with his HP controls. After trying a number of control strategies he concluded that the cheapest was to run the HP continuously. However, most households who experienced problems relied on experts to resolve them.

Occupants' satisfaction levels

In eighteen out of twenty-one cases, occupants were satisfied or very satisfied with their heat pumps. Figure 0.3 shows the levels of satisfaction reported. The case studies revealed the complexity of the notion of satisfaction, which included the level of thermal comfort felt, running costs, ease of use, environmental impact, technical integrity, noise levels and controllability of the system. One social housing case stood out; the occupants were dissatisfied for a variety of reasons that did not seem to correlate with the apparently good performance of the heat pump during the last year of monitoring.

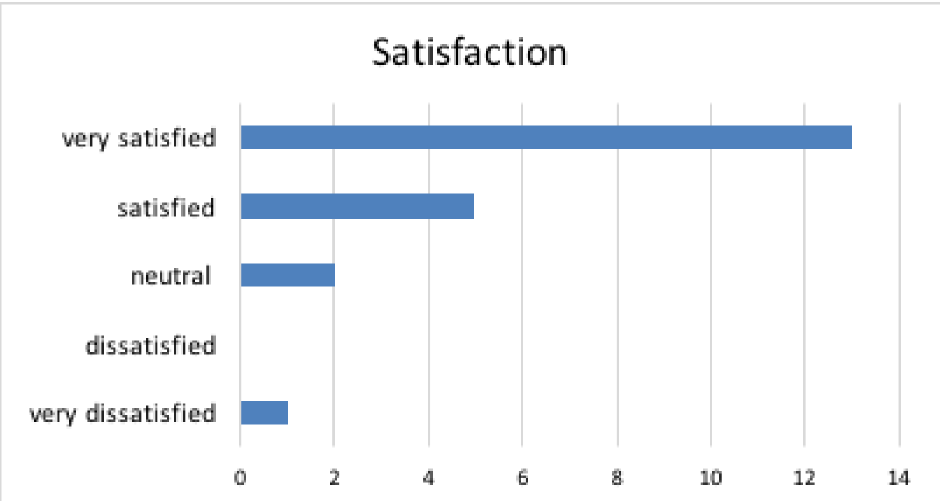


Figure 0-2. Levels of satisfaction reported across the 21 case studies.

Despite significant disruptions (HPs in each of three out of the seven RSL cases suffered a major breakdown, with heating systems out of action for periods of up to two months), six out of seven RSL households were satisfied with their new heating systems, because they were cheaper and less troublesome than their previous heating system (storage heaters). Responses from the RSL occupants show the need for RSLs to have access to competent personnel to deal with troubleshooting. Rapid and competent response to faults is critical to maintain occupants' confidence in their heating systems.

Conclusions and recommendations

The overall aim of this study was to improve the understanding of performance of domestic heat pumps and users' satisfaction with them. The above sections have summarised the process and outcomes of this study.

There is no doubt that the picture of heat pump performance that emerges from this analysis is complex and goes beyond what can be revealed by physical monitoring systems alone; physical and social context are also important. This study has enabled both clarification of some technical details for some installations, and an evaluation of the quality of the metadata available for the RHPP Field Trial installations. The analysis revealed significant inconsistencies in the MCS and EPC metadata available to RAPID-HPC. Reliable metadata is critical to the statistical analysis of data for large numbers of dwellings, in particular with respect to the analysis of differences in performance between groups of installations with different characteristics. The limitations of the statistical analysis reported in the accompanying *RHPP Performance Variations Report* may be ascribed in part to this problem[10].

Many factors appear to contribute to occupants' satisfaction with their heat pumps. These include perceived comfort, bills, perceived environmental benefits, controllability, experience with previous heating system, information provided by the installer, time to fix faults etc. Overall, there was a high level of satisfaction with 18 out of 21 householders declaring themselves satisfied or very satisfied with their heat pump. Control strategies varied across the sample: in all the RSL properties, a single heating zone was controlled by the thermostat only (possibly with night set-back), but the owner-occupiers used a range of strategies, from simple continuous heating (CS19) to multiple secondary sources of space heating (CS16). Further research in this area would elucidate not just the impact on SPF and costs, but also the on occupant comfort and satisfaction in relation to expectation and costs

The value of this study lies in the close examination and detailed understanding of individual cases – a field study is not a small field trial. A critical decision in the design of field trials is the number of cases to include, together with the issues that are to be explored and the resource that is available. These need to be considered carefully during the planning of any trial or evaluation study. This study set out to investigate 20 cases in detail, with one additional case undertaken as a pilot. While a large amount of descriptive data was generated for all 21 cases, resource limitations meant that detailed case and cross-case

[10] The present report is accompanied by two parallel reports, the abbreviated titles of which are *RHPP Performance Variations Report* (RAPID-HPC, 2017a), and *RHPP MCS Compliance Report* (RAPID-HPC, 2017b).

analysis and comparison was undertaken initially on a sub-set of ten cases. Six additional RSL cases were later added to shed light on the performance of the only RSL site selected in the ten.

Much of the work on this study was undertaken by an architect and a heating system engineer, with support of an experienced social scientist. But it also required other members of the consortium, whose main focus was analysis of monitoring data, to provide supporting data and analysis. The resource implications of such support were underestimated in this study.

In general, case study methods can support large scale, predominantly quantitative, statistically oriented field trials in at least two ways. If undertaken during the installation of monitoring equipment, they can help to ensure the quality of both metadata and data collected by remote monitoring systems. If, as in the study reported here, they are undertaken after the onset of physical monitoring, they can make use of insights from monitoring data to aid case selection, and to suggest lines of enquiry for site visits and subsequent analysis. As noted earlier, in this study, such insights were limited by the quality of physical data available. High quality monitoring data is important to mixed methods case studies, particularly in the context of selection of cases, cross-case comparison and the development of socio-technical explanations for physical observations..

One of the ambitions during the genesis of this study was to provide a detailed picture of the relationships between dwelling heat load, heat transfer capacity of the heat distribution system, and heat pump capacity. It transpired that to achieve this would have required significantly more resource and time on site than was available to this trial. There is also a possibility that longer scheduled site visits would affect the number of households that would be willing to engage with a future research team. It is possible that this could be mitigated by requiring recipients of subsidies for new technologies to indicate their willingness to engage with a future evaluation, should one be commissioned. This should include the option of additional contact with dwelling occupants to resolve questions that emerged after a site visit.

The value of both case studies and large-scale field trials would be increased significantly by providing access to utility bills. In principle, such information will become even more valuable as smart meters become more common. The precise mechanism for achieving this is likely to change with the introduction of smart meters, but will require occupant assent. Recording manual reads of utility meters during monitoring system and heat pump commissioning would provide additional redundancy. Consideration should be given to amending the MCS standards and guidance to require the latter.

The performance of HPs defined by SPF is subject to a double contingency: on one hand the interactions between the physical and the social that influence performance, and on the other, issues around remote monitoring practices and technologies, and technical/scientific judgement by which performance is quantified. Despite the complexities and contingencies, this study has revealed that resistance heating and heat load are two significant issues that require attention if performance of HPs in operation is to be improved. These two issues, though at first sight physical in nature, emerge from physical and social substrates that are perhaps most likely to be disentangled and understood through mixed methods case studies such as this.

1 Introduction and background

In 2015/16, the Department of Energy and Climate Change (DECC)[11] commissioned the Consortium (RAPID-HPC) to analyse existing data collected as part of the Renewable Heat Premium Payment Scheme (RHPP) and investigate variations in performance of these HPs. Based on a statistical analysis and technical inference of data from remote physical monitoring, the initial results of the evaluation have identified a wide range of variation in SPFs across the sample. The Consortium also found significant issues with data from the physical monitoring and noted a number of limitations in the original RHPP field trial. These include:

- lack of redundancy in data from the physical monitoring, which has restricted the scope for verifying the quality of the data and for exploring potential explanatory relationships with variables that lay outside those collected through the physical monitoring system;
- metadata quality issues concerning dwellings and heating systems;
- lack of information or insight into the immediate physical context in which the HPs and the physical monitoring systems operate – this fine grained information is absent from the metadata;
- lack of information about the ways the occupants use, modify and adapt to their HPs, as well as their understanding, expectations and satisfaction with them.

This socio-technical field study seeks to address the above limitations and advance our understanding of HP performance using the multiple case study method to investigate in detail a number of HP installations in the RHPP trial. The project was carried out between November 2015 and October 2016. This report describes the development of the field study and sets out the aims, objectives, methods and findings of the work undertaken.

[11] The Department of Energy and Climate Change (DECC) merged with the Department for Business, Innovation and Skills (BIS) in July 2016, to create the new Department for Business, Energy & Industrial Strategy (BEIS)

2 Aims and objectives

Informed by a series of questions raised by initial results of the RHPP project, the overall aim of the field study was to improve the understanding of performance and users' satisfaction of domestic HPs by investigating the application of HPs in a real world context. This steps were:

- Collect and analyse information on the immediate physical context in which the HPs and physical monitoring systems operated;
- Investigate the quality of monitoring data and heating systems on a case-by-case basis;
- Analyse the physical and social data collected in further selected cases and corroborate with the monitored data and metadata available;
- Carry out case analysis and cross-case comparison as hypotheses of performance variation emerge;
- Explore potential explanations for good and poor performance by synthesising available data.

3 Design and methods

Much of the design of this sudy was modelled on post-occupancy evaluation and energy efficiency in buildings, where attention is paid to both energy efficiency measures (e.g. heating, ventilation, and fabric) and the roles of social variables, such as demographics, geographical location and occupants' behaviours or practices in relation to these measures. Experience in post-occupancy evaluation and a good technical understanding of the design and operation of HPs have enabled the field study team to conduct the project within this theoretical and methodological framework, providing structure and boundaries to the investigation and collection of data.

Data were collected for a pilot case, CS01, to test boundaries, tools and instrument for data collection, allowing these to be refined for the collection of data from the remaining 20 cases (CS02 – CS21). An analytic matrix was constructed (Appendix B), based on four socio-technical assumptions about how a typical heat pump should operate, to enable the case and cross-case comparisons to be undertaken coherently (see Section 5.3 for details).

3.1 Sampling method

3.1.1 The estimation and role of SPFs in the case study process

The primary metric for HP performance in this study, both for selecting cases and to provide physical performance context to support wider analysis, is the seasonal performance factor (SPF). At its simplest, this is the ratio of heat output to electricity input for any given HP, over a year. It is therefore important to understand the processes and data by which SPFs have been estimated, and their impact on the implementation of methods and analysis.

The sample selected as a prima facie evidence for performance for the field study was based on the *preliminary and unpublished* dataset (351 sites) derived during the first phase statistical/technical analysis of the SPF data collected in the RHPP trial from data for 699 sites (Sample A) originally provided to RAPID-HPC. However, it is important to note that concurrent with the field study, the statistical team continued to construct different data sets, as their understanding of the data and the technical nuances of individual HPs evolved, and to address different analytical demands. Each of the datasets played a different role in the statistical evaluation and provided different overviews. As part of the *RHPP Performance Variations Report*, the Sample B2 dataset was generated, driven by the need for relatively complete and stable data over a 12 month contiguous period, for as large a sample as possible across the different categories of HPs. The algorithms for Sample B2 utilise a number of simple filters for data quality and completeness, leading to the inclusion of 417 sites. Based on an initial inspection of the degree of scatter in the data and the need to identify relationships between basic HP characteristics and their performance, Sample B2 was further reduced to omit sites outside the range for SPF4 of 1.5 to 4.5. This was named Sample B2 (cropped). The SPFs across the samples mentioned above were calculated as follows:

- **Preliminary and unpublished dataset** – SPFs were calculated for the same annual monitoring period of 01/11/2013 to 31/10/2014.

- **Sample B2** - SPFs were calculated for different periods for each site, i.e. the ones with the best consecutive available data.

It should be noted that estimates of SPF for any given dwelling vary depending on the **precise data used** to calculate them. Different time periods will subject the HP to different weather data, to changing patterns of use, and to events, such as breakdowns either in the HP or the monitoring system, that will affect the calculated value of the SPF. In most cases, SPFs based on these different datasets do not vary much. In four of the cases (namely CS07, CS09, CS15 and CS21) in the twenty-one case samples, significant anomalies were found in the data originally used to estimate the SPF, that is using the *preliminary and unpublished* dataset and the fixed period of 01/11/2013 – 31/10/2014. The estimates were then revised using periods of data free of significant data anomalies. For these four cases, the estimated SPFs are significantly different to the original estimates. In the context of this study, readers are to be reminded that the selection of the twenty-one case samples was based upon the *preliminary, unpublished* estimates of SPF values known to the field study team at that particular time.

3.1.2 Recruitment of participants

The recruitment approach ensured voluntary and informed participant consent via an ongoing process. Recruitment involved the following stages:

- **Invitation via email or post:** Emails and letters were sent to all householders in the *preliminary and unpublished* dataset, inviting them to register their interest to the study based on a brief description of the site investigation process (see Appendix A for sample of cover letter and invitation). These also informed them of the RHPP heat pump analysis project and the relative performance of their HP within the trial, as it was then understood. As shown in Figure 3-1, participants were either approached directly, in the case of owner occupiers, or through the assistance of Registered Social Landlords (RSLs), whose tenants were contacted at their discretion. Initially, emails were sent to 117 private householders[12] and 31 RSLs[13]. Overall, approximately one third of the private householders and almost half of the tenants that were contacted by RSLs responded positively, giving 49 potential participants in total (36 private householders and 13 social tenants).

- **Follow up recruitment contact:** Among householders who accepted the invitation, potential participants were selected based on the sampling strategy detailed in the following section (3.1.3). Contact and further arrangements were made via emails or phone calls to ensure concurrent availability of the occupants and researchers within the project's timescale.

- **Final arrangements:** Interviews and site investigations were arranged at convenient times with those who agreed to take part in the study. An information sheet and consent form were sent to occupants prior to site visits; these can be found in Appendix A**.** The information sheet and consent form outlined the basis for participation, e.g. the nature of the study, what participation would entail, the voluntary nature of the participation, the right to withdraw at any stage, the potential risks and benefits and contact details of the researchers.

Twenty sites were finally selected as specified in Contract Variation II to the original BEIS RHPP contract. An additional dwelling was included to allow the site visit procedure to be piloted, giving twenty-one cases in all.

[12] Letters were sent by post to six private householders who had not provided an email address as well as to 82 non responding householders.

[13] Of the 31 RSLs contacted, approximately 1/3 did not respond. It was not possible to confirm whether non-responses were due to mis-identification of personnel or contact details. Of the remaining 2/3s, 10 RSLs did not respond further, while another 10 said they were happy to contact their tenants (although half of them never reported back). Finally, one RSL decided to withdraw from the study due to shortage of staff to liaise with selected sites - such liaison was important since these sites tended to be occupied by elderly and vulnerable people.

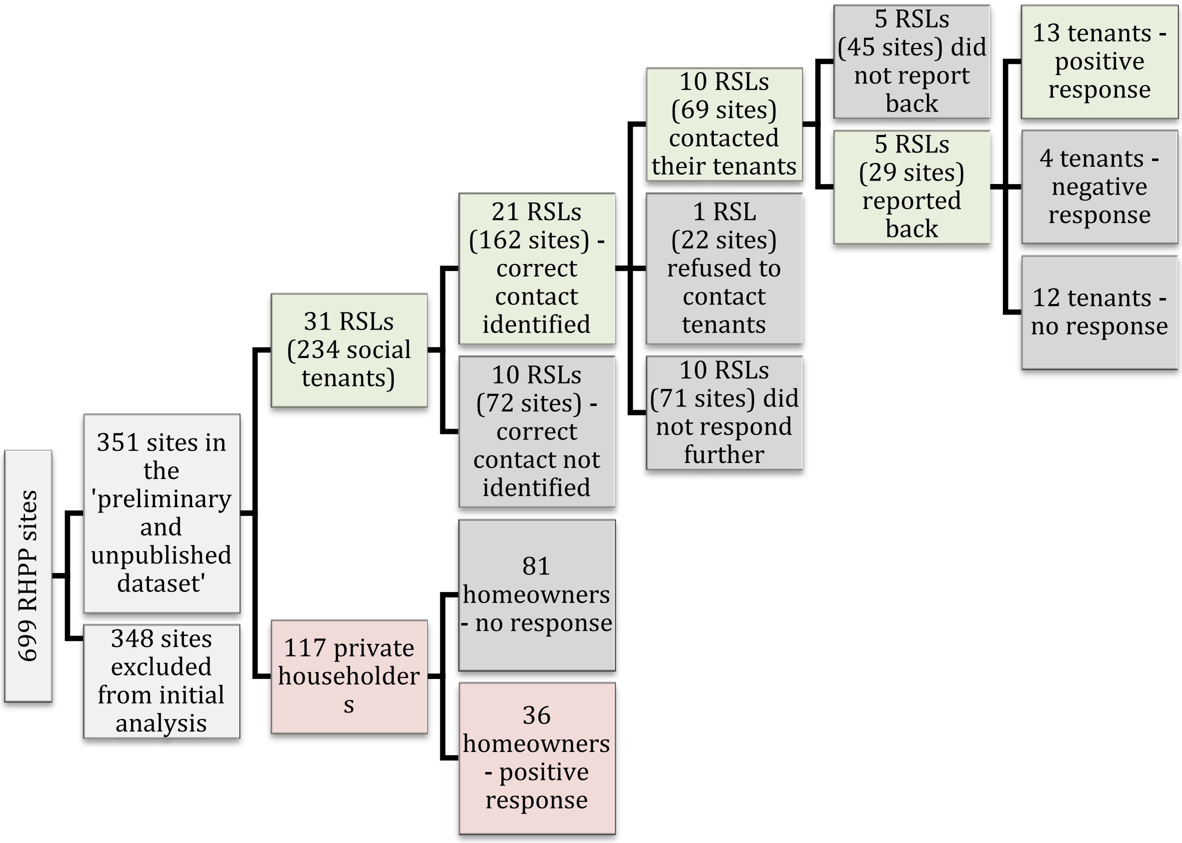


Figure 3-1. Flow chart of the invitation process to participate to the investigation of a small sample of HPs.

3.1.3 Case study sampling

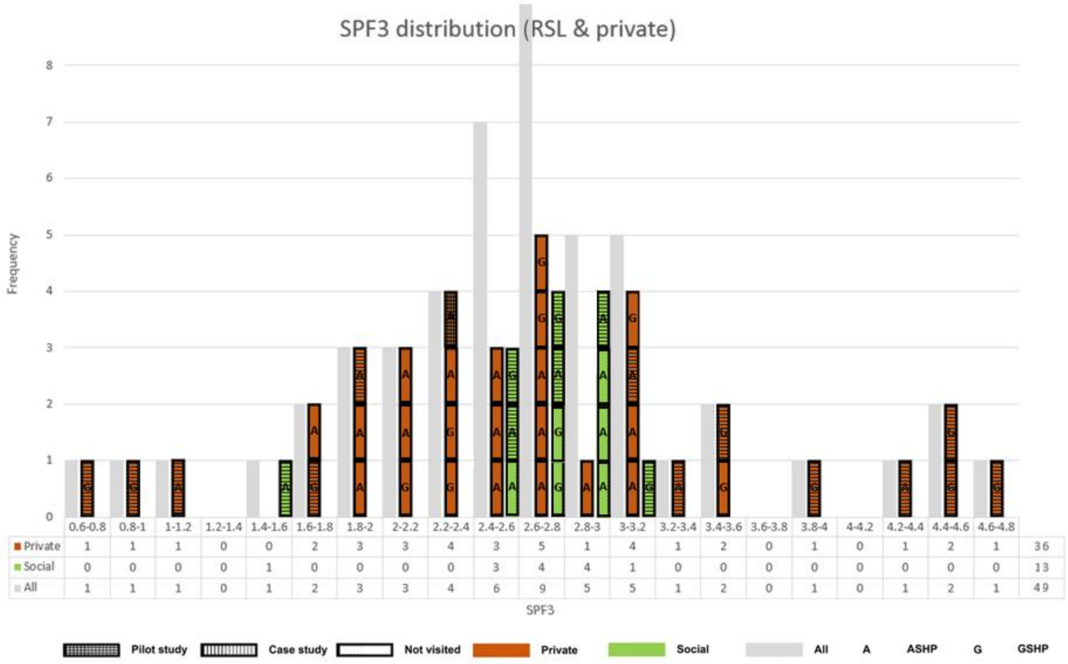
The strategy for selecting the case study sample from those households that volunteered was primarily based on the distribution of SPFs for the sites that volunteered, as presented in Table 3-1 and Figure 3-2. The performance metric used was SPF3 calculated over the same annual monitoring period of 01/11/2013 to 31/10/2014 for all sites; these values are referred to as the *preliminary and unpublished* dataset estimates, throughout this report. Sites at both ends of the normal SPF3 distribution were purposely selected (positive and negative variance) as well as a few in the middle. At the same time, it was important to ensure a good cross-section of different variables in the 20 case study sample (wherever possible) thus a number of secondary selection criteria, such as location, ownership and HP type, were also taken into consideration. These were deemed to be suitable for developing an understanding of possible reasons for variations found in performance. Note that the case study sample was not intended to be statistically representative of the wider RHPP population. The aim of using case study as an investigative method is not to generalise findings but to provide an in-depth understanding of phenomenon at hand (Ritchie et al., 2013).

Table 3-1. Sampling criteria

Primary criterion
Seasonal Performance Factor – The selection of the sample was primarily based on the histogram of the weather adjusted SPFs at level H3, as shown in Figure 3-2. The best (SPF3>3.4) and poorly (SPF3<2.0) performing HPs as well as a few in the middle range of the distribution were selected. Note that preliminary, unpublished estimates of SPF were used.
Secondary criteria*
Location – Ensuring a good geographical coverage in relation to the following areas: North of England, South of England, Wales and Scotland
Ownership – Ensuring private householders as well as social householders were present in the sample
HP type – Ensuring there were similar numbers of air- and ground-source HPs[14].
Emitter type – Ensuring the sample included cases with a variety of emitter types, i.e. radiators, underfloor or a combination of both.

[14] For future studies, it might be appropriate to weight the proportions of ASHP and GSHP by their prevalence in UK households.

**Information on household size, previous fuel, number of bedrooms and dwelling type, age or size were either not available or inadequately recorded in the metadata.*



	0.6-0.8	0.8-1	1-1.2	1.2-1.4	1.4-1.6	1.6-1.8	1.8-2	2-2.2	2.2-2.4	2.4-2.6	2.6-2.8	2.8-3	3-3.2	3.2-3.4	3.4-3.6	3.6-3.8	3.8-4	4-4.2	4.2-4.4	4.4-4.6	4.6-4.8	
Private	1	1	1	0	0	2	3	3	4	3	5	1	4	1	2	0	1	0	1	2	1	36
Social	0	0	0	0	1	0	0	0	0	3	4	4	1	0	0	0	0	0	0	0	0	13
All	1	1	1	0	1	2	3	3	4	6	9	5	5	1	2	0	1	0	1	2	1	49

Figure 3-2. Histogram of the SPF3s for the 48 sites that volunteered to participate in the case study investigation (based on preliminary and unpublished SPF estimates)

3.2 Field procedure

3.2.1 The pilot

The pilot property (CS01) has been included in the analysis, because (a) following the pilot only minor changes were made to the interview guide, (b) the data collected appeared to be of sufficient quality and (c) it appeared relevant. The result of the pilot provided useful insights for subsequent site visits, for example, it highlighted:

- the importance of visiting early in the day when interviewees are not tired and when better quality pictures can be taken both inside and outside;
- the fact that thermal imaging does not perform well on a rainy or sunny day due to the masking effect of water or re-emitted solar radiation[15];

[15] An external reviewer noted that such weather constraints can be circumvented by undertaking IR thermography from inside rather than outside dwellings.

- the limited amount of information that can be collected on ground loops and underfloor heating systems, and the consequent difficulty or impossibility of assessing the quality of technical installation;

- the limited amount of information that can be collected during a two- or three-hour visit.

3.2.2 Case studies investigated

Twenty-one in-depth interviews and site investigations were completed with 7 social and 14 private householders. They were carried out between November 2015 and January 2016 and each of them lasted around two to three hours. All but one private householder (the pilot dwelling) were receiving the RHI fund while in the case of social houses it was the RSL that was receiving the fund. Table 3-2 presents briefly the characteristics of the 20 case studies selected and the one pilot property in relation to the primary and secondary sampling criteria (see Table 3-1). The data collected during the site visits is juxtaposed with the metadata from the RHPP metering database. Other important information, for which there was insufficient metadata at the time of the sample selection, is also presented in the table, i.e. household size, dwelling type, age and size, number of bedrooms and previous fuel. For location information, see Figure 3-3. The bullet points below summarise the main characteristics of the 21 cases.

- **Performance** – equal numbers of HPs were selected from each end of the potential participant distribution, as defined using the *preliminary unpublished* SPFs, i.e. six poorly performing (three ASHPs and three GSHPs, SPF<2.0) and six very well performing (two ASHPs and four GSHPs, SPF>3.4). The remaining HPs fall in the intermediate performance range of between 2 and 3.4[16].

- **Ownership** – there were more private householders (36 sites) than social tenants (13 sites) in the volunteering sample. Seven social and fourteen private households ultimately participated in the case studies. Two groups of social dwellings with identical or very similar building structures and layouts were selected. Their comparison can provide us with useful insights on the effect of occupant behaviour on energy consumption and the performance of the HP.

- **Location** - Figure 3-3 shows the distribution of all sites that volunteered (marked with circles) as well as the final case study selection (marked with stars);

- **HP type** – the final sample includes 10 air source HPs (ASHPs) and 11 ground source HPs (GSHPs);

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[16] In cases CS07, CS09, CS15 and CS21 the initial SPF estimations were re-evaluated using periods of data free of significant data anomalies. This is explained in detail in Section 3.1.1.

- **Household type and size** - most of the dwellings were occupied by couples. Six out of the seven social tenants were retired. Approximately one third of the owner occupiers were also retired and the remainder were spending most or a significant amount of time at home for one of the following reasons:
    - working from home or part time;
    - couple of which only one person of the two was working;
    - not working (by choice, due to inability or due to caring for children).

  Detailed information on the case study households can be found in Table E 1 of Appendix E.

- **Dwelling type and size** - more than half of the dwellings selected fall into the category of detached housing, five are mid-terraced and four are semi-detached or end-terraced; all social houses visited are small, with total floor areas (TFA) not exceeding 52 m^2 while TFA for private houses ranged between 95 and 345 m^2. Half of the private houses were large, i.e. with a total floor area of more than 200m^2.

As shown in Table 3-2, when compared, there are discrepancies between the data collected on site and the metadata that were made available to the Consortium at the outset of the project. Ownership and HP type information was consistent, but for the emitter type, the metadata information were not always accurate; 7 out of 21 entries were recorded as having a single heat distribution system, i.e. radiators *or* underfloor heating, whereas a combination of both, or a mix of radiators and hydronic fan convectors[17] was found during the site investigations. The RHPP metadata database contains no household or dwelling size information, thus the latter was obtained via EPCs. The household size was observed during the site visit. All but one of the dwelling type entries metadata were correct, however half of entries were missing. The dwelling age as narrated by the householder or RSL was generally within the age band recorded in the metadata, however more than 1/3 of the metadata entries were missing. The case studies included new dwellings, existing dwellings of various ages, some of which had been retrofitted, and dwellings that had been extended. It is important that the dates of any extensions are also recorded, as they may differ significantly from the date of the original dwelling and can significantly affect the extended dwelling's performance. Householders reported extensions built to their dwellings in four cases. 1/3 of the metadata entries on number of bedrooms were missing but the remaining were more or less correct (there were minor differences only, e.g. due to a bedroom that had been converted into two smaller rooms after the HP was installed or a room used as a study rather than a bedroom). Finally, metadata entries for

[17] By the term 'hydronic fan convector', we mean a wall mounted fan convector connected like a radiator to the central heating system.

"previous fuel"[18] were accurate for 1/3 of the cases, approximately another 1/3 were incorrect[19] and missing for the remainder.

[18] This refers to the fuel used by the heating system that was used to heat the house before the installation of the HP system.

[19] Most of the errors in the records for "previous fuel" involved new builds, for which the HP was the first system to have been installed. Logically, no entry should have been given for the previous fuel, however the records generally state"oil" or "electricity", which are, presumably the fuels that would have been used if there were no heat pump. Note, new build properties were eligible for the RHPP under certain conditions, i.e. if the property is a new build, then the payment was only available as long as the initial owner retained ownership. In addition, installations where the HP was installed prior to the first occupation of the property were also ineligible.

Table 3-2. Brief summary of the 21 case studies (including one pilot) based on the characteristics they were selected on (metadata database) and comparison with the data obtained during the site visit (observed or narrated by householder or RSL) or from EPCs

Case study ID	Site visit date	SPF3 from preliminary and unpublished estimates	Ownership (metadata)	HP type (metadata)	Emitter type (metadata)	Emitter type (observed)	Household size (metadata)	Household size (observed)	Dwelling type (metadata)	Dwelling type (observed)	Dwelling age (metadata)	Dwelling age (narrated)	Dwelling size (metadata)	Dwelling size (EPC)	Bedrooms (metadata)	Bedrooms (observed)	Previous fuel (metadata)	Previous fuel (narrated)
CS01 (pilot)	18/11/15	2.4	Private	ASHP	Underfloor	Underfloor	-	2-3	-	Detached	After 2000	2011-12	-	201	4	4	Oil	N/A
CS02	20/11/15	2.6	Social	ASHP	Rads	Rads	-	1	-	Mid terrace	-	1945-64	-	50	-	1	-	Gas
CS03	25/11/15	2.5	Social	GSHP	Rads	Rads	-	1	-	End terrace	-	1945-64	-	50	-	1	-	Gas
CS04	25/11/15	3.1	Social	GSHP	Rads	Rads	-	1	-	End terrace	-	1945-64	-	52	-	1	-	Gas
CS05	25/11/15	2.6	Social	GSHP	Rads	Rads	-	2	-	Mid terrace	-	1945-64	-	52	-	1	-	Gas
CS06	09/12/15	2.9	Social	ASHP	Rads	Rads+hy-dronic fan convector	-	2	-	Semi	-	1930s	-	34	-	1	-	Electricity
CS07	09/12/15	1.5	Social	ASHP	Rads	Rads+hy-dronic fan convector	-	2	-	Mid terrace	-	1930s	-	41	-	1	-	Electricity
CS08	09/12/15	2.6	Social	ASHP	Rads	Rads+hy-dronic fan convector	-	1	-	Mid terrace	-	1930s	-	34	-	1	-	Electricity

Case study ID	Site visit date	SPF3 from preliminary and unpublished estimates	Ownership (metadata)	HP type (metadata)	Emitter type (metadata)	Emitter type (observed)	Household size (metadata)	Household size (observed)	Dwelling type (metadata)	Dwelling type (observed)	Dwelling age (metadata)	Dwelling age (narrated)	Dwelling size (metadata)	Dwelling size (EPC)	Bedrooms (metadata)	Bedrooms (observed)	Previous fuel (metadata)	Previous fuel (narrated)
CS09	16/12/15	1.0	Private	ASHP	Rads	Rads	-	2	Detached	Detached	1965-1980	1973	-	164	4	3-4*	Oil	Oil
CS10	18/12/15	3.3	Private	ASHP	Rads	Underfloor + Rads	-	4	Detached	Detached	Pre 1919	Pre 1919	-	293	5	5	Oil	Coal
CS11	18/12/15	3.2	Private	ASHP	Rads	Rads	-	2	-	Detached	1945-1964	1958	-	178	4	4	Oil	Oil
CS12	13/01/16	0.7	Private	GSHP	Underfloor + Rads	Underfloor + Rads	-	1	-	Detached	After 2000	2008-9	-	106	2	2	Electricity	N/A
CS13	13/01/16	4.7	Private	GSHP	Underfloor	Underfloor	-	4	-	Detached	Pre 1919	1780s	-	252	5	5	Oil	Oil
CS14	14/01/16	3.9	Private	GSHP	Underfloor	Underfloor	-	2	Detached	Detached	After 2000	2012	-	293	4	3 (+1***)	Oil	N/A
CS15	14/01/16	0.8	Private	GSHP	Underfloor	Underfloor + Rads	-	2	-	Detached	After 2000	2011	-	262	4	4	Oil	N/A
CS16	20/01/16	1.7	Private	GSHP	Underfloor	Underfloor +Bath Rads	-	2-4	-	Detached	After 2000	2012	-	314	3	3	Oil	N/A
CS17	22/01/16	3.5	Private	GSHP	Rads	Rads	-	2	-	Detached	-	1992	-	179	4	3	Oil	Oil

Case study ID	Site visit date	SPF3 from preliminary and unpublished estimates	Ownership (metadata)	HP type (metadata)	Emitter type (metadata)	Emitter type (observed)	Household size (metadata)	Household size (observed)	Dwelling type (metadata)	Dwelling type (observed)	Dwelling age (metadata)	Dwelling age (narrated)	Dwelling size (metadata)	Dwelling size (EPC)	Bedrooms (metadata)	Bedrooms (observed)	Previous fuel (metadata)	Previous fuel (narrated)
CS18	22/01/16	4.6	Private	GSHP	Underfloor	Underfloor	-	3-4	Detached	Detached	After 2000	2012	-	346	4	4	Oil	N/A
CS19	27/01/16	4.5	Private	GSHP	Rads	Underfloor + Rads	-	1-2	Detached	Detached	Pre 1919	1920s	-	95	3	3	Oil	Oil
CS20	27/01/16	4.3	Private	ASHP	Rads	Rads	-	2	Semi	Semi	1945-1964	1956	-	99	3	2	Electricity	Electricity
CS21	29/01/16	1.9	Private	ASHP	Rads	Rads	-	1	Semi	Mid terrace**	1965-1980	1970s	-	102	3	3	Electricity	Oil

** Number of bedrooms varied throughout the monitoring period.*
*** Difference is probably due to the unheated garage being converted into living space.*
**** Guest room in a separate building.*

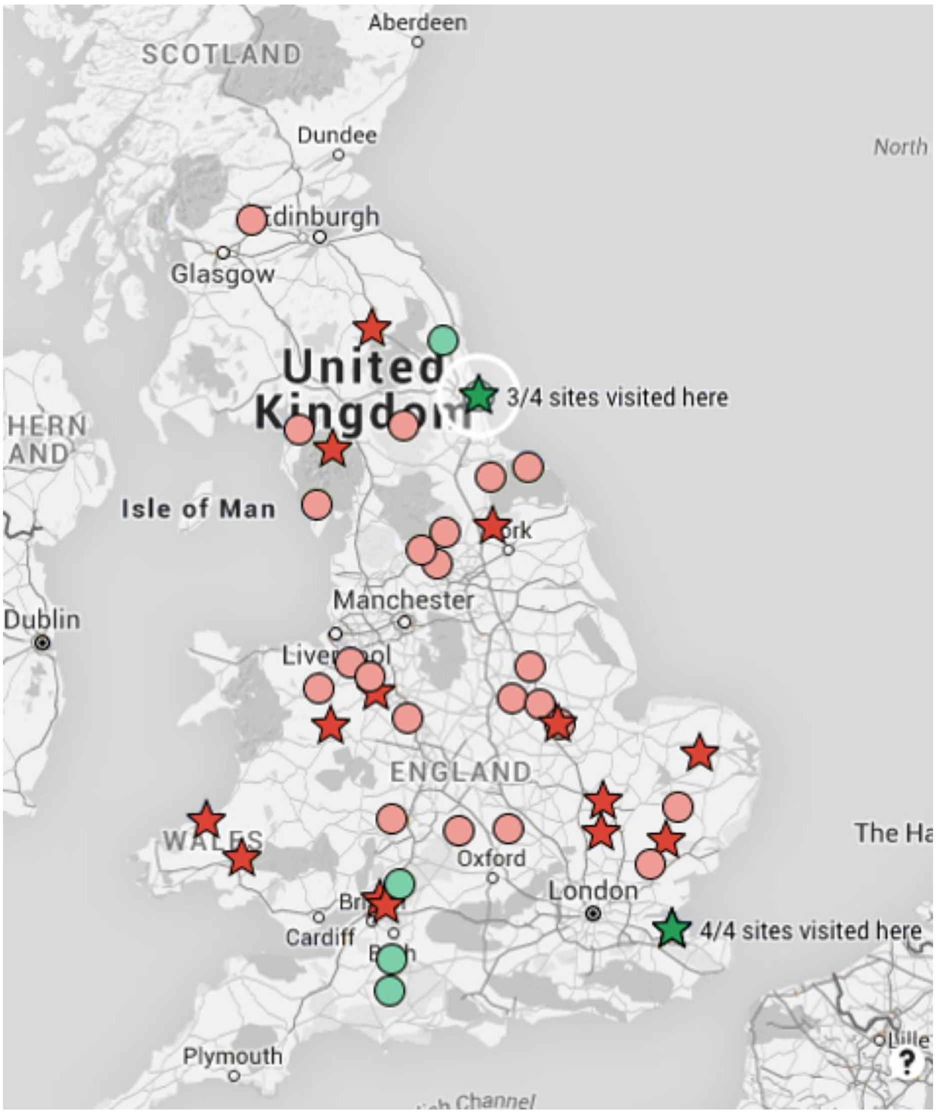

Figure 3-3. Location for each one of the 49 sites that volunteered for the case study investigation is represented by circular and star shapes, the latter showing the final selection of the 21 case studies; red and green colours show the location of private households and social tenants respectively.

3.2.3 Interview and site investigation routine

Before each site visit, a number of technical parameters were established for each case study using the monitored data and metadata that were provided by BEIS as part of the main contract: HP type, configuration and efficiency, energy consumed for space and water heating, daily usage patterns, dwelling and household information available. Any unusual facets of the installation, efficiency or metering were highlighted by the monitored data analysis team.

The study team consisted of three researchers, Dr Colin Gleeson, Ms Eleni Oikonomou, and Dr. Lai Fong Chiu. Dr. Gleeson and Ms Oikonomou covered both the technical and the social aspect of the site visits. Some site visits also involved Dr Chiu, but to lessen the feeling of intrusion by occupants, most were covered by only two people. Dr. Chiu, Professor Robert Lowe and the quantitative team have supported the analysis throughout.

The topic guide, designed by the research team and BEIS, was piloted and revised, resulting in a few minor changes in content and the sequence of the questions. The guide was semi-structured, to encourage conversation with participants and to address the individual nature and content for each discussion. The final topic guide (see Appendix A) was structured in four parts:

a. **Briefing session**: the researchers explained why they were there and what they were going to do; participants were provided with the field trial information sheet and consent sheet with the option for them to give their signed consent to participate. Photographs, thermal imaging and audio recording took place only after the participants' consent had been confirmed.

b. **Confirmation of details:** the participants were asked to confirm some personal information (name, address, household size, contact details) and to answer some general questions about their household and HP (e.g. how long they had been living in the house and why they had chosen this technology[20]);

c. **Walk through:** the purpose of the walk through was to prompt responses from occupants in specific contexts, and to allow the gathering of qualitative and quantitative data on the house configuration, structure type and conditions (e.g. room dimensions, thermal characteristics, identifying warm/cold rooms), the equipment installed in the house and their operation (e.g. HP and its monitoring equipment, controls and frequency of use as well as any secondary heating), either via observation, taking pictures or asking participants directly.

d. **Sit down session:** participants were asked a final set of questions to elicit information about their habits, lifestyle and use of heating (e.g. energy use, thermal comfort and occupancy hours).

[20] Note that it was predominantly private householders that had chosen to have a HP – the decision to fit HPs in social housing was taken by RSLs in all cases, sometimes against the wishes of occupants.

All but one households gave their permission for the discussions to be audio recorded and for photographs to be taken. The exception, CS12, was not audio recorded and photography was limited to just the HP installation, however detailed notes were made during and after the site visit.

3.3 Data management and analysis

3.3.1 Data operations

Given that the field procedure aimed not just to collect interview data but also to use direct observational methods (e.g. measure dwelling floor areas, thickness of walls and areas of emitters), it generated a large amount of data – these included architectural drawings and sketches, HP documentation, and photographs. Data for each case, including pre-visit material (e.g. metering schematics, monitoring data and EPCs) and post-visit material (e.g. photographs of dwellings and systems, audio recordings and field notes) were filed on Bartshare, a physically and electronically secured server, sited at UCL and operated in accordance with UCL Information Security Policy. Whenever data containing sensitive information is transferred outside Bartshare for processing and analysis purposes, the laptops/desktops used are encrypted and password protected. Under the terms of the contract, all un-anonymised technical and social data collected as part of the case studies, through the home and occupant surveys, will be erased at the end of October 2017 and any case study technical data or reports made publicly available, will be fully anonymised.

3.3.2 Data analysis

As noted earlier in Section 3.1.3, the case studies were initially selected from the *preliminary and unpublished* dataset based on their performance at boundary level H3. Even though SPF3s were used for the case study selection, SPF4s were eventually judged to be more reliable and appropriate for detailed analysis. This is because, for the majority of sites, the performance at system boundary H4 is available directly from the measurements, whereas to calculate the performance at system boundary H3, the electricity use of the circulation pump and the heat that it adds to the heating fluid must be subtracted. However, neither heat emitted nor electricity used by the circulation pumps are measured directly and so assumptions must be made. More information on the calculation at the SEPEMO system boundaries can be found in *The Detailed Analysis of Data from HPs installed via the RHPP Scheme* (DECC, 2016a).

The analysis of the field study was undertaken at two levels:

1st level analysis: As a first step, the raw data obtained from the visits to sites were sorted into case details that contained structured and un-structured information. These details were then organised into descriptive codes and entered into a master matrix. Due to the limited time available, each one of the 21 case study audio recordings[21] was partially transcribed and summary notes were produced. The coding was selective, based on questions and topics from the interview guide. The process was done manually, by highlighting relevant themes and concepts. The codes were then organised into broader themes and categories. This involved identifying themes from existing codes, reducing themes to a manageable number and creating hierarchies within the themes.

A total of 16 codes and sub-codes have been used. These range from dwelling characteristics, occupants' expectation and satisfaction, adaptive behaviours, energy use, bills, documentation provided, to room-by-room observations and short field notes. These partial transcriptions and notes focus on key sections of the discussion, such as the initiative behind the HP installation, the household, heating system and dwelling characteristics, the reasoning behind certain decisions and control settings and the householders' expectations and satisfaction.

The master matrix was a major source of data for the first level of analysis, from which patterns of physical and social configurations and arrangements were identified. As a first step, individual themes were examined closely. All the text passages coded for each theme were read together to facilitate a better understanding of the theme. During this process, it became evident that some themes had to be partitioned, as more than one themes were captured in the codes, and some had to be combined or submerged within another. The goal was to achieve a faithful representation of the data on each theme for all 21 case studies. This is summarised in Section 5 where both consistencies and apparent contradictions that emerge from cross-case comparisons are captured.

2nd level analysis: The results of the first level analysis, together with all the available data mentioned above and the master matrix were the primary resources utilised at the second level of analysis i.e. the case and cross-case comparison in Section 5.3.

3.4 Presentation of results and analysis

The case study results and analysis are presented in the following two sections: namely, Section 4 - *Anatomy of the case study sample and associated variables* and Section 5 – *Case and cross-case comparison*. Section 4 presents the characteristics of all 21 case studies, grouped in seven categories, i.e. calculated SPFs, social information and decision making, dwelling information and ventilation patterns, technical information on HPs, control usage of heating systems, overall energy cost and occupant perception of comfort and satisfaction. Due to the limited resources and time available, the detailed analysis is focused on specific cases. The physical arrangements of the heat pump system and social and behavioural responses of occupants of these cases were closely examined. Comparison was also undertaken in different

[21] Note, at the occupants' request, audio-recording was not undertaken in CS12.

dimensions, i.e. between cases of interest, sub-groups and emergent hypotheses and themes (See Section 5.4).

4 Anatomy of the case study sample and associated variables

The results section reports on the range of observation data, which are both quantitative and qualitative. It presents an overview of the main characteristics of the sample as they were put together after the site visits. These include technical and social parameters of interest, such as information regarding the household, the dwelling, the HP installation and its use, as well as the household satisfaction, perception and recommendation. These are presented in tables and charts as appropriate. Much of this work was undertaken concurrently. While the content of this part of the report formed an invaluable resource for the detailed case and cross-case comparison analysis in Section 5, the latter has also informed the former.

4.1 SPFs across the cases and data samples

Cases for this study were selected on the basis of SPFs calculated for the *preliminary and unpublished dataset*, for the period November 2013-November 2014. This dataset was subsequently superseded by samples B, B2 and B2 cropped, all of which are documented in the *RHPP Performance Variations Report*. SPFs for space heating and domestic hot water combined, for the *preliminary and unpublished*, B, B2 and cropped B2 datasets are presented in Table 4-1.

Eight of the cases studies (CS03, CS04, CS05, CS08, CS10, CS12, CS16 and CS20) selected on the basis of the *preliminary and unpublished* dataset, were subsequently excluded from sample B2. This is because the <u>exclusion criteria for the</u> *preliminary and unpublished* dataset and sample B2 were different. The former excluded sites where there is an uninterrupted missing heat and electricity data period lasting 14 days or more, in the period 1st Nov 2013 – 31st Oct 2014. The latter applied a different, less restrictive test for missing data, and allowed the selected period of data to vary from site-to-site; but in addition, it included:

- a test for stability of circulation through the heat meter (Fhp) over a 13 month period;
- a check for consistency between monitoring schematic and channels of data in the monitored dataset.
- checks on monitoring schematics.

By the time sample B2 was defined, field work had already begun. Since the case study sample was selected <u>not</u> for the purpose of statistical analysis, but to reflect the overall distribution of heat pumps in the RHPP sample, analysis continued with all 21 cases. It was then necessary to confirm representative SPFs for the eight excluded cases. This was done by examining data from these sites during the period November 2013-November 2014 and assessing the degree to which the SPFH4's were affected by missing data; it was concluded that, in most cases, missing data would have little impact on SPFH4 (see Appendix C).

There are four sites where the *preliminary and unpublished* SPF and the B2 SPF differ by more than 0.5: CS07, CS09, CS15 and CS21. Detailed examination of the data for these sites indicated that there had been instrumentation problems during the period of the preliminary and unpublished dataset, November 2013-November 2014. Finally, detailed examination of CS15 showed significant monitoring problems during the period both of the *preliminary and unpublished* and of the B2 dataset - these problems were confirmed through discussions with householders (see section 5.4.1); for this site, the period March 2014-March 2015, was selected by eye as the basis for an estimate of SPFH4.

The estimate of SPFH4 that resulted from the above process for each of the 21 case study sites is referred to as the *representative SPFH4*.

Table 4-1. SPFs at levels H2, H3 and H4 based on the *'preliminary and unpublished'* and Sample B2 cropped and B2 datasets

ID	SPF2 preliminary and unpublished	SPF3 preliminary and unpublished	SPF4 preliminary and unpublished	SPF4 Sample B2	SPF4 sample B2 cropped	Representative SPF4 estimate	Representative SPF calculation period
CS01	2.4	2.4	2.3	2.3	2.3	2.3	Dec 2013 – Dec 2014
CS02	3	2.6	2.3	2.3	2.3	2.3	Mar 2014 – Mar 2015
CS03	2.5	2.5	2.4	N/A	N/A	2.4	Nov 2013 – Nov 2014
CS04	3.1	3.1	3.0	N/A	N/A	3.0	Nov 2013 – Nov 2014
CS05	2.6	2.6	2.6	N/A	N/A	2.6	Nov 2013 – Nov 2014
CS06	3.2	2.9	2.8	2.8	2.8	2.8	Apr 2013 – Apr 2014
CS07	1.6	1.5	1.5	2.7	2.7	2.7	Feb 2014 – Feb 2015
CS08	2.6	2.6	2.4	N/A	N/A	2.4	Nov 2013 – Nov 2014
CS09	1.0	1.0	1.0	2.7	2.7	2.7	Mar 2012 – Mar 2013
CS10	3.3	3.3	3.2	N/A	N/A	3.2	Nov 2013 – Nov 2014
CS11	3.2	3.2	3.0	2.9	2.9	2.9	Feb 2014 – Feb 2015
CS12	0.7	0.7	0.8	N/A	N/A	0.8	Nov 2013 – Nov 2014
CS13	4.7	4.7	4.2	4.1	4.1	4.1	Jan 2014 – Jan 2015
CS14	3.9	3.9	3.5	3.6	3.6	3.6	Nov 2013 – Nov 2014
CS15	0.8	0.8	0.8	0.6	N/A	3.0	Mar 2014 – Mar 2015
CS16	1.7	1.7	1.7	N/A	N/A	1.7	Nov 2013 – Nov 2014
CS17	3.5	3.5	3.1	3.1	3.1	3.1	Jan 2014 – Jan 2015
CS18	4.6	4.6	4.3	4.4	4.4	4.4	Aug 2013 – Aug 2014
CS19	4.5	4.5	4.1	4.0	4.0	4.0	Mar 2014 – Mar 2015
CS20	4.3	4.3	3.5	N/A	N/A	3.5	Nov 2013 – Nov 2014
CS21	1.9	1.9	1.8	1.3	N/A	1.3	Dec 2012 – Dec 2013

**Sites that did not meet the criteria for inclusion into Sample B2 and B2 cropped are marked as N/A.*

4.2 Social information and decision making

This section explores the main household characteristics of the case study sample, how the occupants (or somebody else) decided to install the HPs in their homes and whether they had any choice or not. Table E 1, and Table E 3 of Appendix E set out household size and composition, time living in property, daily at home patterns and information around decision making in the social and private sector, for each one of the 21 case studies.

4.2.1 Household characteristics

- The majority of all households were small (1-2 people). While there were no large social households, a 1/3rd of private households had 3-4 occupants (including children).
- Even though the time householders have been living in the property varies widely (i.e. between one and 38 years), most of them have only been living with their HP for a couple of years and only one of them has been using the system for more than five years.
- In 1/3 of the households investigated there was at least one occupant that claimed to have some sort of technical knowledge (not necessarily relating directly to HPs).
- The majority of houses were mostly occupied during the day, excluding holiday absences that were minimal for approximately half of the case studies and varying anywhere between 2 to 8 weeks for the remainder. CS18 was the only house consistently occupied half the day (afternoons).

4.2.2 Factors influencing the installation of HPs

In the case of social tenants, it was the RSL's initiative to install the HP, who was also receiving the RHI payments. In the majority of cases, tenants were not asked for their consent. Some tenants thought the RSL was testing the potential of different renewable energy systems (RES) solution to see what would work best for the association, thus leaving a few tenants feeling as though they were being experimented on.

The factors that private owners mentioned as contributing towards their choice to install HPs are summarised below:

- **Environmental** – low energy and carbon footprint;
- **Financial** – lower running and overall cost, receiving RHI payments, fits well with other RES systems such as photovoltaics and feed-in-tariff payments;

- **Practical** – low maintenance, no refuelling needed, long standing system;

- **Comfort** – provides constant heat;

- **Technical** – no mains gas available, oil tank installation restricted or prohibited by regulations;

- **Expert or social advice** – attending information days relating to RES, recommendation by experts (e.g. installers) or social circle (e.g. friends having already installed a HP).

Note that occupants were not prompted during this part of the interview.

4.3 Dwelling information

This section briefly presents the case study parameters relating to the dwellings' heat losses. Table E 4 of Appendix E presents summary information on property type, size, construction, insulation levels and EPC rating, interventions since HP installation and information about any problematic areas in each house. Table E 5 of Appendix E summarises information on window opening practices, ventilation systems and use, as narrated by occupants and thus the inherent uncertainty of this information should be taken into consideration.

4.3.1 Dwelling characteristics

- **Type and size** - As mentioned earlier (Section 3.2.2) the social houses in the sample were significantly smaller than the private, i.e. the former having a gross floor area up to 52 m^2 (one bedroom) and the latter being between two and seven times larger (three to four bedrooms on average). All social houses were ground floor mid-terraced or semi-detached bungalows, whereas the majority of owner occupied houses were detached houses spanning over two or three floors and just in three cases spanning over a single floor.

- **Age band** – All social houses visited were built around the 1930s-1960s whereas only four out of the 14 private houses were built around the same period. Of the remaining, almost half were new-builds (2008 onwards), one fairly recent (1992) and three were built around or pre- 1900. Four of the private houses have had some sort of extension implemented, ranging from the addition of one room to a number of floors above the original structure.

- **Thermal characteristics of the fabric** – all dwellings in the sample had insulated walls, with the exception of the uninsulated thick stone walls in cases CS10 and CS19. Roofs were all pitched, with varied levels of insulation, i.e. from moderate levels of partially insulated roofs due to structural difficulties (e.g. CS10) to highly insulated roofs (e.g. 300mm in CS01). In terms of floor insulation, it seems that it was present whenever there was underfloor heating or at least reported where the occupants were aware of it. Windows were mostly double glazed with a few triple glazed cases (CS04, CS09 and CS14). The EPC ratings varied from A to F, however half of them were rated as D and another 1/3 were rated as B or C. Some major fabric interventions that are likely to have influenced the building performance were implemented in a few of them during the monitoring period. In particular, the cavity walls were filled in social houses CS06, CS07 and CS08. In case CS07 loft insulation was added as well. Roof insulation was added in cases CS10 and CS17. Finally, the brick cavity of the kitchen area was filled in CS19 and the conservatory roof was insulated in CS17.

- **Draught and condensation issues** – in approximately half of the case studies the occupants felt there were some draughts in the house. In the older houses with draught problems, it was felt that the draught was mostly associated with particularly leaky doors (CS07, CS10, CS13[22]). In some of the social houses with MVHR systems the occupants reported that they could feel cold air coming through whenever the system was turned on (CS02, CS04, CS05). The draughts reported in new-builds were usually of minor intensity (e.g. due to wood burner air vents or big glazing surfaces) apart from one case where a major structural defect was identified (CS18) causing rooms on the prevailing wind side to become colder and for which the owner is seeking expert advice. In terms of mould or damp problems, just four of the cases reported some sort of problem, i.e. mould around the window frame in the bathroom in two of the social houses (CS06 and CS08), rising damp on the gable wall of a 1950s semi-detached house (CS20), and damp issues - assumed by the occupant to have been caused by air leakage through a defective window frame in CS19.

4.3.2 Ventilation patterns

The main reasons for the occupants opening their windows in the case study sample were to control temperature and to let fresh air into the house. Other reasons mentioned include leaving doors open for the occupants or pets to go in and out of the house and due to smoking habits. However, there were two cases where windows were never opened for different reasons. In particular, the owner-occupier of CS10 said that there was no need for fresh air as the house was extremely leaky and it was very hard to bring it up to temperature. The social tenant of CS03 on the other hand was not able to open any windows apart from the garden patio door (used in the summer only) due to the windows being locked, however the MVHR system that was set to 'full'. CS03 and CS04 were the only two cases (out of four social houses with MVHR available) where MVHR was operating most of the time, possibly because both occupants were smokers. The remaining two (CS02 and CS05) would turn it on occasionally as they felt

[22] With the exception of the leaky front door, CS13 appeared to be an airtight and well insulated house (even between floors) to the extent that the householder was considering installing MVHR to resolve dry air issues.

uncomfortable with the cold air coming through the system. More information on the ventilation practices of the sample can be found below.

- **Winter regime** – The majority of the householders (almost two thirds) reported that they never or very occasionally opened windows in the winter, e.g. in exceptionally good weather or when drying clothes inside. Except for CS08, whose occupant has a whole-house standard ventilation routine (i.e. windows open every morning), the remaining reported that limited or very limited window or door opening activity takes place on a regular basis but only if not too cold outside.

- **Summer regime** – Except for CS10, mentioned earlier for not opening windows at all throughout the year, and another 1/3 of the cases where windows were opened occasionally (in particular rooms only and when it was really warm outside), the remaining reported frequent ventilation activity. Their occupants tended to keep most windows of the house open during daytime and when the house was occupied.

4.4 Technical information on heat pumps

This section presents the main characteristics of the HPs, the emitters and their configuration in the case study sample and comments on the monitoring schematics available in comparison to what was observed during the site visit. Detailed information of the technical specifications can be found in Appendix E. In particular, Table E 6 of Appendix E details the main characteristics of the HP systems, as they were observed by researchers during the site visits or narrated by householders and crosschecked with the data in the MCS certificates. Table E 7 (Appendix E) compares the information in the monitoring schematics with the actual installation to check whether they represent reality or not. Table E 8 lists information, where available, on the presence and type of resistance heating (boost or immersion) and the presence of weather compensation or not. It also provides estimations of the average and peak flow SH temperatures, the percentage of SH/DHW and the amount of heat provided by the DHW immersion. Finally, Table E 9 presents an estimation of the median monthly cycle lengths in each case study. Two of the sites, CS01 and CS11 were found to have relatively short median monthly cycle lengths (<=10 minutes on-to-on time). This has the potential to adversely affect performance.

4.4.1 System characteristics

- **Type and size** – The case study sample is made up of 10 ASHPs and 11 GSHPs (boreholes and horizontal collectors) with their declared net capacity (as reported in the metadata) ranging between 6 kW and 14 kW. As expected, smaller properties (i.e. all social houses with a gross floor area of less than 52m^2) have smaller system capacities, up to 6 kW. Owner occupied properties of 95-100m^2 and those over 150m^2 have system capacities of 7-11 kW and 11-14 kW accordingly.

Notably, there were two inaccurate entries in the MCS certificates. In CS03 information for solar panels had been entered instead of the HP details. During the inspection of CS10 two HPs were identified (14 and 8.5kW) but only one was monitored. The MCS certificate refers to a single heat pump, of capacity 22.5 kW[23].

- **Heat emitters** – the heat emitters identified in the sample were as follows: radiators in 12 cases, underfloor heating in 5 cases and a combination of both in 4 cases. This generic count does not include the following single emitter units that are listed in Appendix E): a towel radiator in the bathroom of CS16, a single hydronic fan convector linked to the HP system in CS07 (kitchen area) and two hydronic fan convectors in cases CS06 and CS08 (kitchen and bathroom). These emitters had not been listed in the metering database along with some other omissions, i.e. CS10, CS15 and CS19 were listed as having radiators or underfloor only, however a mixed system of radiators and underfloor was observed in all. Except for new-builds and those cases that have moved from storage heaters or coal to HPs, the remaining seven cases have kept all or some of the radiators from the previous heating system, i.e. oil or gas.

- **Metering schematics** – When comparing the data collected against the metering schematics (except for two cases for which the schematics were unknown, i.e. CS10 and CS20), it was clear that 7 out of 19 were incorrect[24]. The inaccurate schematics corresponded to the following cases: CS11, CS13, CS14, CS17, CS18, CS19, CS21. In case CS21, for example, none of the existing schematics match the type of installation presented in Figure 4-1, which is an ASHP attached to a thermal store with instantaneous DHW, solar plate heat exchanger, minimum store temperature of 50°C and three circulation pumps.

[23] The manufacturer's technical documentation confirms that a combination of two heat pumps in this way is an option offered by the product range. RAPID-HPC have not been able to ascertain which heat pump was monitored, but the householders stated that both were used.

[24] As part of the overall project, many schematics were re-evaluated and RAPID-HPC has attempted to provide revised estimates of the schematics in the metadata – see Table E 7 of Appendix E. The site visits revealed that these estimates were not always correct.

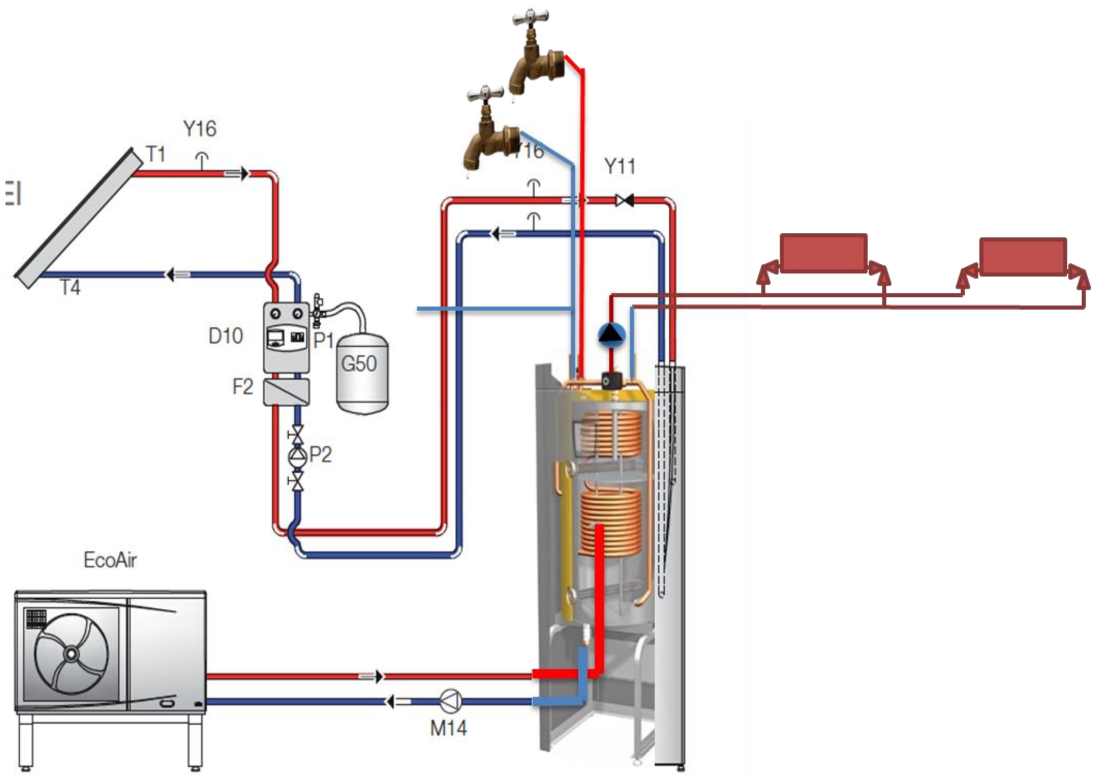

Figure 4-1. ASHP with thermal store and connection to solar thermal panels (CS21)

During the investigation, it became clear that case CS20 had been mistakenly excluded from Sample B2 due to absence of DHW data in the monitoring data. On inspection, it turned out that the HP only provided space heat. DHW was provided from solar thermal panels and an un-metered immersion heater[25]. There was no metering schematic available for this site.

- **Resistance heaters** – based on the site investigations alone, it was not always possible to identify the presence or absence of a booster[26] or immersion[27] heater during the site investigation, partly because many were installed in the roof space that the researchers could not access due to health and safety reasons. From the manufacturers' technical specifications, it appears that there was an integrated booster heater in 11 of the 21 cases (CS03-CS05, CS09 and CS12-CS18). In cases CS12 and CS17 , the occupants were certain about the presence of some sort of resistance heater in the system because these had been accidentally turned on leading to excessive bills. Based on the site investigation, it appears that there was a DHW immersion in at least nine cases (CS01-CS02, CS06-CS11 and CS18). The site investigation also confirmed the

[25] The effective COP of this arrangement could be of the order of 2, within the range of COPs for DHW heating of heat pumps in the RHPP field trial.
[26] The term "booster" refers to a resistance heater typically integrated into the HP. The boost can provide SH, DHW or both, depending on the HP model.
[27] The term "immersion" refers to a resistance heater integrated into a water vessel (DHW cylinder, buffer vessel or thermal store) that can provide SH and/or DHW according to the function of the water vessel in question.

presence of a buffer vessel immersion in two cases (CS19-CS20) but for most cases this was not possible to ascertain. In addition, CS21 was the only case with a thermal store immersion. The immersion heaters identified during the site visits in cases CS11 and CS20 were not metered.

4.4.2 Installation and metering issues

In general during site visits, the team was able to observe the outcome of the physical installation but could not investigate whether the systems were correctly installed first hand. In order to do so they would have had to unscrew HP covers and remove insulation or other parts of the installation to interact with the system interface, which was not appropriate for this study. Similarly, it was not always possible to provide a definitive answer with regard to the correct installation of the metering sensors, neither from remotely monitored physical data, nor from metering photographs supplied by BRE, nor during the site visits. Most sensors were covered by pipe insulation or were hidden behind miscellaneous items left in the HP plantroom. What was observed were instances where, for example, two HPs were installed but only one had a heat meter (CS10) or the heat meter was incorrectly attached to the flow rather than the return (CS18). The occupants also provided valuable information, e.g. the occupant of CS15 reported that two sensors were initially installed on the wrong pipes and that the problem was revisited and fixed much later[28]. This would explain the extended period of the extremely low initial SPF provided by the data for this case, which the owner occupier thought was patently wrong. The data collected were also checked against the MCS reports and metering schematics to confirm whether the schematic was correctly assigned. The following list highlights any issues or unusual facets of the installations affecting performance, as they were observed during the site visits. Detailed information can be found in Table E 7 of Appendix E.

- **Missing/inadequate insulation on pipework (internal or external)** – with a few exceptions, such as those pictured in Figure 4-2 (a,b) and Figure 4-3 (a, b) most pipework in the sample was not perfectly insulated. For example, in case CS12 (Figure 4-4a) the room thermostat is located near the uninsulated installation, which may be affecting the room thermostat control of the system. Figure 4-4b shows uninsulated valves on the external refrigeration line. Figure 4-5a and Figure 4-5b show examples of unevenly insulated pipework (e.g. pumps and valves are exposed) or insulation of poorer quality within unheated spaces, such as lofts and utility rooms.

[28] This issue was noted in the audit data supplied to RAPID-HPC: "25/06/2013 – No heat meter pulses 12/07/2013 - +Hhp, +Fhp (intervention), integrator replaced by installer."

Figure 4-2. (a) Example of high quality insulation (CS15) and (b) detail of high quality valve insulation (CS15)

Figure 4-3. (a) High quality insulation of pipework in outdoor, unheated shed with and (b) with insulated pump and manifold covers removed (CS13)

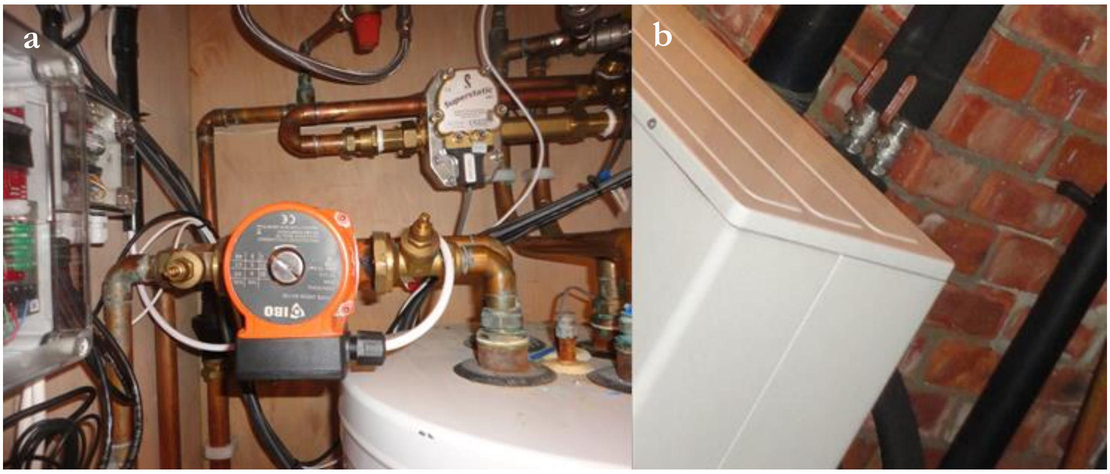

Figure 4-4. (a) Uninsulated pipework in cupboard within house (close to main thermostat (CS12), (b) Detail of refrigeration line insulation (CS07)

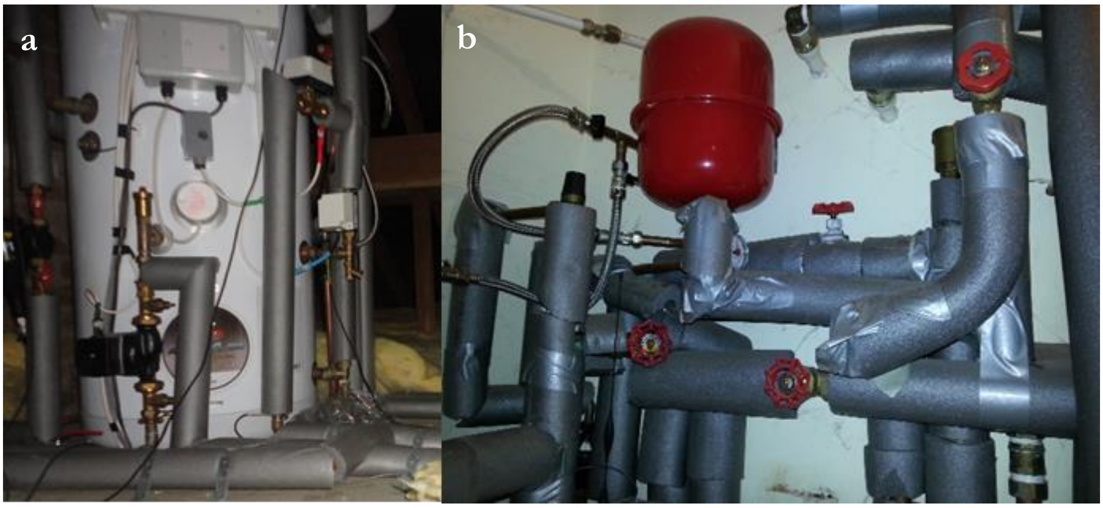

Figure 4-5. (a) Insulation of pipework in unheated loft (CS07), (b) Split foam insulation of pipework in unheated utility room (CS13)

- **Positioning HP internal units in unheated and/or uninsulated spaces** – in many cases the HP, cylinder and circulation pipes were located in a 'cold roof' space (e.g. CS02, CS06, CS07), unheated garage (e.g. CS01, CS14, CS17) or unheated shed (e.g. CS19, CS20). Figure 4-6 (a,b) and Figure 4-7 (a,b) show some of these examples.

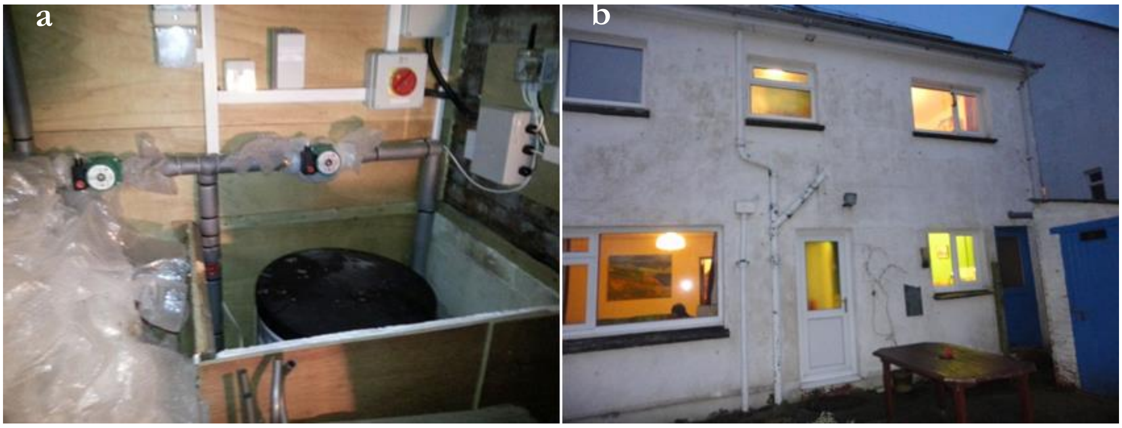

Figure 4-6. (a) Buffer tank (with additional bubblewrap to act as insulation) and circulation pumps in unheated shed (CS20), (b) location of the shed, to the right of blue door (CS20)

Figure 4-7. (a) DHW cylinder located in ventilated roof space (CS07), (b) HP units located in unheated garage (CS14)

- **External pipework not kept to a minimum** – As shown in Figure 4-8 (a,b) in cases CS09, CS20 and CS10 (not pictured), the external units of the ASHPs were located many metres away from the house, with insulated but long pipe runs connecting the two, thus incurring some heat losses. Some shorter but also externally insulated pipes were observed running vertically up the outside wall of cases CS07 and CS08 before entry into the attic.

Figure 4-8. (a) Outdoor unit behind trellis (CS09), (b) Insulated external pipework (CS20)

- **Installation quality and system complexity** – Notably, some very complicated installations were observed during the team's site investigation, including sites with more than one HPs (CS10), long pipework, plate heat exchangers and many more circulation pumps than originally assumed (e.g. in CS10, CS11, CS12, CS5 and CS19). Figure 4-9 (a,b) show some of these cases while Figure 4-10 (a,b) show the evolving technical practice in heat pump installation, i.e. the introduction of variable speed circulation pumps.

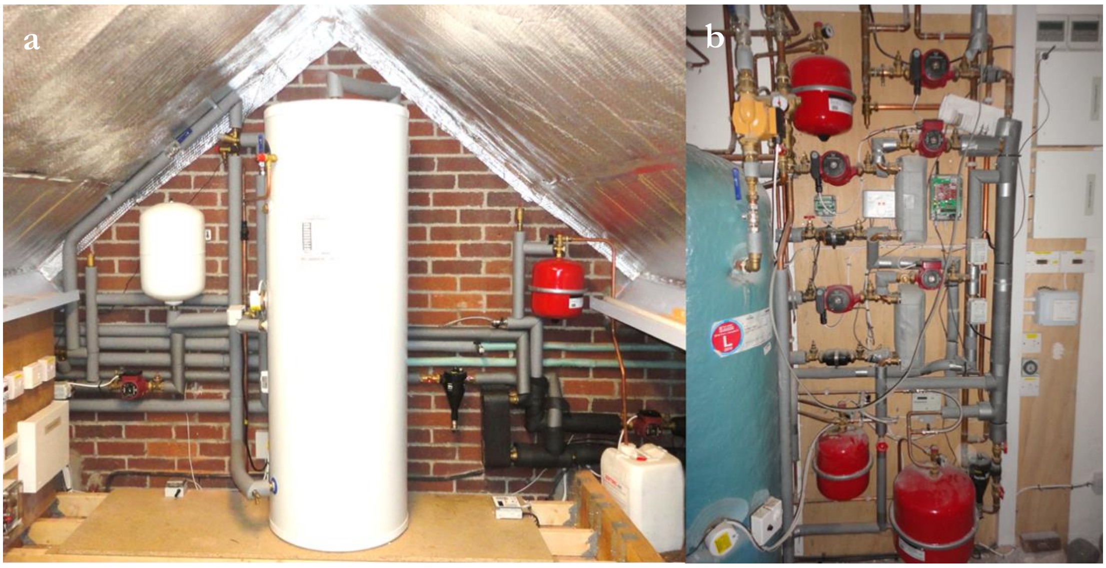

Figure 4-9. (a) Neat installation with plate heat exchanger (CS11), (b) Plate heat exchangers by the same installer (CS10)

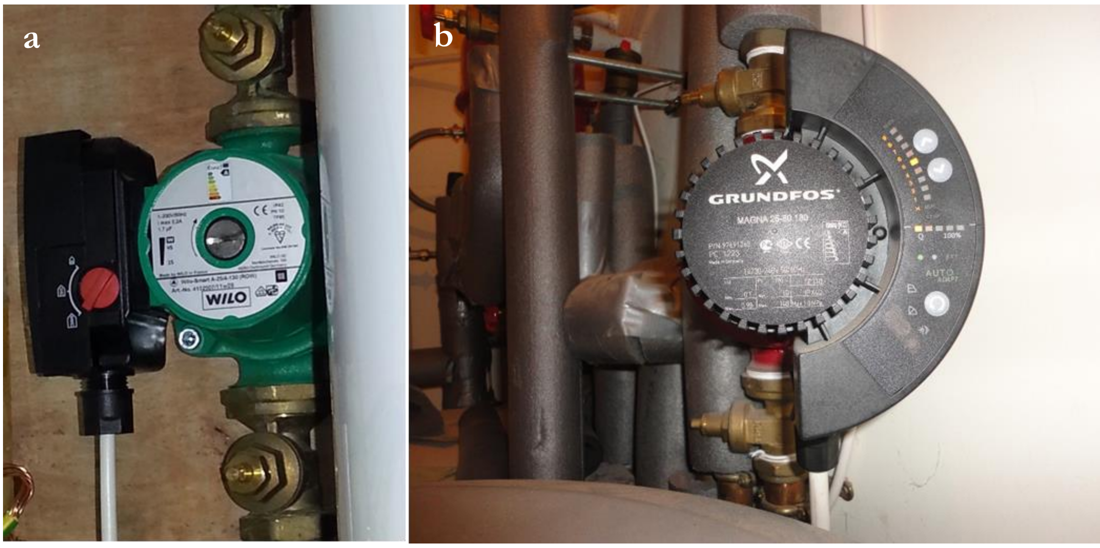

Figure 4-10. Variable speed circulation pumps in case studies (a) CS17 and (b) CS13

- **Variation in sensor installation** – The installation quality of the monitoring equipment varied throughout the sample. As an example, Figure 4-11a and Figure 4-11b show an inconsistently fitted jubilee clip holding a temperature sensor and a properly positioned clip and sensor in the same house (CS12). In case CS20, the position of the heat meter, located near the HP but with a long pipe run into the house, gives a potentially inaccurate measurement of the heat provided to the house[29]. As shown in Figure 4-12 (a,b,c,d), the pipes run a long way between the house and the garden shed, where the HP buffer vessel is located. The metering equipment is all located in the shed, measuring the temperature of the water as it comes out of the ASHP. In case CS10, only one of the two HPs was heat metered and the fact that two HPs were installed was not logged into the RHPP metering database or MCS certificate.

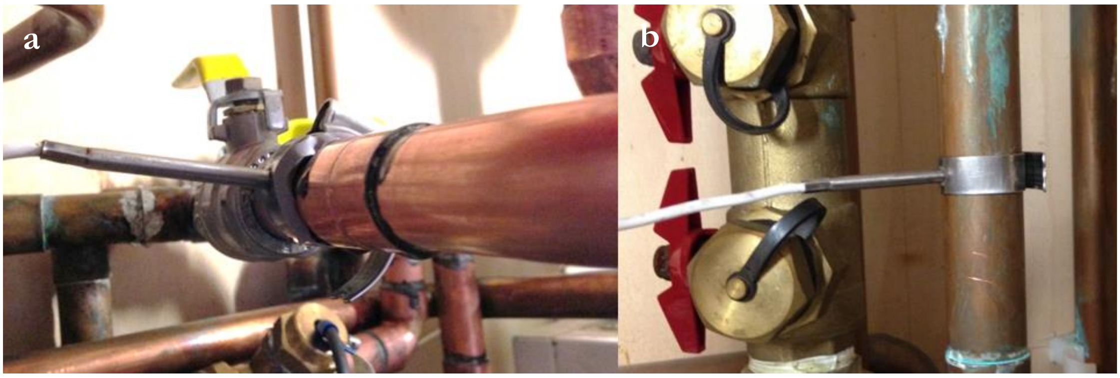

Figure 4-11. (a) Sensors reporting pipe temperature appear to be inconsistently fitted (CS12), (b) Proper positioning of temperature sensors (CS12)

[29] The SPF of the heat pump is not affected by heat losses from long pipe runs, but both from the wider energy policy perspective and from the perspective of the houseolder, this is potentially significant. Moreover the phenomenon of remote siting is unlikely to be co-incidental to the physical characteristics (size, visual intrusion, fan noise etc.) of heat pumps, and therefore represents a legitimate whole-system issue.

Figure 4-12. (a) pipes running through the externally accessed, unheated outdoor toilet, (b) between the house and the external shed, (c) circulating pumps, buffer vessel and heat meters within the shed, (d) external HP unit, located next to the shed (CS20)

4.5 Control and usage of heating systems

This section discusses the level of control the householders have (or could have) over their HP, both in terms of SH and DHW. Room and cylinder thermostat, TRV and HP flow temperature settings are explored, distinguishing between summer and winter operation and householders with technical and non-technical background. A variety of SH control methods were observed in the site visits, ranging from simple on/off control by room thermostat through to use of weather compensation control. Occupant HP control is dependent on both access to control settings and the ability to vary the installer's commissioning set up. In some instances, occupants developed coping strategies that ranged in sophistication from turning up or down the room thermostat, manually adjusting flow temperature in response to feeling too cold or hot, through to understanding and adjusting weather compensation curves. In most cases householders considered they had a broad idea of what their HP settings were, though this did not always prove to be the case on deeper enquiry. In terms of DHW, more than half of the householders were not aware of the exact schedule.

There was a distinct difference between the controls available in the social and owner occupied houses.. In particular, many social tenants were 'locked out' of the controller with access to the room thermostat only, whereas the majority of owner occupiers had full access to the controller. Thus, they were able to make specific changes to the settings and some of them reported that they had been continually experimenting with their SH control settings. Overall, the main SH patterns that emerge can be classified as continuous, night setback, off at night and intermittent[30].

Any supplementary sources of SH and DHW are also mentioned in this section and the reasons for their use is discussed. Baths, showers and washing up habits are reported in most cases but they are difficult to ascertain. Detailed information on individual heating schedules and use of SH and DHW can be found in Table E 10 of Appendix E.

[30] Industry practice is to recommend continuous operation.

4.5.1 Space heating (SH)

- **SH control in social houses** – All social houses were using thermostats as the main way of controlling internal temperature and only few of them were also making use of a timer programmer. A wall-mounted thermostat in the living room wall was used to control heating throughout the house, which was setup in a single heating zone. Where thermostatic radiator valves were available, occupants did not generally adjust their settings.

  Room thermostat temperatures were mostly kept constant but the comfort temperature settings varied significantly between houses, i.e. from 18 to 23°C for most cases. The exception was CS06, where the householder had a health problem and set the thermostat to 30°C (although at the time of the visit, when the room thermostat was set at 30°C, the air temperature was approximately 26°C). Of all social tenants, only those that claimed to have some technical background (CS03 and CS07) reported having lower thermostat temperatures (15-17°C) during the night. Some of the tenants reported they had been advised to keep the thermostat temperature constant and never go below 15°C.

  Two of the social households were using a timer programmer as a secondary means of controlling internal temperature. The majority of the remaining were unsure of whether there was a programmer setting already in place for them since they had no access to it. Most of them thought that their system was either running continuously or that was turning itself off at night (either completely or using a setback temperature). The occupant of CS03, was the only one that reported turning down the thermostat manually at night.

  None of the social occupants had access to the flow temperature settings. These were hidden from the user, either by physically placing the controller in a hard to reach area (e.g. narrow cupboard or loft), as shown in Figure 4-13, or by verbally advising them not to interfere with the system.

Figure 4-13. (a) Controller and hot water vessel in hard-to-reach attic space (CS07), (b) controller and hot water cylinder located in a narrow cupboard with controller facing the wall and thus unreadable (CS04)

- **SH control in owner occupied houses** – A range of methods were used in the owner occupied houses in order to control SH, i.e. using single or multiple thermostats and programmers, adjusting HP flow temperature settings and very rarely by adjusting thermostatic radiator valves.

  In more than half of the owner occupied houses (mostly the bigger houses with underfloor heating), the heating system was setup in multiple zones, controlled by multiple thermostats (fixed or portable). Different zones were set at different temperatures (bedrooms and infrequently used rooms being on the lower temperature scale). The remaining single zoned properties were controlled either by a single thermostat or by accessing the controller and altering the flow temperature of the system (CS09, CS19 and CS21). All of the latter had thermostatic radiator valves installed and although they were set at different levels in each room, the occupants would rarely change the settings. Overall, the comfort temperature settings varied between 17 and 21.5°C and setback temperatures ranged from 14.5 to 16°C. At least six houses were making use of one or more timer programmers.

  In terms of the SH running mode, in more than half of the 14 owner occupied cases, the occupants reported that their system was running continuously. Two systems were running intermittently and four were running during the daytime either by switching off completely at night or by using a low setback temperature. With the exception of CS09, the owner occupiers without technical background did not interfere with their HP's controller, unless there was a problem to solve. The more technically competent occupants were generally more capable of interacting with their HP and even identifying setup problems. As an example, the occupant with a physicist background in CS17 was capable of changing the flow temperature curves using the controller's weather compensation graphs, as shown in Figure 4-14.

> *"I set the temperature on the thermostat and if it is not warm enough I turn the flow temperature up a bit […] [the interface] gives a series of graphs allowing the HP to run on a higher or lower temperature."* (CS17)

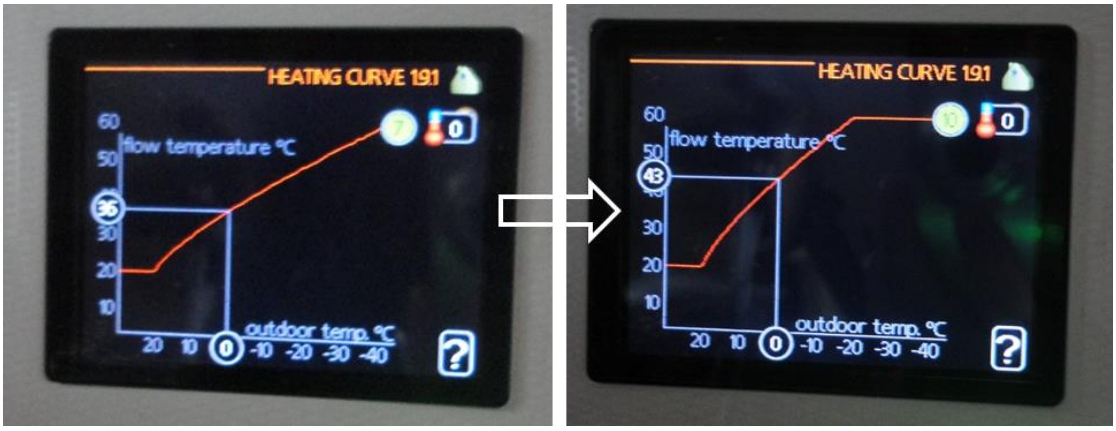

Figure 4-14. Interface for changing heating curves on HP controller (CS17)

- **Changes in SH controls since installation** – The majority of occupants reported there was no change in the controls of their HP during the monitoring period. There were, however, four cases (CS09, CS09, CS10 and CS12) in which some changes took place. In particular, the DHW immersion heater and booster heater were accidentally left on for a period of time in cases CS08 and CS12, respectively. The SH patterns of CS10 had also changed during the monitoring period, as the house was being upgraded and renovated, but the occupant was uncertain of the kind of changes that took place with regard to the heating system settings. Finally, the occupants of CS09 were controlling the heat pump by switching it on and off and by altering the flow temperature to satisfy their needs. The reason for this was that their thermostat was located in the unheated entry space. Initially, the occupants kept lowering the flow temperature to achieve a good balance of cost efficiency and warmth but they eventually came to the following conclusion:

> *"We found out it's more efficient to run it all the time at lower temperature"* (CS09)

In addition, some important changes to the SH control were reported to have taken place after the end of the monitoring period. In particular, the occupants of CS09 had a portable thermostat fitted but they had not had the chance to use it much and thus could not comment further. The heating patterns also changed in CS16, but only after the monitoring period, as the occupants were trying out different control methods to work out why their HP was "so expensive". Previously, they heated up the whole house intermittently, keeping their thermostats at 20-21°C and with a setback temperature of 16°C.

> *"HP is currently on frost protection, used for background heating really, in most areas of the house because it uses too much energy. HP is only on in bathroom upstairs and sometimes on hallways but it's only up to 16°C [in all other rooms] […] We don't use the HP really, it hasn't been a very cold winter, we use wood burners more"* (CS16)

In one case, some important SH control changes took place prior to the start of the monitoring period. Shortly after the installation, the occupant of CS19 decided to experiment with his HP controls. Of all control strategies that he tried, he concluded that the cheapest was to run the HP continuously.

> *"I tried out controlling it as a boiler, using a choice of two-three heating periods, different temperatures of these periods and different modes (auto, holiday, frost protection etc.) […] it turned out less expensive to run it continuously."* (CS19)

- **Secondary SH in social houses** – A number of supplementary heating sources were installed in most houses. In the case of social houses, there were either electric resistance fan heaters mounted on the bathroom wall or electric fires in the lounge, installed by the RSL in addition to the HP connected radiators in those rooms. Most of them were not used, except for one or two cases and only under extraordinary circumstances. In case CS03, a portable electric heater was brought in to heat up the house quickly when the occupant was away for a long period of time and the HP was off.

- **Secondary SH in owner occupied houses** – all but two (CS11 and CS19) of the 14 owner occupied houses were equipped with at least one wood burner. Only a few of the occupants would use them on a regular basis, either to top up heat or for decorative purposes. Most of them used them as a backup system, to top up heat if a rapid warm up was needed and during social gatherings.

  Other supplementary heating systems used in the sample include electric bathroom heating, an oil condensing boiler, a portable electric resistance fan heater and a range cooker. The electric bathroom heating systems (either underfloor or towel radiators) were all installed for different reasons such as, due to them being fitted at a later stage than the HP system (CS09), due to the occupant being unaware that they could connect the towel radiators to the remaining underfloor heating system (CS18) and to boost internal temperature (CS16). In the case of the hybrid system (CS19), the oil-condensing boiler used to be the previous heating system and the owner decided to keep it as a backup. For CS11 the portable electric resistance fan heater would only be used in exceptional circumstances. The use of the range cooker (on snooze) in case CS16 system forms part of the occupants' wider strategy to reduce the overall heating costs by confining their HP to background heating supported by wood burners and the range cooker.

4.5.2 Domestic hot water (DHW)

The occupants were asked questions relevant to their DHW use and patterns, however, their answers in many cases were based on estimations or assumptions since for some, their use of hot water was not consciously planned. These included answers relating to the number of showers, baths and washing up frequency, which are listed in Table E 11 of Appendix E. The occupants were also mostly unaware of their DHW heating schedule. Only about a third of them claimed to know when the HP was bringing DHW up to temperature, whether once or twice a day, whilst the occupant of CS21 understood that hot water was produced instantaneously via the HP thermal store. In the majority of cases, the DHW was provided by the HP, however some occupants were using alternative methods for the provision of all or part of their DHW. These are summarised below:

- **Electric showers** – social cases CS02, CS03, CS04 and CS05 were all equipped with electric showers. These were installed by the RSL and the reason for this is unknown. One of the owner occupied houses also had an electric shower installed in one of the bathrooms. Even though they admitted they could have connected the DHW supply for this bathroom with the HP, they wanted to have an electric shower as they were used to it and they liked it.

- **Solar thermal/resistance heater** - in case CS20 the HP was used for SH only. The DHW is provided by solar thermal panels supported by a resistance immersion heater. The occupants had installed solar thermal panels before the installation of the HP and they decided not to integrate it as they were happy with the hot water provision, although they need to top up with the immersion heater in the winter.

- **Kettle** – Although the HP of CS07 provides DHW, the occupants felt this was problematic when it came to washing up the dishes, as they have to wait several minutes before hot water came through. Thus, the female occupant uses hot water from the kettle instead.

> *"I do not run water from the HP to wash the dishes, I boil the kettle. By the time it gets from up there to the tap here, I have to wait several minutes before the water becomes warm, because otherwise it drains the hot water out of the tank. The sink is the furthest away. The shower is good."* (CS07)

4.6 Overall energy cost

This section presents summary information on energy bills, comments on whether the householders benefited or not from the RHI payments or any other RES technologies installed. As with the previous section, the estimation of energy bills in this section is difficult to ascertain as it is based partly on bills (covering different periods of the year) and partly on assumptions made by the occupants. Note that the bills do not directly translate to the energy consumed by the house as they vary, based for example, on the energy provider prices, the type of energy use (i.e. electricity or electricity plus gas), the amount of electricity produced by PVs or, where present, heat from solar thermal panels, gas, oil and wood. See Table E 12 of Appendix E for more details.

- **Annual total energy cost** - Figure 4-15 shows the annual cost per m² per house *based on the occupants' estimations and/or the bills* provided. This includes electricity and gas bills, where appropriate[31]. Whenever a high and a low estimate was given by the occupant, the average was used to calculate costs per unit area. In a few cases, such as CS08, periods of excessively high electricity consumption, due to the unintentional use of the HP integrated resistance heating, were reported by occupants and a separate cost estimate was given for this period (see Table E 12). This was not included in the cost estimations presented here. Also, the RHI and feed-in-tariff payments are separate from the electricity bills and thus not included in the costs estimations. In general, as shown in Figure 4-16, the bigger the area of the house in the sample, the lower the cost per m² tended to be. All houses were on a standard tariff, except for CS06 and CS19, which were on an economy tariff. Also, all of them were running on a single-phase supply, except for CS16, which belongs to a farming complex.

  Social houses of 52m² or less paid approximately £400-£820 on energy per year. Of all social houses, CS05, CS07 and CS08 reported significantly higher bills per unit area. Note that CS05 and CS08 were the only two social houses with double occupancy during the monitoring period and CS08 was the only one with frequent window opening during the heating season (see Table E 5 of Appendix E).

  Owner occupied houses of 95-105m², 165-180m² and 200-350m² paid approximately £650-£1150, £1000-£1750 and £1000-£2150 accordingly. The owner occupied houses in the sample with the lowest bills per unit area were all large houses of 262m² or more, i.e. CS18, CS10 and CS15. At the other end of the spectrum, the houses that reported higher energy bills per unit area were of 200m² or less, i.e. CS01 and CS09, followed by CS19, CS12 and CS21.

[31] The RHPP programme was not intended to support the installation of heat pumps in dwellings connected to the gas grid. Despite this, photographs taken during site visits show gas hobs in four RSL case study dwellings, CS02, CS03, CS04, CS05 (all of which were on a single site). Interview data are consistent with this. This confirms that all four had gas before and after the installation of the heat pump.

- **RES systems** – 10 out of the 14 owner occupied houses had photovoltaics (PV), either mounted on their roof or as a free-standing system at the edge of the garden and occupants were receiving the feed-in-tariff (FIT). The PVs were grid-connected and thus offsetting part of the home's electricity needs and/or exporting electricity[32]. As well as PV, cases CS20 and CS21 had solar thermal units mounted on their roof, however in CS21, the occupant was told that they had been disconnected at the time of the HP installation, as the solar thermal system "had not been working properly". Thus, DHW in CS21 was provided exclusively by the HP. None of the social houses owned any RES, except for CS04, which had a Trombe wall[33] installed on the south facing facade. It appears that the RSL installed one as a trial but the occupant was not using it much, i.e. external shutters were kept closed most of the time.

- **Other sources alleviating the HP running cost** – All but one (CS01) of the owner occupiers were receiving RHI payments. Although the occupants of CS01 received an one-off RHPP payment, they could not claim the RHI grant as when they bought their new-build house, the HP system was already in place. None of the social tenants were receiving the RHI grant, however, some of them were receiving some government help to alleviate heating costs, e.g. the warm home grant and winter fuel payment.

[32] The FIT payment is not included in their estimate of bills but the electricity generated and used on site does reduce their bills.

[33] A Trombe wall (named after French engineer, Félix Trombe), is a passive solar system, consisting of high heat capacity wall with a glass external layer separated by a layer of air, and oriented to catch the winter sun. The glazing may have exterior insulation, e.g. shutters or blinds, to prevent heat loss at night.

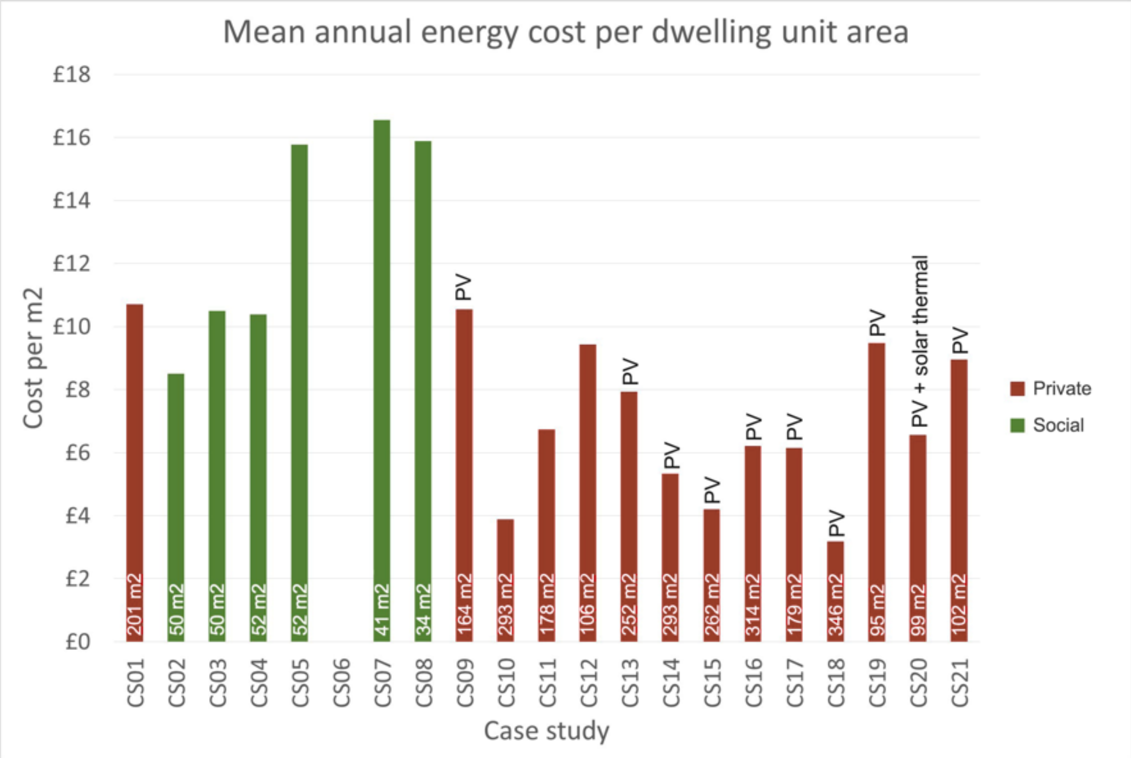

Figure 4-15. Annual energy cost estimation per dwelling unit area, derived from occupants' narration or bills – the total floor area of each dwelling and any RES systems used are noted at the bottom and top of each bar respectively

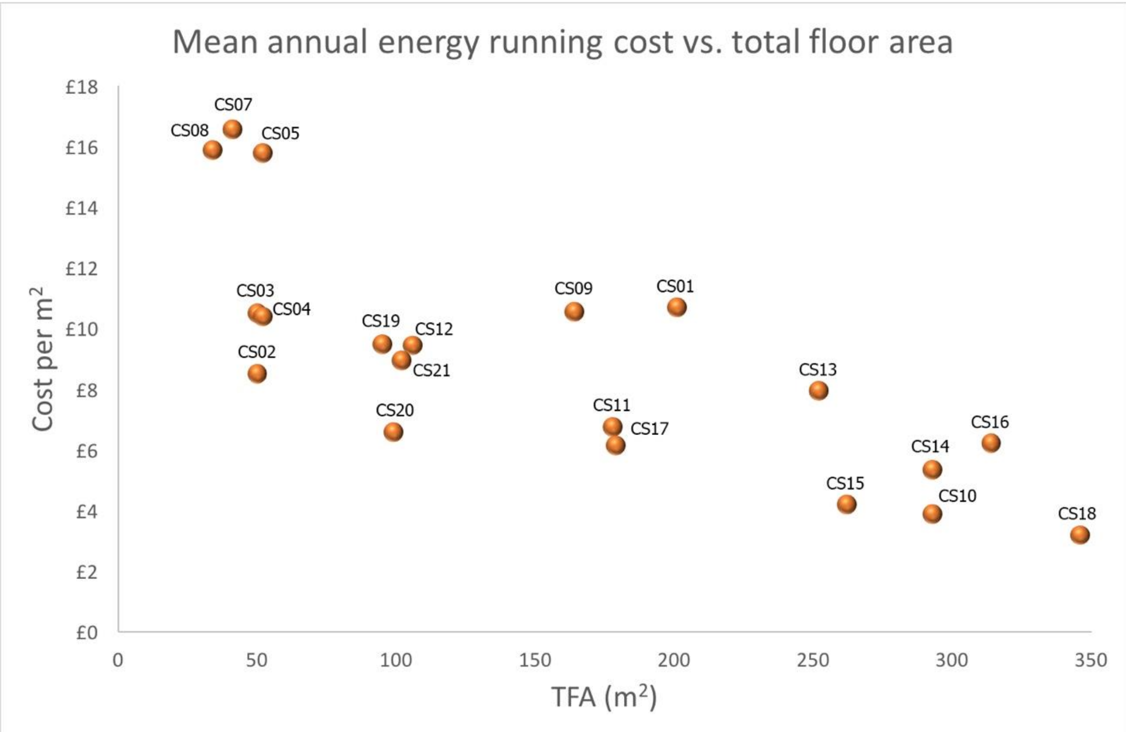

Figure 4-16. Total floor area in relation to mean annual energy[34] cost estimation, *derived from occupants' verbal responses, or from bills*.

[34] The RHPP was intended to relace oil, coal and electric heating systems. However, some of the householders had gas for cooking. The bills above include electicity and gas if appropriate.

4.7 Occupant perception of comfort and satisfaction

This section comments on the householders' expectations and satisfaction levels both with the previous (if applicable) and the current heating system. Any thermal comfort issues are discussed in conjunction with the householders' ability (or not) to change the system in order to meet their needs. Finally, the training sources available to the occupants, the level and quality of support they get from the installers in terms of understanding controls and resolving any issues coming up as well as the problems they have experienced are discussed here. Details can be found in Table E 13, Table E 14 and Table E 15 of Appendix E.

4.7.1 Occupant satisfaction with current and previous system

- **Satisfaction with HP** – As shown in Figure 4-17, the majority of the households interviewed were either satisfied or very satisfied with their HP. There were only three cases where occupants felt either neutral or very dissatisfied with the system. In particular, the occupants of CS16 were happy with the warmth produced by the HP but they thought there must be some technical problem as the running cost was very high, and thus they did not want to express satisfaction before resolving this issue. In case CS14 the occupant said they were neither satisfied nor dissatisfied, due to the HP not producing the savings they expected. Finally, the social tenants of CS07 were very dissatisfied as they felt they were paying too much in bills, without getting sufficient SH or DHW. The remaining satisfied occupants mentioned the following factors as the main reasons for their satisfaction: running cost, constant and whole-house heat, low maintenance, environmental impact, technical reliability and noise levels (GSHP only). Table 4-2 lists the main influencing factors along some of the occupants' quotes.

  Other peripheral factors that may affect satisfaction include the technical knowledge and background of the user, whether they receive any grant or have any RES installed to alleviate the running costs of the HP, whether they own the system and the circumstances under which it was installed (own initiative, imposed etc.). The quote below provides some indication of the complexities encountered by some users that may impact on their purported satisfaction:

> The male occupant of CS01 said: *"When HP was first installed the front room wouldn't heat up. The manifold floor valves were back to front. They came and fixed it after a month, they had to balance it all [...] I could spot the problem, if I was not around [my wife] would have given up and say I cannot get it to work."*

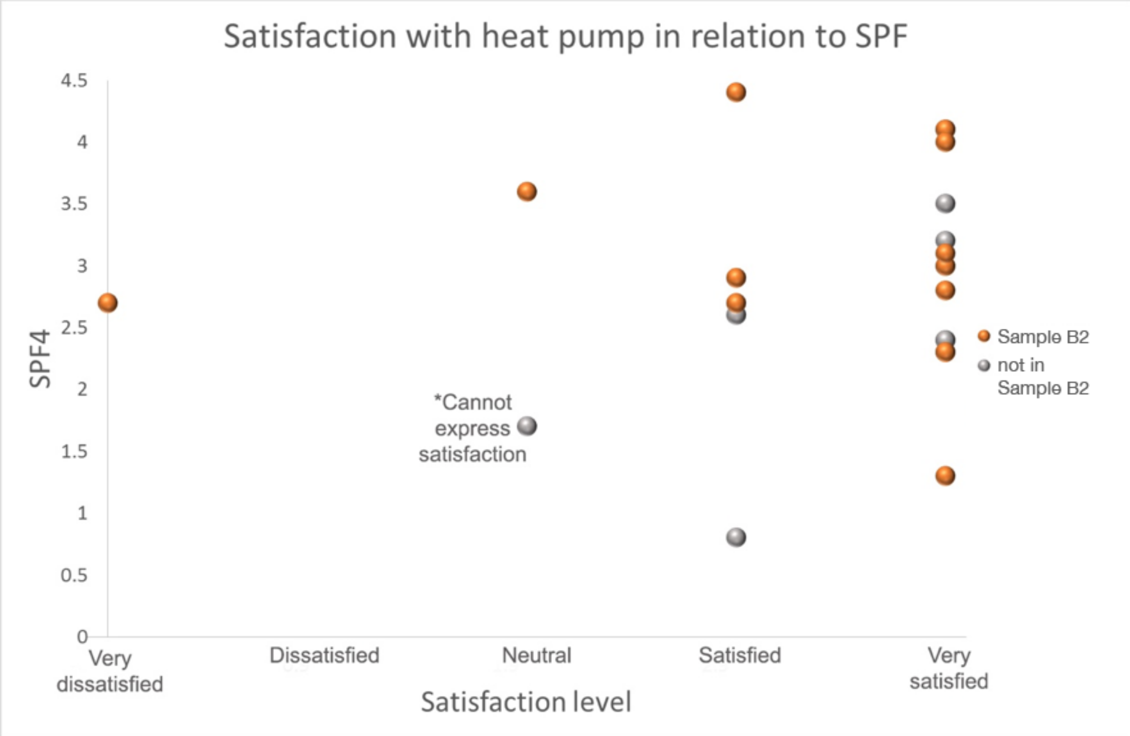

Figure 4-17. Occupant satisfaction with HP presented in relation to SPF4 based on the representative SPFs as in Table 4-1.

Table 4-2. Main factors influencing satisfaction as stated by the occupants

Core influencing factors on satisfaction	
Running cost	*"running cost is good", "too expensive, not enough SH and DHW", "would have expected more savings"*
Constant, whole house warmth	*"keeps house warm", "happy even if HP and gas cost the same as we get constant heat" "expensive system but it's worth the money to spend"*
Low maintenance	*"fit and forget", "no need to worry about it", "hassle free"*
Environmental impact	*"minimum cost and carbon footprint", "environmentally friendly"*
Technical problems	*"disappointed when HP broke down", "satisfied apart from little problems", "want to find out what is going wrong first before expressing satisfaction"*
Noise levels	*"quiet" (occupant referred to GSHP)*

- **Comparison with other heating systems** – Figure 4-18 shows that all but three of the households visited preferred the HP in comparison to their previous heating system, as they experienced it in their current or previous home if new-build. Table 4-3 lists the main reasons for which occupants preferred the HP or another heating solution. Factors appreciated by occupants included the "constant and whole-house heat" provided by the HP, the low maintenance required and the "hassle free control" (once the system is setup and working properly). The occupants were generally happy if all this was coming at a reasonable cost, and extremely pleased if they thought this formed a cost-effective package in comparison to other technologies.

  In some cases, the occupants, although happy with their HP, were sceptical about particular aspects of the technology, such as the lack of heat in certain rooms and the amount of time needed to identify and fix a problem. For example, the occupant of CS06 felt his bathroom and kitchen, both served by hydronic fan convectors connected to the HP, were not warm enough. He thought that he would not have had this problem with a gas boiler. In case CS04, although the occupant was overall satisfied with her HP, she would have felt more secure with a gas boiler since, on one occasion, the HP had broken down and left her without heating during the winter months[35]. She said:

  > *"The boiler never broke down, even though it was an old one […] I would suggest the HP if there was no chance of breaking down." (CS04)*

  Finally, there were two cases where the occupants thought that there was something seriously wrong with the HP and thus would have preferred to have had another system. The female occupant of CS16 thought that the HP was heating up the house but was extremely expensive probably due to some technical problem that they had long been trying to work out. Thus, she thought it would have been better if she had an oil or pellet boiler instead. Her exact words were:

  > *"[The HP] costs an awful lot of money for what it is […] it is very efficient in terms of warmth apart from the master bedroom [but] without the PVs it would have been even more costly. […] I was happy with the oil boiler in the previous house, oil was easier to control. […] Next time [I would] probably try something else, not a HP, pellet boilers might be a good option." (CS16)*

  The occupants of CS07 were deeply dissatisfied with their HP as not only did they consider it expensive to run, they also felt it did not provide them with sufficient SH and DHW. Therefore, they would ideally have liked to have had a gas boiler or even to have had their storage heaters back:

[35] The householder informed the RSL.

"We were told by experts how wonderful the HP was and we thought that we could not refuse the system because the storage heaters were outdated [couldn't get spare parts] and didn't know we could refuse and keep the storage heaters. [We] would have been happier as we knew how to work them and they were more efficient, in my opinion. […] My mum lives across the road in a similar house and has gas. Fantastic! The washing dries, the heat is on all day and she pays less in gas and electric. […] Hopefully they are going to get it out and put gas." (CS07)

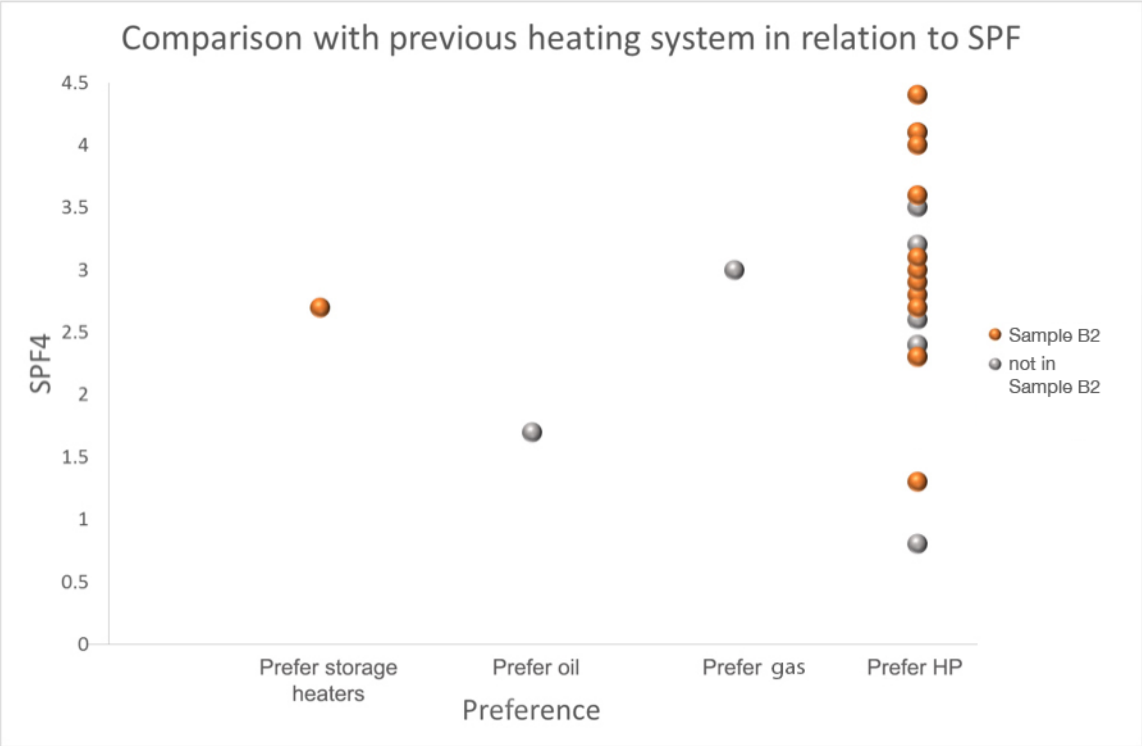

Figure 4-18. Occupants' preferred system presented in relation to SPF4 based on the reference period SPF's as in Table 4-1.

Table 4-3. Comparison between the HP and alternative heating systems, based on occupants' experience

	Alternative system	Oil boiler	Gas boiler	Electric storage heaters
Comparative advantages of a HP (as seen by occupants)	Cost	HP has lower running cost (CS13, CS21), no worrying about oil price (CS01), more cost effective in the long run (CS14).	HP has lower running cost (CS02).	HP works out cheaper (CS08).
	Controllability	HP is easier to control after initial setup (CS01, CS03,CS21).	HP is easier to control after initial setup (CS03, CS18, CS19), easier to control zones (CS18),	HP is easier to control after initial setup (CS20).
	Comfort	HP offers stable/whole-house heat (CS09, CS11, CS21), no hassle of filling up the tank (CS01, CS09, CS11, CS14), less maintenance needed.	HP offers constant/whole-house heat (CS05, CS17, CS19), less noisy (CS05), fit and forget (CS18, CS19).	
	Environmental considerations	HP is environmentally friendly (CS14).	N/A	HP provides comfortable and constant heat (CS06, CS12, SC20), same running cost but more heat (CS20).
Comparative advantages of alternative heating systems (as seen by occupants)	Cost	N/A	Occupant thinks gas works out a bit cheaper as electricity is expensive (CS03), costs less and provides more physical heat and instant DHW (CS07),	Storage heaters were cheaper and more efficient (CS07).
	Controllability	Oil is more straightforward settings/control (CS01, CS09, CS16).	Gas is more straightforward settings/control (CS05), more responsive/instant heat (CS17, CS18),	Occupants felt they knew how to control the storage heaters (CS07).
	Comfort	Oil is more responsive/instant heat (CS01, CS09).	Gas boiler is easier to identify and fix a problem or breakdown - boiler never broke down (CS04).	N/A

To summarise, factors such as cost and controllability may appear both as advantages of heat pumps, and as advantages of more conventional oil, electric or gas systems. Taken together with detailed accounts from individual cases, this suggests that whether the heat pump is perceived as an improvement or not, may depend to a greater or lesser extent on individual occupants' detailed experience with their system. This in turn may depend on the extent to which they have mastered the heat pump, in the context of information provided by installers, quality of installation and control systems, specific details of individual dwellings, their own general technical competence and so on. That one household preferred electric storage heaters to a heat pump on controllability grounds, suggests that there may be more to do.

4.7.2 Occupant perception around comfort with HP

With the exception of CS07 and CS16, all occupants felt the temperature of their home with the HP was meeting their expectations to a great extent, i.e. feeling comfortable, quite warm or warm. A detailed list of their answers can be found in Table E 14, Appendix E. Case CS07 was mentioned earlier as the occupants were the only ones feeling very dissatisfied with their HP. They felt they were paying a lot in electricity without getting sufficient heat. The female occupant said:

> *"It feels cool, we want it warm. […] We sit here freezing and cannot get the washing to dry. This is not the heat we were expecting. We were told we cannot have both DHW and SH at the same time."(CS07)*

Of the remaining cases, the owner occupiers of CS01 felt that they would like their home to be a little bit warmer but they compromised by putting on a jumper/duvet or lighting the fire and they never changed the thermostat settings. The majority of occupants said that they did not usually need to employ an additional warming measure, except for rare occasions when they might decide to turn up the thermostat a bit or adjust the flow temperature, put on more clothes, light a fire or use an electric resistance fan heater.

4.7.3 Occupant experiences of the HP

- **Quality of training** – Figure 4-19 presents the occupants' satisfaction with the training provided. 80% appeared to be satisfied or very satisfied with the quality of training, one was neutral about it and four dissatisfied or very dissatisfied. The training sources ranged from booklets, leaflets and cards, demonstrations from installers or RSL officers to full technical group briefings. The majority of social tenants were advised not to interfere with the HP, other than using the thermostat and to try to keep the temperature constant. Some of the installers of the HPs in owner occupied properties also suggested that the HP runs better when running all the time at a constant temperature.

Almost everybody agreed that the information given was too technical and difficult to understand. Those dissatisfied or very dissatisfied would fall into two groups: (A) those generally happy with the performance of their HP and (B) those unhappy with the performance of their HP. Group A would have liked more information that could help them improve further the performance (e.g. how to fine tune it, optimise running conditions or a central resource of knowledge with examples of how typical installations work). Group B would have liked more practical information that could help them understand how the system works, in the hope of getting their system to work efficiently themselves.

Those satisfied or very satisfied with the training given were all content with the performance of their HP. Thus, even though they found the training and material given too technical and difficult to understand, they never had to use it to solve a major problem. A few, especially those with a technical background, thought it looked complicated at first but they then found their way and learnt to use certain features. Finally, some occupants suggested that a number of post installation visits would be very useful, i.e. once they had familiarised themselves with the system.

Figure 4-19. Occupants' satisfaction with training presented in relation to SPF4 (representative estimate), based on the reference period SPF's as in Table 4-1.

- **Ease of use** – As shown in Figure 4-20, all but one of the households (CS07) said that they found it easy or very easy to use their HP. All social tenants were controlling their HP via the room thermostat or programmer but they knew that there was a more complicated system setup 'hiding' in the background. The occupants of CS07 were the only ones that did not express an opinion, as they felt the question was not relevant since their system was not functioning as expected. The female occupant said:

> *"We know how to use it and I don't think we do anything wrong. We rely on the settings and everything being correct" (CS07)*

Most of the owner occupiers felt that once the system is all set up, then it was easy to use, either via room thermostat control, by altering the flow temperature or using some more advanced but limited features of the interface, such as heat curves or vacation mode. The setup was carried out by the installer in most cases, or by the installer in collaboration with the owner occupiers (for some of those with a technical background). Finally, two of the occupiers thought that being able to call the manufacturer's helpdesk to discuss any problems or for further guidance was very useful.

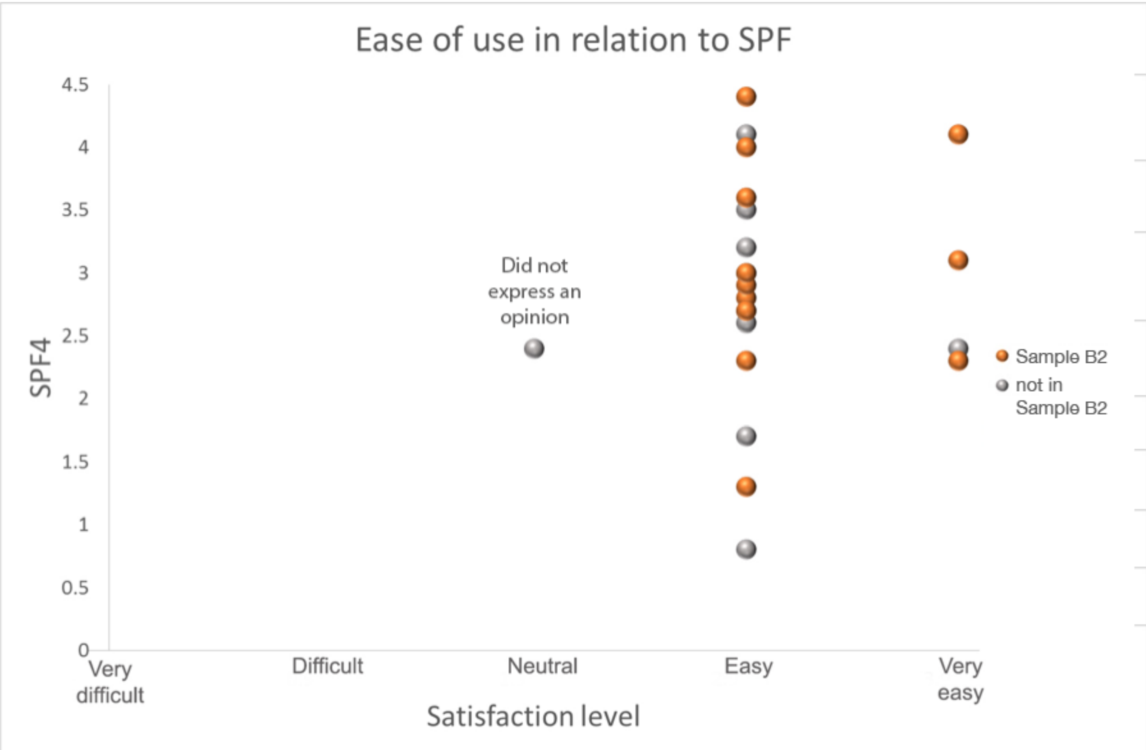

Figure 4-20. Occupants' view on the HP ease of use presented in relation to SPF4 (representative estimate), calculated based on reference period SPF's as in Table 4-1.

- **Problems with HPs and technical support** – At least 10 (four social and 6 owner occupied) out of the 21 cases experienced some major problem since the installation, such that the occupants could not resolve it themselves, at least not easily. In at least four cases, the occupants had experienced more than one issue. Note that for CS07 and CS16, there were ongoing issues with the HP at the time of the visit. Overall, the main technical issues as described by occupants are listed in Table 4-4 and these relate to faulty HPs or faulty parts of the system, installation and antifreeze problems, dripping issues, blockages and unintentional use of resistance heating resulting in excessively high electricity bills.

  Minor issues included power cuts causing the HP to go off or a hydronic fan convector going off. These were easily and intuitively resolved by the occupants (or friends) via switching the HP off and on again and playing around with the control settings for the hydronic fan convector. In contrast, the major issues were much harder to identify and resolve, taking a long time to fix and leaving the occupants without heating for up to two months. In some cases, the installer had to collaborate with other technicians, such as an electrician (CS12), the manufacturer (CS17) or even a knowledgeable householder (CS01) to work out what was going on. In case CS08, many technicians came around but only one could spot what were considered straightforward problems, such as the resistance heating being turned on. Some of the occupants with a technical background, i.e. in CS01 and CS13, were able to identify the causes of problems that the technicians had overlooked.

  The issues causing high electricity bills in case CS16 were still being investigated at the time of the site visit when the occupant mentioned that a technician was monitoring the HP for this purpose. However, the social tenants of CS07 were unfortunately left feeling hopeless, as they described how technicians and RSL representatives had visited them but none were able to identify a reason for poor performance or to lessen their negative feelings towards the HP installation.

Table 4-4. Main technical problems as described by occupants

Problem cause	Case ID	HP type	Description	Resolved?
Issues with antifreeze	CS04	GSHP	• Cracked antifreeze tube in outside cupboard;	Yes
	CS14	GSHP	• Antifreeze leak in both boreholes of a HP system;	Yes
Faulty HP or other part of the system	CS06	ASHP	• HP burnt out due to faulty generator	Yes
	CS07	ASHP	• HP burnt out due to faulty air inlet fan in external unit	Yes
	CS08	ASHP	• Faulty motherboard	Yes
	CS12	GSHP	• Faulty pump	Yes
	CS21	ASHP	• Faulty air inlet fan in external unit	Yes
	CS17	GSHP	• HP broke down after a big surge in voltage	Yes
	CS12	GSHP	• Faulty sensor / miscommunication between sensor and controller	Yes
Installation problem	CS13	GSHP	• Air in ground loops	Yes
	CS01	ASHP	• Specific zone wouldn't heat up due to manifold floor valves installed back to front	Yes
Dripping issues	CS08	ASHP	• Missing drip-tray causing excessive spillage	Yes
	CS06	ASHP	• Missing drip-tray causing slippery damp patch	No
Blockages	CS06	ASHP	• Tank and radiator blockage cause water flow problems	Yes
Resistance heater	CS12	GSHP	• Booster heater left on by plumbers led to increased electricity bills	Yes
	CS08	ASHP	• Booster heater left on by renovation team or HP reset itself and booster was turned on led to increased electricity bills	Yes
Unknown cause	CS16	GSHP	• Occupants feel there is excessive electricity consumption	No
	CS07	ASHP	• Occupants feel there is insufficient heat / high electricity bills	No

5 Case and cross-case comparison

5.1 Introduction

Section 4 above has offered a general picture of the physical and social characteristics of the 21 sample cases. In this Section, case and cross-case analysis is employed to explore further how HPs and performance monitoring systems operate in their physical and social contexts, and how these contexts might have affected performance. Due to constraints of time and limited resources, and the emergent nature of the findings, the design and execution of this analysis was necessarily pragmatic, yet needed to be capable of capturing some of the features of the complex pathways to performance. To this end, a strategy for sub-sampling was formulated and an analytical matrix (see Appendix B) was constructed to support this work.

5.2 Strategy for sub-sampling and cross-case comparison

The analytical strategy to explore factors influencing performance was primarily based on a detailed analysis of the five well and five poorly performing cases Table 5-1). At the time of case selection, it was considered that the ideal candidates for this sub-sample should be selected from the two extremes of the SPF distribution that was provided by the statistical analysis team, based on the *preliminary and unpublished* dataset. It should be noted that the team was aware of the possibility of metering anomalies in the volunteering sample, but the extent and significance of such anomalies were still unclear at the time of the selection of the case study sites.

Subsequent detailed examination of data revealed that three of the five case studies that were originally considered to perform poorly would be more appropriately categorised as well performing.

Table 5-1 presents the original and revised estimates of the SPF's for the sites examined in detail. As noted in Section 3.2.2, the site visits were approximately three hours long and therefore not all issues could be resolved. Furthermore, various errors in the RHPP metadata have been identified (also noted in Section 3.2.2).

Table 5-1. Matrix of the well and poorly performing cases selected for the sub-sample

ID	SPF4: Preliminary and unpublished	SPF4: Representative estimate	HP type	Owner ship	TFA (m2)	Declared net capacity (kW)	Heat emitter	Suspected metering data anomalies (based on raw data)	Suspected metering data anomalies (based on observation or occupant narration)	EPC: Estimated SH demand (kWh/year	EPC: Band
Well performing											
CS18	4.3	4.4	GSHP	Private	346	12	UFH	Heat output when no electricity input in re-presentative period.	Heat meter on flow rather than return.	20,421	B
CS13	4.2	4.1	GSHP	Private	252	12	UFH	Heat output when no electricity input in re-presentative period.	None observed or narrated.	20,044	B
CS19	4.1	4.0	GSHP	Private	95	9	UFH +Rads	None observed.	None observed or narrated.	17,774	C
CS14	3.5	3.6	GSHP	Private	293	12	UFH	None observed.	None observed or narrated.	16,824	B
CS20	3.5	3.5	ASHP	Private	99	11	Rads	Unknown - Did not pass Sample B2 quality criteria due to missing schematic.	Incorrect heat meter location (does not account for pipework heat losses).	9,922	C
Poorly performing											
CS16	1.7	1.7	GSHP	Private	314	12	UFH +Bath Rads	Electricity input when not heat output.	None observed or narrated.	26,269	A
CS07	1.5	2.7	ASHP	Social	41	5	Rads+ hydronic fan convecto r	Electricity input when no heat output during 01/11/13 – 30/11/14.	None observed or narrated.	4,161	E

ID	SPF4		HP type	Owner ship	TFA (m2)	Declared net capacity (kW)	Heat emitter	Suspected metering data anomalies (based on raw data)	Suspected metering data anomalies (based on observation or occupant narration)	EPC	
	Preliminary and unpublished	Representative estimate								Estimated SH demand (kWh/year	Band
CS09	1.0	2.7	ASHP	Private	164	16	Rads	Erroneous flow meter readings outside representive period.	Multiple monitoring system issues.	16,402	D
CS15	0.8	3.0	GSHP	Private	260	11	UFH +Rads	Faulty heat meter data until the end of winter 2013/14.	Wrong sensor fitting reported, installers visited to fix.	21,712	B
CS12	0.8	0.8	GSHP	Private	106	7	UFH +Rads	Did not pass sample B2 quality criteria due to electricity data missing/ improper monitoring in re-presentative period.	Recording fault reported, installers visited to fix. Wrongly attached jubilee clip on T sensor observed.	9,383	D

The readers should note that it was not possible to check all the data for each of the ten cases. If anomalies are reported in the above table as having been found outside the representative period (see Table 4-1), this does not guarantee that they are absent from within the representative period.

While the physical and social factors of each case were examined to understand performance, comparisons were also undertaken within the best and poorly performing groups, and within sub-groups (e.g. ASHPs versus GSHPs, and social housing occupants versus owner occupiers). Different dimensions of comparison were also employed, as hypotheses emerged. For example, the SPFs for similarly sized houses with similarly sized heat pumps were compared when it emerged that load factor might play a part in affecting annual performance. Because out of the five "poorly performing cases", only one was initially in the social housing sector, the six social housing cases that were initially outside the sub-sample of 10 sites, were retrospectively brought in to support cross-case analysis within social housing. Thus, sixteen cases, mapped onto the following four dimensions were, in the end, employed in these comparisons:

1) analysis based on estimates of performance from physical monitoring

2) analysis based on physical characteristics of dwellings

3) analysis based on characteristics of social housing

4) analysis of occupants' social and behavioural responses to their system.

5.3 An analytic matrix

The analytical matrix presented in Appendix B was constructed to support case and cross case analysis. It is based on the following socio-technical assumptions:

Technical design of installation – the design process involves calculation of the dwelling's heat losses in order to determine the heat output rating needed to adequately heat the property[36]. Apart from the system layout and design, and the general control strategies (including with respect to legionella), one of the designer's key objectives should be to enable the lowest possible operating temperatures (Tsf and Twf), consistent with providing sufficient heating and adequate legionella control. This has implications for the configuration and control of the HP system and for the heating-related experiences of the occupants. Tsf emerges from the interplay of the characteristics of the heat distribution system (underfloor heating versus radiators, sizing, positioning of radiators, location of underfloor circuits), with heat demand, which in turn is dependent on the daily variations of inside and outside temperature, the heat loss coefficient of the dwelling, and intermittency. All of these factors will be affected by decisions and actions of the installer and/or occupants. The performance achieved in any given set of circumstances will also be influenced by:

b. **Installation quality** - which is affected by the interactions between the system designer, the existing dwelling and the occupants, and by practical, cultural and aesthetic considerations (such as the cost and potential inconvenience of new, larger radiators), all mediated by the installer's competence and expertise, and the commercial context.

c. **Initial commissioning** - including modes of operation selected and set by installers, e.g. settings for maximum flow temperature, weather compensation, initial thermostat settings and heating on- and off-periods, control of electric resistance boost heaters and DHW sterilisation, and operating modes for auxiliary pumps and fans. It is important to differentiate between the designer's intended control strategy (where known) and actual commissioning settings, which may not necessarily match up.

d. **Changes or variation in commissioning** - an iterative process of matching flow temperature to heat loss (though occupants are unlikely to perceive or express it in such terms), in the context of

[36] Note that while MCS establishes minimum heat output ratings for any given installation, capital cost and need to bid for work in a competitive marketplace represent powerful incentives not to oversize.

occupants' preferences, enablements (availability of technical documentation and advice) and constraints (financial, level of technical understanding etc.), which is mainly controlled by occupants.

The analytic matrix is a template that follows the socio-technical systemic logic of HP performance, from thermodynamics (as expressed qualitatively by the highly simplified equation[37], COP ≈ 0.5 x 330/ΔT), through the configuration of system components and their interactions with the characteristics of the dwelling (built-form and heat loss as taken from the EPC), to impacts of human behaviours (commissioning of system by installers and in some cases, occupants, and occupants' operating strategy in the context of lifestyles and costs). The act of inputting available data for each case into the analytic matrix, bounds the analytical space and exploration can then proceed.

Findings from the five well performing cases and the five cases that were initially thought to be poorly performing are presented in the following in two sub-sections, 5.4 and 5.5. The main focus of sub-section 5.4 is to explore how physical arrangements (HP system and dwelling) might influence performance. In sub-section 5.5 social factors such as knowledge and control of systems are explored. It is important to note that although technical and social factors are presented in separate sections, these two domains often lack clear-cut boundaries: their influences on heat pump performance are inter-connected and dynamically related. Therefore, in both sections, interactions between these two domains are also highlighted, as and when it is appropriate to aid understanding.

5.4 Exploring physical factors influencing performance

Physical factors that in principle influence heat pump performance include:

- Heat pump type.
- Quality of installation – e.g. degree of insulation of pipes, especially between the external unit and the house and the degree of insulation of any hot water tanks.

[37] This equation is derived from the equation for the Carnot limit on COP of a heat pump:

$$COP_{Carnot} = T_{hi}/(T_{hi}-T_{lo})$$

where:

T_{hi} is the temperature (in Kelvin) at which the heat pump delivers heat to the dwelling (≈55°C)
T_{lo} is the temperature (in Kelvin) at which the heat pump extracts heat from the environment

Real heat pumps achieve roughly half of this thermodynamic limit. Taking T_{hi} as 330 K (equivalent to ≈55°C), the practical COP of a heat pump then approximates to:

$$COP \approx 0.5 \times 330/(T_{hi}-T_{lo})$$

which by replacing $(T_{hi}-T_{lo})$ with ΔT, can be further simplified to:

$$COP \approx 0.5 \times 330/\Delta T$$

- Relationships between HP rating, heat emitter sizing, dwelling heat loss, hot water cylinder size, space and water heating control strategies, and their impact on phenomena such as cycling, part load performance, operating temperatures, and use of electric resistance heating.
- Quality of commissioning.
- Sizing, number and operation of auxiliary systems (circulation pumps in the central heating circuit, ground loop pumps etc.).
- Relative split between space and water heating loads.
- Direct and indirect impacts of occupants' actions and interactions with the heat pump and its controls, secondary heating systems, and the dwelling[38].

Detailed technical information per case study can be found in the tables of Section E3 Technical *information on HPs* (Appendix E).

Constraints of time, resource and most importantly, availability and observability of factors meant that a thorough analysis of all of the above would have been impossible in the context of this project. Therefore, the analysis began with a sub-set of factors that was observable and available. This sub-set played a double role at this stage of analysis, serving, firstly to guide the selection of cases, and then to support the analysis and interpretation of occupants' interview data. The physical factors in question were:

- heat pump type.
- SPF, as estimated at the outset of the case selection process.
- a qualitative visual evaluation of quality of planning and insulation of pipework associated with the heat pump.
- sizing of heat emitters.

As the analysis proceeded, and understanding of individual cases deepened, a number of additional factors, such as controls, load factor and the presence and use of internal booster heaters, were brought into the analysis and interpretation process.

As mentioned in Section 5.2, a sub-sample of 10 cases was selected from the initial sample of 21 cases, the basis of estimates of SPF4 based on the *preliminary and unpublished* monitoring dataset. The 10 sub-sample cases were divided into two groups: poorly performing and well-performing. The cases that were initially thought to be poorly performing were CS12 (0.7), CS15 (0.8), CS09 (1.0), CS07 (1.5) and CS16 (1.7); and the well performing cases were, CS13 (4.2), CS14 (3.5), CS18 (4.3), CS19 (4.1) and CS20 (3.5). In the course of the analysis, it was realised that SPF4 values for CS15, CS09, and CS07 based on the

[38] An extended set of physical and social factors influencing performance is laid out in the analytic matrix (see an example in Appendix ?). The unfilled cells represent unavailable and unobservable data.

preliminary and unpublished monitoring dataset had been affected by specific metering or system anomalies. Following a reassessment of metering anomalies and reselection of analysis datasets by the quantitative team, SPF4s of 3.0, 2.7 and 2.7 respectively, were considered to be more representative of periods of stable HP and monitoring system operation for these cases.

5.4.1 System insulation and heat loss in poorly performing cases

Among the five cases originally thought to be poorly performing, a variety of arrangements and configurations were observed that appeared likely to result in increased heat losses from pipework. However, as the analysis deepened, a much more complex picture began to emerge. This process is illustrated through an exploration of three dwellings that were initially placed among the five poorly performing cases: CS09, CS07, and CS15.

CS09

In the case of CS09 the occupant had asked, for aesthetic reasons, that the outdoor unit of their split ASHP system, be moved from the position originally suggested by installer, immediately adjacent to the dwelling, to a new position about 10 metres away (Figure 5-1). This would have increased the heat losses from the pipework that ran from the outdoor unit[39] to the house, and affected system efficiency through two possible mechanisms:

- by increasing the temperature that the heat pump needs to operate at to satisfy space and water heating demands, as mediated by the actual space and water heating systems present in any given dwelling, and thus reducing the SPF, and/or increasing the proportion of electric resistance heat used by the system;

- depending on where the heat meter was sited, through unmetered heat losses from distribution pipework between heat pump condenser and heat meter(s).

There is the possibility of a third, indirect pathway to performance, resting on the hypothesis that good planning, as indicated by short pipe-runs and well executed thermal insulation of pipework, may be linked with other, less visible factors associated with effective design and commissioning[40].

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[39] All ASHPs have an outdoor unit, which contains a fan and the HP compressor and evaporator, as well as other components, which vary with manufacturer and model.
[40] Calculations undertaken shortly before the end of the project indicate that 10m of uninsulated external pipe-runs may reduce SPFs by up to 10% (for example, from 3.0 to 2.7), and potentially more for HPs that cycle frequently.

Figure 5-1. CS09 – External unit behind trellis in corner of garden

At the time of the case study selection, the SPF4 of the CS09 ASHP based on the *preliminary and unpublished* data from 1/11/2013 to 31/10/2014 (Figure 5-2) was calculated to be 1.0. As discussed in Table 4-1, recalculation as part of sample B2 led to increased SPF4 of 2.7.

The occupants reported that there had been a flat battery in the monitoring system which had been replaced in the period between September 2013 and September 2014. Examination of the data for this HP showed an unexplained reduction in mass flow (F_{HP}) through the heat meter over most of the original period. This reduction began with a slow decline and finished with a slow recovery to the original flow rate, a pattern which does not appear to be consistent with a "flat battery" explanation. Although the reduction in mass flow varies across the period in question, it is large enough to explain much of the reduction in SPF.

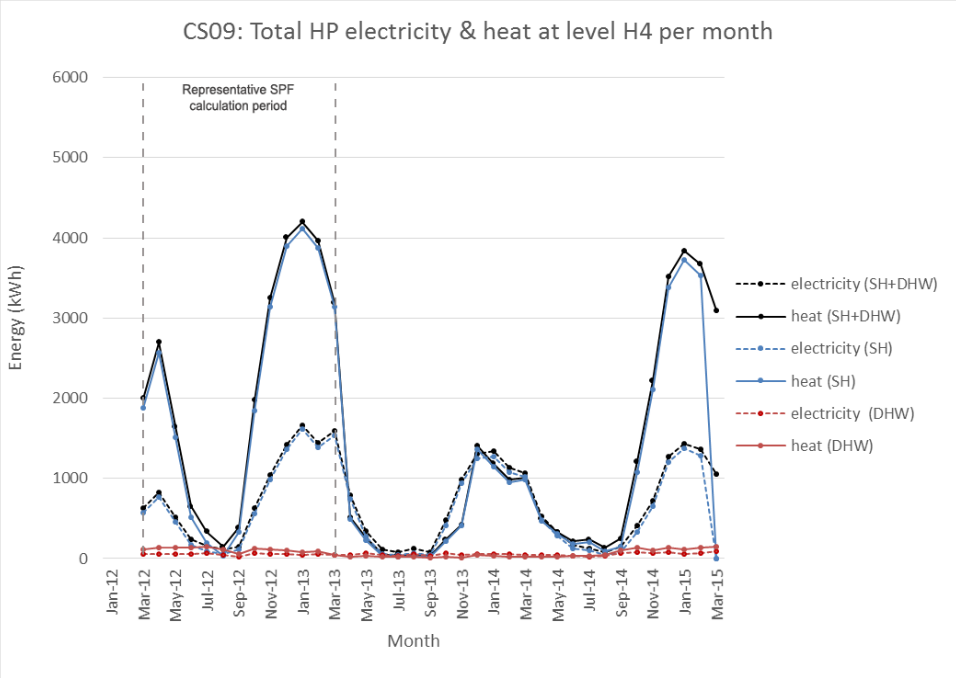

Figure 5-2. CS09 - Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both from raw data. Note period between 1/11/2013 and 31/10/2014 has low output compared with other periods.

CS07

As shown in Figure 5-3, the outdoor unit of CS07 was sited immediately adjacent to the junction of two external walls of the dwelling, thus potentially restricting the flow of air through the unit, and in turn potentially reducing the performance of the HP[41]. In addition, the refrigerant line and valve connecting the outdoor unit with the internal unit that was housed in the unheated attic, was not fully insulated. Insulation to the pipework around the DHW cylinder was also observed to be incomplete.

[41] Confirming this conjecture would require additional on-site investigation.

Figure 5-3. CS07 – External fan unit and installation

However, the conjecture that these features were the primary causes of the low SPF was challenged by information gathered about CS07 occupants' experience of the installation of the heat pump. Prompted by the interviewer's questioning, the CS07 occupants recalled that many problems with their HP started approximately 12 months after it was installed, and that it eventually "burnt out"[42]. The male occupant suggested that the time was around February, 2013 before the new unit was brought in and the re-installation process began. This observation coincides with a significant anomaly in the physical data, see Figure 5-4.

The interview data serves to explain the difference between the initial estimate of SPF (0.7) and the value (2.7) subsequently estimated in the light of a reassessment of metering anomalies and reselection of analysis datasets by the quantitative team.

[42] Perhaps compressor failure. But the audio recording is unclear.

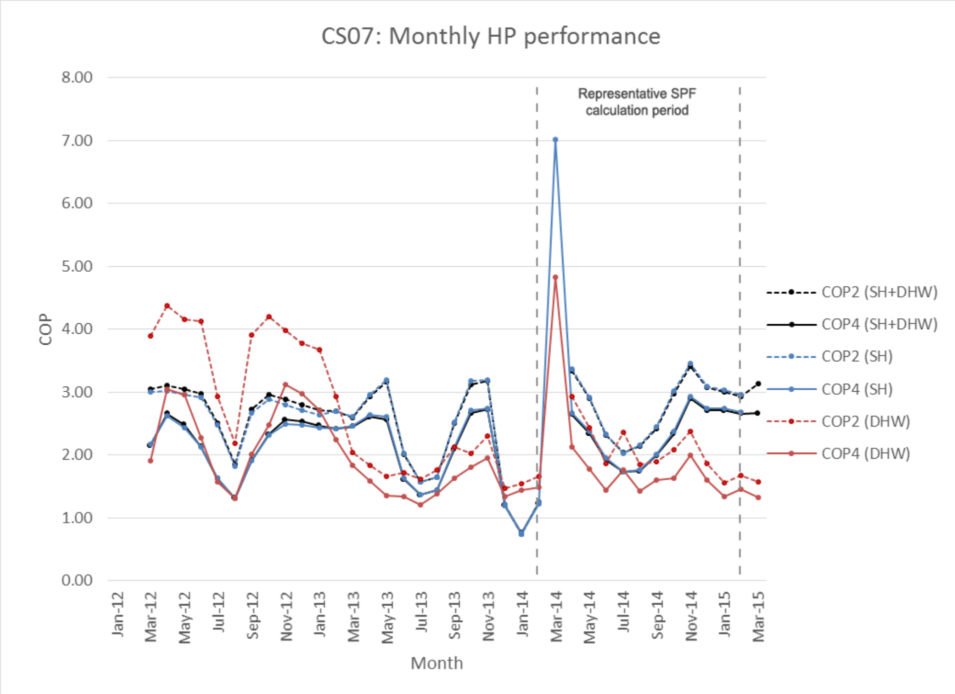

Figure 5-4. CS07 - Monthly COPs for SH, DHW and combined at levels H2 and H4, showing anomaly in February/March 2013 when the heat pump broke down and was replaced.

CS15

The initial estimate of the SPF for **CS15** (0.6) appeared to challenge the hypothesised connection between pipework insulation and layout and performance. Figure 5-5 shows the system pipework within the unheated attached garage was very competently laid out and insulated.

Figure 5-5. CS15 – High quality insulation and layout of pipework

The male occupant was aware of the low SPF4 value (i.e. 0.6) from the letter sent to him inviting him to participate in the interview, and was not convinced that the value was correct. As he was trying to make sense of the low SPF value, during the interview, he recalled that there had been a problem with the installation of monitoring equipment but that this had recently been put right.

> "When sensors were placed, [the] fitting was wrong – it was running backwards for a long time[43] – then they came back and altered it; they'd put the sensors on the wrong pipes; this happened [maybe] around 18 months ago". (CS15[44])

The occupants found it difficult to remember exactly when the monitoring fault was corrected, but the graph below indicates that no heat was recorded between July 2013 – January, 2014, and very low space heating was recorded in the ensuing heating period between Jan, 2014 – May, 2014. Then, between September 2014 and March 2015, the ratio of heat output and electricity input appears to be reasonable Figure 5-6. The male occupant insisted that the SPF of 0.6 was incorrect as the HP had been running well.

> He said he knew "how it works, everything is installed rightly and the bills are not bad at all!". (CS15)

[43] The Sontex heat meters are designed not to register reverse heat flows (from the house to the HP). If the positions of the heat meter temperature sensors are reversed, this reverses the apparent direction of the heat flow, and the heat meter will record zero heat flow.

[44] This would place the correction to the heat metering system in 2014. However, it must be borne in mind that memories fade over such periods.

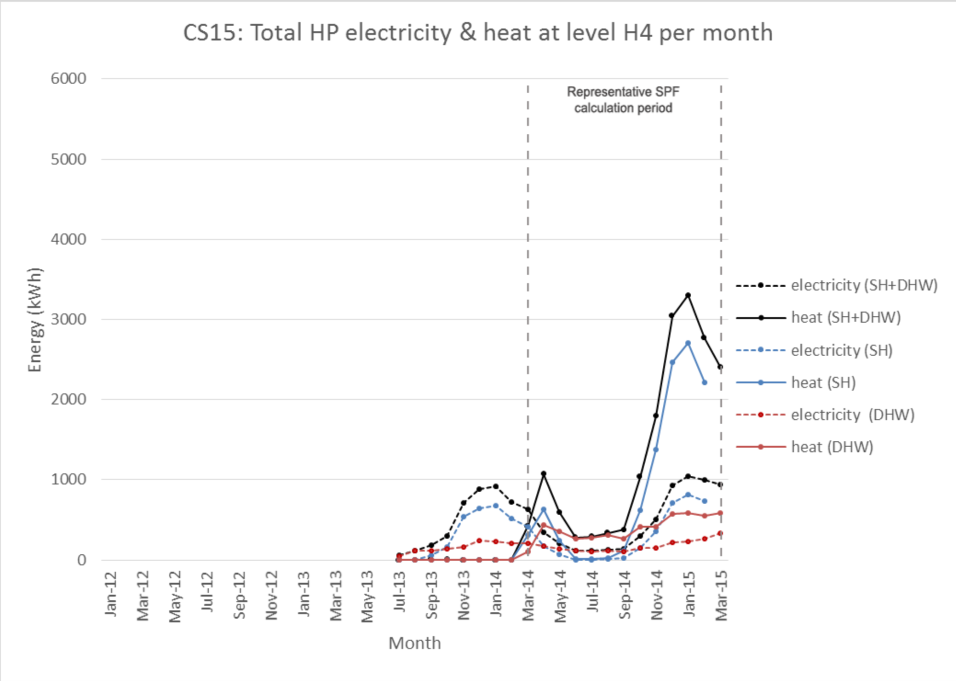

Figure 5-6. CS15 - Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both: the effect of incorrectly installed heat meter temperature sensors can be seen in the period between July 2014 and May 2015.

The SPF of CS15 was initially estimated at 0.8, based on the *preliminary and unpublished* dataset. Based on data for the period March 2014 to March 2015, the SPF is closer to 3.0, thus moving this case from among the poorly performing cases, to above average.

This revised estimate of SPF would appear to be consistent with the observation of well-insulated pipework at this site. However, it is likely that other factors might also have influenced performance and that these would warrant further exploration.

In-depth analysis of CS12 and CS16

The two remaining poorly performing cases were CS12 and CS16 with initial SPF values of 0.7 and 1.7, and with EPC ratings of D and A respectively. The analysis of these cases follows the same approach as above: to survey evidence for suspected heat loss that might be due to specific configuration and arrangement of the system, siting of units, insulation of pipework etc. However, further evidence surrounding these cases suggests additional explanations for the low values of SPF recorded.

Case 12 is a moderately sized house at 106 m^2, with a south facing conservatory, occupied by a single woman. Although the dwelling was under private ownership at the time of the trial, it was built around 2008/9 under an affordable housing scheme, and probably under the 2006 version of Part L. The EPC rating is D and the EPC estimate of heat demand for the dwelling is 9383 kWh/year. The heating system is characterised by un-insulated pipework (see Figure 5-7).

However, on closer examination, the relationship between un-insulated pipework and performance appeared to be not so simple. It was observed that the GSHP and hot water cylinder were installed in a cupboard fitted within a heated utility room. The heating system consisted of underfloor heating on the ground floor, with radiators upstairs – a hybrid. Visible pipework was uninsulated. At first glance, such an arrangement should be less detrimental to the efficiency of the HP than uninsulated external pipework. However, the room thermostat was located in the kitchen immediate adjacent to the heated utility room. It is possible the room thermostat in the kitchen might have been affected both by heat gain from cooking and heat gain from uninsulated pipes in the adjacent utility space. Either factor might in turn have increased the tendency of this system to cycle.

Figure 5-7. CS12 – Uninsulated pipework associated with the HP

In order to understand in detail what other factors might influence the performance of this case, the analysis turns to more complex factors such as heat demand of the dwelling in relation to electricity and heat consumption indicated by monitoring data.

The monitoring data show the HP using just over 3000 kWh per year of electricity. When asked about the electricity cost, the occupant said that she was paying around £3-4/day in the winter period, and £850-1150 per year. This would have been equivalent to roughly 7000 kWh/year, consistent with a dwelling using 4000 kWh per year for lights, electrical appliances and cooking, and 3000 kWh for the HP.

Plots of monthly mean electricity and heat demand for CS12 (Figure 5-8) show heat demand for space and water heating below electricity input in every month for two consecutive years. The analysts were puzzled by this, and inquired further into whether such readings could be a matter of metering error alone. Two features of the monthly mean electricity and heat demand plot suggest it might be. First, the extreme seasonality of hot water demand – a factor of 17 between mid-winter and mid-summer – and the persistence of space heating demand through the summer, suggest that there may have been a misallocation of total HP heat output between space and water heating – this appears likely in the light of a photograph taken on site of the monitoring installation (See Figure 5-9) showing an auxiliary temperature sensor (Tsf or Twf) on one of the primary circulation pipes, which has been installed with insulation between it and the pipe.

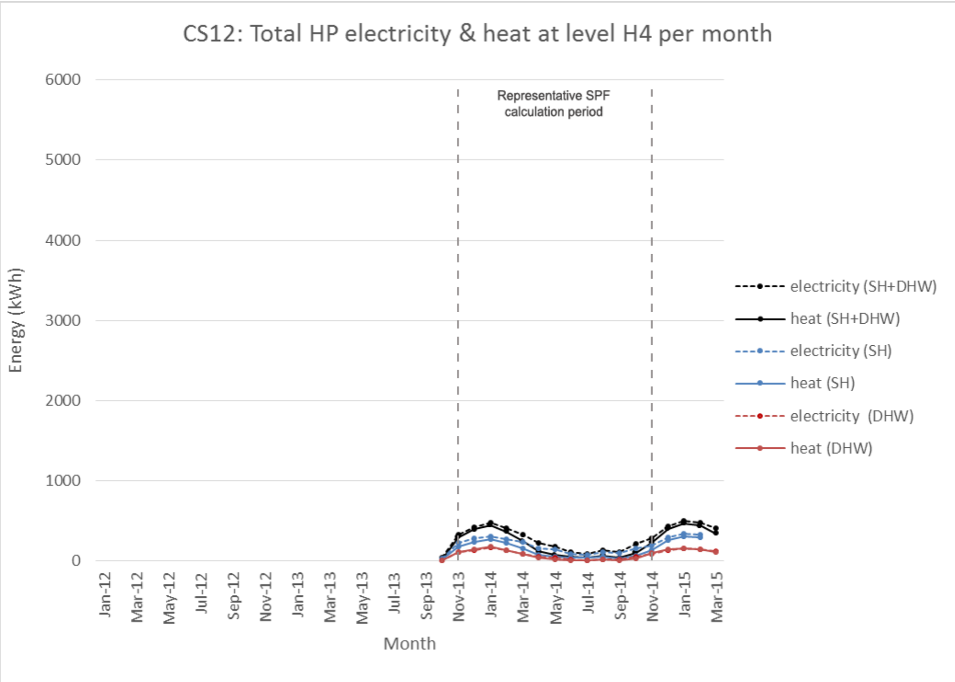

Figure 5-8. CS12 - Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both

Figure 5-9. CS12 - Close up of pipework showing insulation between temperature sensor and pipe (centre of image). The external temperature sensor for the heat meter can also be seen, just right of centre, in a pocket

The level of both space and water heating recorded by the monitoring system are implausibly low, even in a well-insulated dwelling with a single occupant. The total heat output of the HP in January is sufficient to raise the internal temperature of the dwelling by about 4 K. Without other sources of heat, this would bring the mean internal temperature in January to around 8°C. Solar gain in January is negligible, and internal free heat gains are unlikely to add more than a few Kelvin. The set-point temperature observed on most room thermostats in this dwelling during the site visit (which took place in the middle of December) was 17-18°C and the occupant said this temperature setting is very rarely overridden. The study did not measure internal temperature and therefore we are unable to determine whether this temperature was reached or not, but the occupant stated that she was "comfortable" (Appendix D6). The manufacturer's documentation shows the system is fitted with either a 6 or 9 kW 'additional electric heater'. Given the doubts about the monitoring in this dwelling, it is not possible to determine from the monitored data what proportion of HP output was produced by electric resistance heating.

A final piece of evidence from the physical monitoring consists of a plot of heat output from the HP against electricity input (Hhp versus Ehp) – Figure 5-10. This suggests that a significant proportion of the heat output of this system is derived from resistance heating (indicated by the cloud of data lying around the "efficiency=1" line, and that a proportion of the electricity input results in no measured heat output[45].

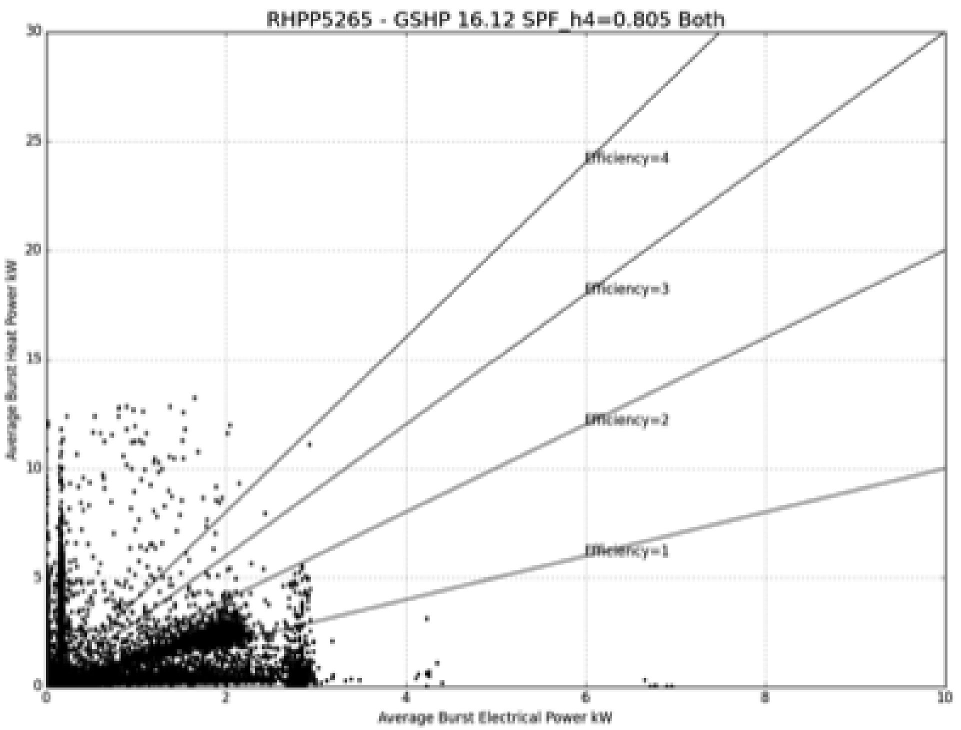

Figure 5-10. CS12 – Average burst electricity power and average heat power

This interpretation is consistent with a statement made by the occupant during the interview.

45 The laws of thermodynamics state that this electricity must eventually be degraded to heat. It is possible that the electric resistance heating takes place downstream of the heat meter and therefore that this heat has bypassed the heat meter.

The occupant stated during the site visits that: " …once plumbers came in and left it [boost] on', and when the occupant realised something was not quite right from her increased energy bills, she tried [and managed] to switch the immersion heater off on the control panel with the help of her father and the 'book". (CS12)

From the above one can conclude:

- Photos and monitoring data for CS12 indicate multiple problems with the monitoring system.
- The EPC estimated demand is 9383 kWh.
- The electricity used by the heat pump was 3,000 kWh, and the actual heat output measured during periods when heat metering appeared to be working properly was of the order of 9000 kWh/a – in line with the EPC estimate.
- The householder had a relatively low set point (17-18°C), but appeared to achieve comfort.

It is clear that, despite a comparatively rich dataset, this case study is unable to yield definitive answers because of the presence of multiple problems.

The analysis now moves to CS16. Despite the fact that CS16 has an EPC rating of A, denoting high efficiency in all aspects of the dwelling and its systems, the initial estimate of SPF4 for this HP was 1.7[46]. This case appeared to be an anomaly that warranted closer investigation.

CS16 was built in 2012, and is well insulated with high performance glazing. The pipework associated with the HP was also well insulated. The reluctance of the occupants to express any opinion on whether or not they were satisfied with their HP, and the nature of their heating (using HP for background heating only in an attempt to lower their bills) and showering practices (partly using an electric shower) prompted the checking of the design capacity of the HP and an assessment of whether it was adequate to meet the heat demand of the 314 m^2 dwelling. The EPC gives the rating as "A" and the annual heat demand as 26,269 kWh/year, but does not provide an estimate of the dwelling's heat loss coefficient. However, the house would either have been built to the Part L 2006 or 2010, and would therefore have had a design Heat Loss Parameter of between 1.0 and 1.5 W/m^2K. This would imply a heat loss coefficient of 300 to 450 W/K, and a design day heat load of between 6 and 9 kW. The heat pump that was installed in this dwelling had a capacity of 12 kW. One can therefore conclude that there was sufficient capacity in the heat pump to heat the dwelling down to external temperatures of around 0°C.

[46] The estimate from the preliminary and unpublished dataset.

The occupants of CS16 (a new build property) considered that their system 'uses too much energy'. They noticed their bill 'goes up hugely during the winter quarter' [they paid around £720 in the 2015 winter quarter and approximately 1/3 of that in the 2015 summer quarter]. Despite having PVs installed, the occupants did not feel that the payments from the FIT for electricity produced from PVs and the RHI payments were sufficiently offsetting the cost of their energy bill. When asked if they were satisfied with the system, the female occupant was rather reserved in her judgement and remarked:

> "…I want to wait until we find out what is going on [before] we express satisfaction, [the system] keeps the house warm but [we] have spent an awful lot of money (high capital + running cost), without PVs would have been even **more costly**". (CS16)

It is of course to be expected that in an electrically heated house, a winter quarter electricity bill would be significantly higher than a summer quarter bill. In this particular clash between outcome and expectation, it is possible that the problem lies with the latter. So the occupants' observation begs a series of questions but without further detailed exploration with the occupants in the interview, it is difficult to know how occupants' expectations were formed.

Inspection of the mean monthly energy flows in CS16 reveals further questions (Figure 5-11). The split between DHW and space heat changes by a large amount between the two years. DHW goes up. Space heat goes down by about the same amount. Total heat output, Hhp, stays roughly the same. Between November 2013 and March 2014, the water heating load is about 250 kWh/month, falling to 100 kWh/month in summer 2014, and then rising to 600-700 kWh/month in the period from November 2014 to March 2015.

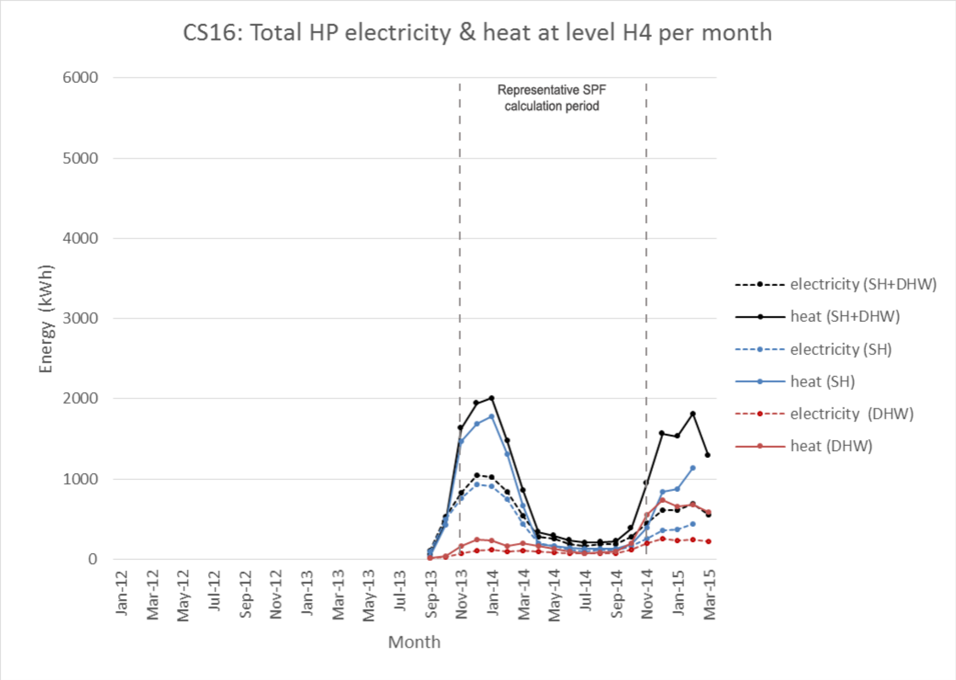

Figure 5-11. CS16 - Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both

In addition, detailed examination of the monitoring data for this dwelling denotes possible problems with the monitoring system. These are illustrated in Figure 5-12.

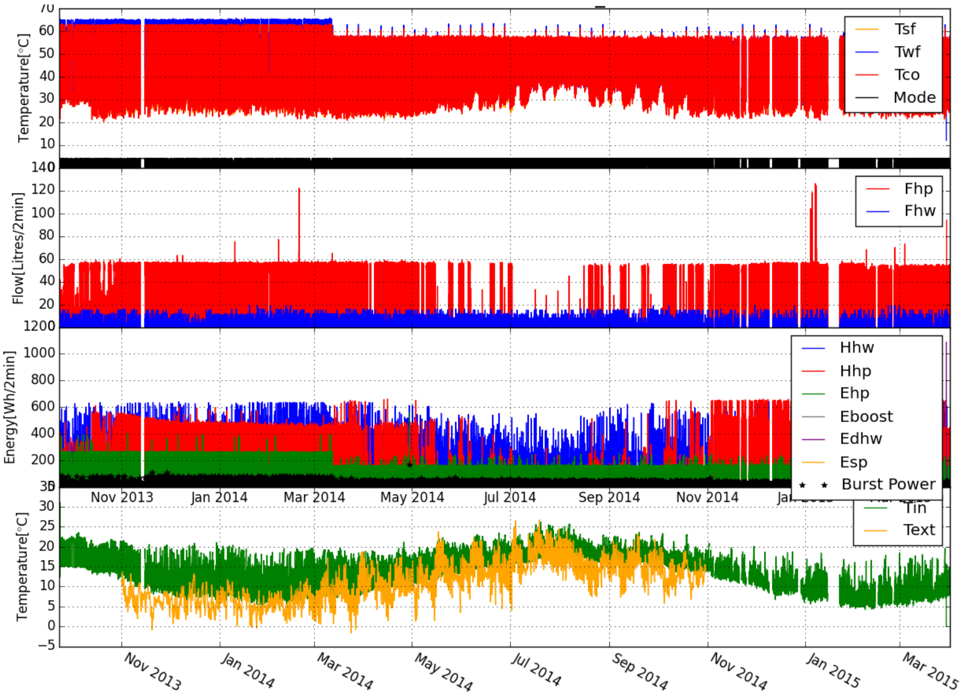

Figure 5-12. CS16 - Intermediate frequency plots of monitoring data

The envelope of electricity consumption for the HP drops abruptly by roughly 3 kW in late March 2014 and Tco drops abruptly at the same time, as do the flow temperatures. A possible explanation is that the booster heater was turned off at this point. Note that the HP is consuming electricity for the whole of this period, and the envelope of Tin, temperature at the outlet of the ground loop, shows that the ground loop is active throughout the year[47]. There appear to be a range of issues affecting performance driven by occupant changes to the control protocol (see section 5.5.1).

CS16 is a large dwelling with 2 guest bedrooms[48]. The occupants reported that numbers of visitors had fluctuated, e.g. one of their relatives had lived with them for a while during the monitoring period. This might have impacted on hot water demand both directly and perhaps also for washing linen, and on demand for space heating. But comparison of CS16 with CS14 (see Figure D 32 and Figure D 28 of Appendix D), which shows a similar increase in demand for hot water in winter of 2014/15, suggests that the "guest rooms" hypothesis may be a weak one. An alternative hypothesis was therefore considered, namely that the load factor may be influencing the efficiency.

[47] Tin reaches 20 degrees C. This is compatible with the Tin sensor being inside the heated volume of the dwelling. When the ground loop circulation pumps are off, Tin floats up to the internal temperature of the dwelling, □ 20C

[48] The CS16 house is formed of two wings, which join at a right angle. Guest rooms were located in one wing while the occupants inhabited the other.

Load factor hypothesis: comparison of CS16 with CS14 and CS18

In order to understand why CS16 only achieved an SPF4 of 1.7, monthly heat and electricity data recorded for this case were compared with those of two other dwellings of similar size and level of insulation from the well-performing cases, namely CS14 and CS18.

All three dwellings are over 290 m^2 floor area (roughly 3.5 times the UK mean floor area per dwelling, and the largest dwellings among the case studies). The GSHP installed in CS12 was rated at 12 kW, the same rating and from the same manufacturer as CS18 (initial SPF4 = 4.3). CS14 was also of the same rating but from a different manufacturer (initial SPF4=3.5 and without obvious metering anomalies).

The systems in cases CS14, CS16 and CS18 all have an integrated auxiliary heat unit, which backs up and supplements the output from the HP. The estimated heat annual demands recorded on the EPCs for these houses are:

- CS14 - 16,824 kWh/year
- CS16 - 26,269 kWh/year
- CS18 – 20,421 kWh/year

Comparison of the monitoring data for the three cases shows that in **CS16** mean heat demand ranged between 1.3 and 2.7 kW in the period from November to February, while in CS14 and CS18, mean heat demand ranged between 3.3 and 7 kW in these four winter months. Setting aside the possibility of errors in heat metering for the moment, the question is whether the low heat demand of CS16 might have contributed to the low SPF. This working hypothesis was put to the test by plotting the monthly mean COP versus load factor for these three cases (Figure 5.13).

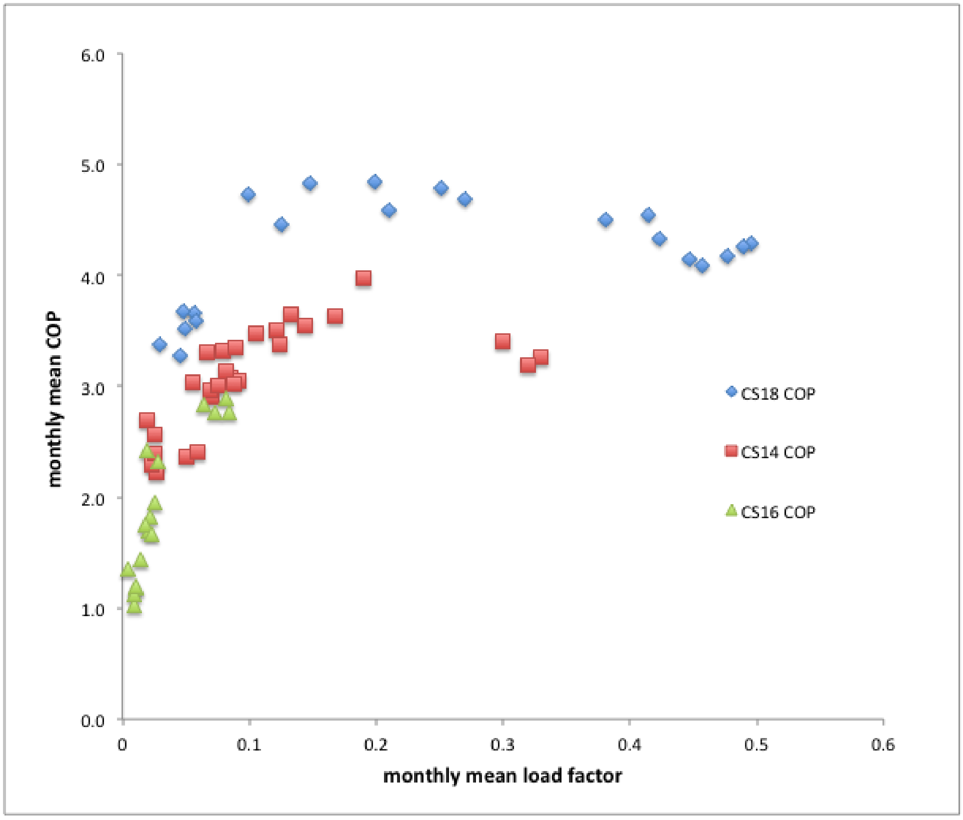

Figure 5-13. CS14, CS16 and CS18 - Monthly mean COP versus monthly mean heat load factor. Graphic indicates that at low mean monthly load factor, monthly mean COP is correspondingly low. Data for CS14 and CS18 appear to show a reduction in montly mean COP at high load factors. This is possibly associated with the onset of resistance heating.

This graph suggests that:

- the low SPFH4 of 1.7 for CS16 is in fact likely to be correct (rather than a metering error) and can be explained by the low heat load factor in this dwelling: the HP itself is not unusual, and indeed its performance profile is more or less indistinguishable from the installation in CS14, which has an SPFH4 of 3.5;
- monthly COP for CS14 rises monotonically with heat load factor up to a load factor of 0.3 - at higher load factors, monthly COP falls, perhaps suggesting the onset of electric resistance heating;
- monthly COP for CS18 is more or less flat for load factors between 0.1 and 0.4 - as with CS14, there is a suggestion of onset of electric resistance heating at load factors above this range.

It appears that efficiency could well be a function of load factor, which may be driven by behavioural and social factors, such as a requirement to save energy or reduce high fuel bills, or the use of secondary heating not metered by the heat pump monitoring system, and mediated by the part load performance of the heat pump in question[49]. It appears that this has a fixed speed compressor, but it is not known whether ground loop and primary circuit circulation pumps are fixed or variable speed.

5.4.2 System insulation and heat loss in well-performing cases

The SPF4 values of the 5 well performing cases selected, CS13 (GSHP), CS14 (GSHP), CS18 (GSHP), CS19 (GSHP) and CS20 (ASHP), were 4.2, 3.5, 4.3, 4.1 and 3.5 respectively.

The main physical characteristics of each dwelling, its systems, and discrepancies found when compared with observational data are summarised in Table 5-2.

[49] In the context of condensing boilers, the potential for part load performance to equal or exceed performance at full load was first raised by Pickup & Miles (1977). It then took the gas boiler industry more than twenty years to make this a reality.

Table 5-2. Physical characteristics of the five well performing cases, suspected metering issues and discrepancies found on inspection of data

ID	SPF4 (unadjusted)	HP type	Emitter type	DHW source	Metring error	Ventilation system	Floor area (m2)	EPC band[50]	Annual heat demand] (EPC estimated in kWh)	Discrepancies data recorded on EPC and on-site observations
CS18	4.3	GSHP	Under floor	HP, electric shower	YES	Natural	346	B	20421	HP 4 star[51], EPC incorrectly states that the heat pump is an ASHP, everything 5 star except hot water; EPC recommendation solar thermal, PV, and wind turbine) (now has PVs but were installed Nov 2015)
CS13	4.2	GSHP	Under floor	HP, electric shower	YES	Natural	252	B	20044	4 star, other thermal ratings are also 4 star; EPC recommends solar thermal and wind turbine)
CS19	4.1	GSHP	Under floor +Rads	HP, electric shower	NO	Natural	95	C	17774	5 star partial wall (uninsulated thick stone wall and filled cavity but cavity in kitchen area filled in late 2015)EPC says no floor insulation but occupant said they put in 25mm of polyurethane in 1999))
CS14	3.5	GSHP	Under floor	HP, electric shower	NO	Natural	293	B	16824	4 Star (EPC incorrectly states that the heat pump is an ASHP). EPC recommends solar hot water water to raise the house to an A rating
CS20	3.5	ASHP	Rads	HP	YES	Natural	99	C	9922	No floor insulation

The dwelling characteristics observed and recorded during site visits were compared with EPC reports, and with occupants' statements, to gain an impression of how airtight and well-insulated these dwellings might be[52]. Amongst the five well-performing cases (CS13, CS14, CS18, CS19, and CS20), three out of

[50] Table D4 (Appendix D) shows the issue date for EPC certificates and Table D6 (Appendix D) the HP installation date. For most properties, the EPC was issued post HP installation. The exceptions are CS13 (1980s building with extensions, EPC issued one year before the HP installation) and CS14 (newbuild, EPC issued 3 years before the HP installation).
[51] Star ratings in this table refer to the EPC star ratings for energy efficiency of components (e.g. a heat pump or wall insulation).
[52] None of these sources of information are comprehensive or, in principle, necessarily reliable – see e.g. DECC (2014). The HEG and EPC ratings are produced by different people, with different training, working to different documentation. Inconsistencies are therefore to be expected.

five were large dwellings, over 250 m² floor area, all recently built and well-insulated with EPC ratings of B. The two C ratings (CS19 and CS20) may be underestimates. CS19 is a part-converted Victorian farm building with rendered and wet plastered stone walls approximately 500 mm thickness, with a more recent extension with insulated cavity-walls (polystyrene insulation) and 25mm polyurethane floor insulation – this floor insulation was not noted in the EPC[53]. The walls in this dwelling are likely to be very airtight. CS20 as analysed above is a semi-detached house, which, though well-insulated, has an EPC rating that appears to have been compromised by a poor rating - 2 star[54] - assumed for the ASHP. However, as mentioned earlier, the initial estimate of SPF4 for the ASHP was 3.5, which puts it among a handful of outliers at the top of the distribution – see histogram below (Figure 5-14).

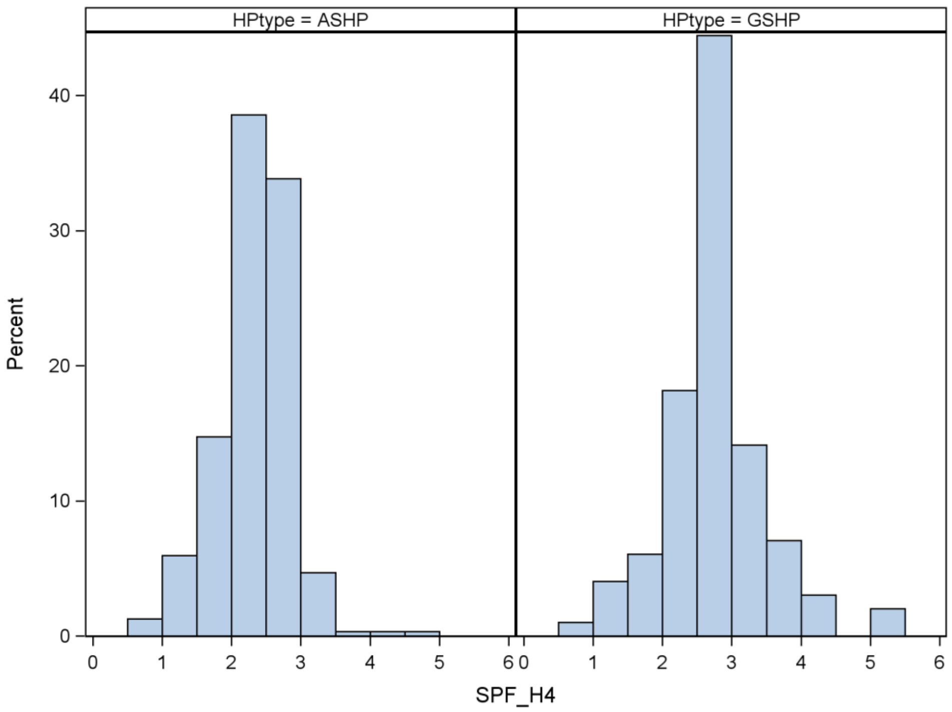

Figure 5-14. Histogram of SPF4 for ASHPs and GSHPs in Sample B2, as defined in the *RHPP Performance Variations Report*.

CS18 has been discussed under Load Factor hypothesis above. CS20 is an ASHP with space heating only – the only case to have been installed in this way. This dwelling and its HP system will therefore be analysed as a single case, in Section 5.4.6. Of the three remaining cases, CS14 and CS19 were judged to have no obvious metering error, and these will now be examined.

[53] This is significantly less than recommended in Part L for new dwellings. Nevertheless, a rough calculation suggests that it would reduce the floor U value by about 40%.
[54] Note that this section refers to EPC star ratings, as opposed to MCS Heat Emitter Guide star ratings.

5.4.3 Well-performing cases without overt metering issues – CS14 and CS19

Of the five well-performing cases, CS14 and CS19 appeared to have no obvious metering issue detected by the quantitative team. The initial estimates of SPF4 for these two cases were 3.5 and 4.1 respectively. On this basis, it was thought that an examination of their characteristics might be useful.

Outwardly, there seems to be little in common between CS14 and CS19 with respect to configuration of physical system and the characteristics of dwelling. CS14 is a single storey dwelling of 293 m^2, designed and built in 2012 by its present occupants. The heat pump was installed when the property was built. CS19 is a two storey house of 95 m^2, built around 1820, extended once in the 1930s, and then again in the late 50 or early 60s. As for EPC ratings, CS14 was rated as B, and CS19 as C. The EPC wrongly recorded CS14 as having an ASHP rated as a 4 star unit. The CS19 EPC rated the GSHP as 5 star.

It was observed on site visits that CS14's HP and cylinder was installed in an insulated garage, whereas the HP in CS19 was in an unheated shed with the cylinder located inside the house. However, **both heat pumps appear to have been competently installed in well-insulated dwellings**.

On closer observation, the difference in dwelling size is probably largely offset by the level of fabric insulation - the annual heat demands estimated by the EPC assessors of CS14 and CS19 are 16,824 kWh/year and 17,774 kWh/year respectively. CS19 differs by the use of underfloor heating downstairs with radiators upstairs, whereas CS14 has underfloor heating throughout. The occupant of CS19 reported that he had planned to install a HP a long time ago, and had thus deliberately oversized the upstairs radiators[55], which had previously been installed with an oil-fired condensing boiler. When he subsequently installed a 9 kW GSHP, the boiler was retained as a back-up system, making this perhaps the only definitive example of a bivalent, dual-fuel system in the RHPP dataset. As observed earlier, both GSHPs were installed with good workmanship, well-insulated external pipework and in CS19, with simple and clearly labelled switches to allow the occupant to switch from HP to back-up boiler. The CS19 occupant stated that underfloor heating was installed with 25mm of insulation located under the ground floor slab. The occupant of this three-bedroom house appeared to use only one bedroom and the bathroom with the other bedrooms on low TRV settings thus limiting the space heating load that was supplied by the radiator system.

5.4.4 Well-performing cases with suspected metering issues – CS13 and CS18

As noted above, the GSHP systems of CS13 and CS18, were both flagged as potentially having metering issues due to heat output with no electricity input for short periods. Despite this, most of the data appears plausible – see Figure 5-15 and Figure 5-16.

[55] This is a clear example of what Schatzki (2002; 2011) refers to as prefiguration.

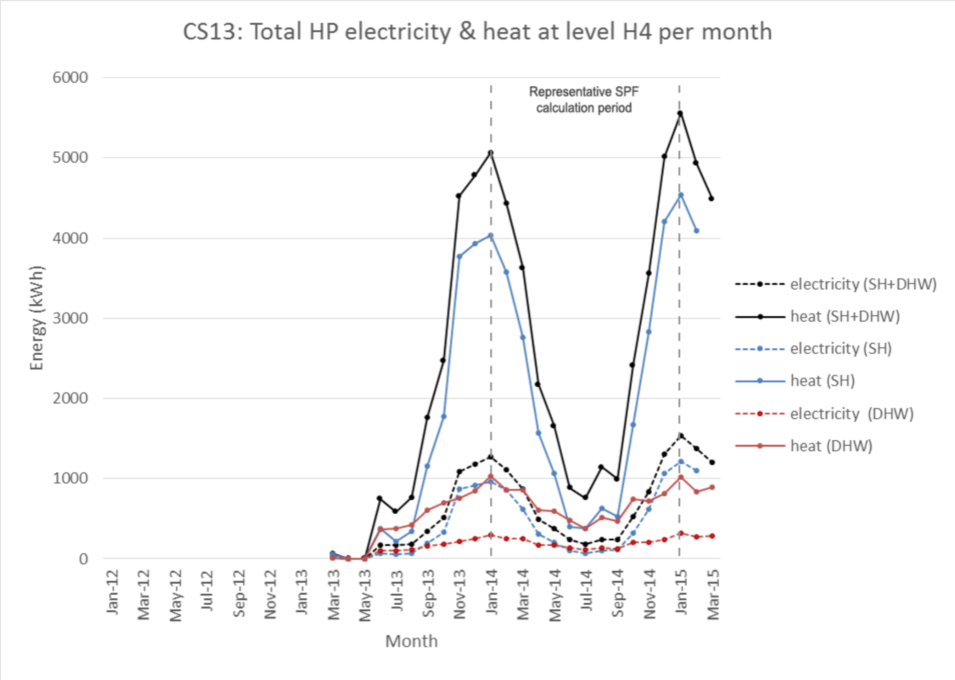

Figure 5-15. CS13 - Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both

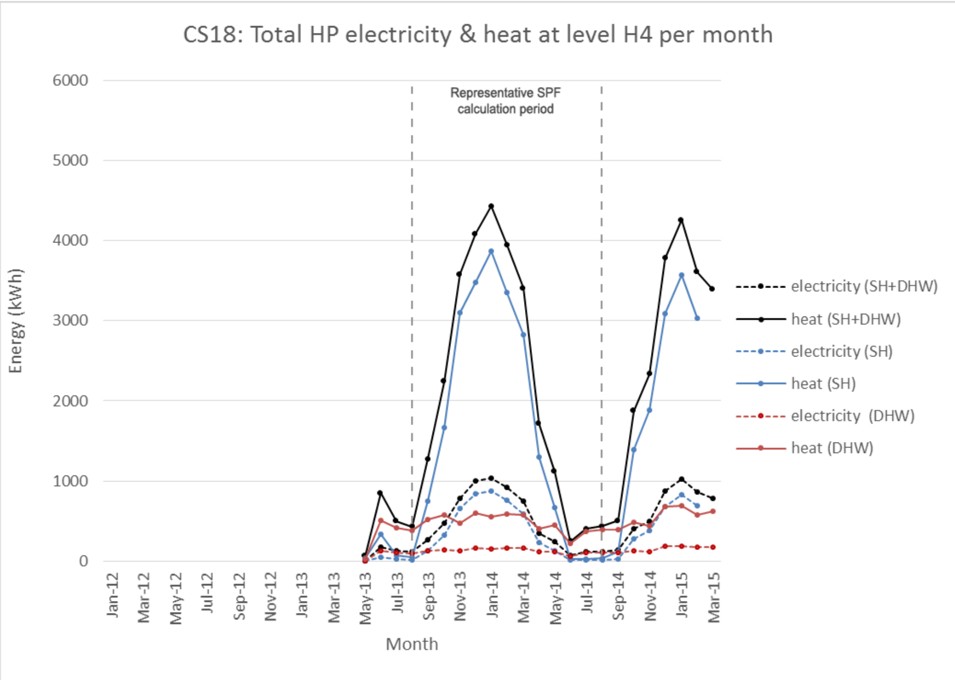

Figure 5-16. CS18 - Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both

The common characteristics displayed by the two cases above are well-configured systems, with good workmanship in well-insulated and reasonably airtight dwellings. It seems these cases have satisfied the first two technical assumptions (i.e. design configuration and installation quality) laid out in the analytical matrix section (see Section 5.3) as preliminary steps to good performance. However, occupants of CS18 did report a recurring "pump motor" problem. They suspected this happened because of power surges during stormy weather. They stated that the first sign of this would be that there would be no hot water. When this happened they would turn the pump off for 10 minutes and back on again. The pump would then work again.

5.4.5 CS20 – a well performing, space heating only ASHP

While CS20 was excluded from the Sample B2) due to suspected metering error, it was selected as one of the five well performing cases based on the preliminary and unpublished data set with a SPF estimate of 3.5. The reason for CS20 not being included in Sample B2 was that from observing the schematic the quantitative team was unclear whether there was a hot water tank associated with the heat pump as the monitored data includes no domestic hot water readings (Figure 5-17). From the metadata and physical data that were available, it was impossible to know whether this was due to missing data or whether the HP was simply not providing DHW for this household. Because this ambiguity could not be resolved, the quantitative team did not include CS20 in the Sample B2.

From the EPC data, CS20 appears to be a reasonably insulated dwelling, with an EPC rating of C. On visiting the dwelling, it was observed that the HP was sited roughly 5 metres from the house, between a brick-built out-house and a timber garden shed. The buffer vessel, circulation pump and metering were installed inside the out-house (see Figure 5-18a,b and Figure 5-19a,b). Pipework, but not pumps and valves in the out-house were insulated with split foam insulation. The buffer vessel is in a DIY insulated plywood box packed with bubble wrap, which would tend to reduce heat loss from connections and fittings to the buffer vessel (the vessel itself would be insulated).

The heat supply pipes running from the shed to the house were insulated with split foam insulation, and run through what appears to be a length of drainpipe, presumably to keep the pipe insulation dry. Despite the *ad hoc* nature of this arrangement, heat loss is likely to be relatively low[56]. Overall, the system could be judged to be moderately well insulated.

Although the initial SPF4 of this system was estimated to be 3.5, the location of the heat meters (near the HP but with the relatively long pipe run into the house) mean this figure may not be fully representative of the amount of useful heat delivered to the house[57]. The radiators were not well sized in terms of star rating.

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[56] The reader should note that there was a range of opinion within the team as to the quality of this DIY installation.
[57] The problem of estimating losses from external distribution pipes was discussed briefly in section 5.4.

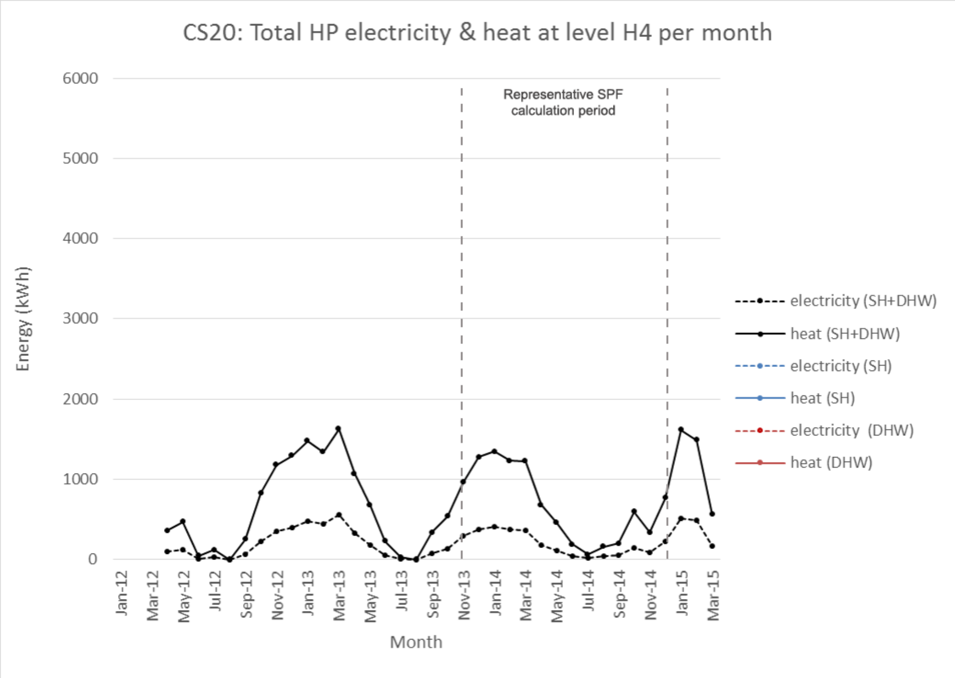

Figure 5-17. CS20 - Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both. Note the absence of data for water heating

Figure 5-18. CS20 - (a) View from the kitchen to out-house and (b) installation of buffer vessels and pipework in out-house

Figure 5-19. CS20 - (a) Buffer tank (with additional bubblewrap to act as insulation) and circulation pumps in unheated shed and (b) location of the shed, to the right of blue door

On visiting the dwelling, it immediately became clear that hot water was provided by a combination of a solar thermal system and an immersion heater (the dwelling also had a PV system). This arrangement predated the installation of the HP. The occupants had retained it, because it worked and it did not seem worth replacing. The occupant explained:

> "When we moved in [2005] there was electric storage heaters which were not particularly useful, there also a wood burner here and an open fire place in the living room with a wood burner, so two wood burners, so talked to people for a few years, we had the [installer] came to us, we wanted a system that we could use PV with, we had the PV installed at the same time so that we could off-set the price of electricity. That is all done in one big job. We put passive solar [thermal] water heating in, that was quite early though because we had that in our last place, we wanted that here as well. Because we had the solar thermal in, so the immersion heater is not running with the heating system. Because we already have passive solar system put in, so we didn't have the water heating system tied into the central heating

system. Because we did that later. So it wasn't worth having the water heater [with the system]. We'd already replaced that with the passive solar, and upgraded the cylinder. There was an option to have the water heater integrated into the central heating but it didn't seem to be much point as it was already working well, we do need to top up with the immersion heater in the winter. [Anyhow], it is only two of us here."

The above interview data clearly explained the seemingly 'incomprehensible' schematic and 'missing data'. At least in this respect, the metadata and physical data were consistent and the monitoring data appeared to be good.

In addition, the predicted annual heat demand in the EPC was 9,922 kWh/year, which is broadly consistent with the annual heat output of the HP, which totalled 9691 kWh between May 2013 and April 2014, and 8527 kWh between May 2014 and April 2015.

The absence of water heating from CS20 confers a significant advantage on this system – much of the complexity of HP systems and monitoring systems arises from the need to deal with both SH and DHW. CS20 avoids all of this. As a consequence, the question about the attribution of heat output simply does not arise. SPF might be expected to be higher in this case than in those systems that provide SH and DHW, because of the higher temperature requirements of domestic hot water and the year-round nature of the demand. This would partially explain the very high (for an ASHP) SPF of this system.

This case shows that evaluation of quality and completeness of physical data simply by 'eye-balling' data and schematics might result in interesting and unusual cases, which in principle have the capacity to extend understanding of the range of possible configurations and performance, being overlooked.

5.4.6 Performance of HPs in social housing

Seven of the twenty-one case studies – CS02, CS03, CS04, CS05, CS06, CS07 and CS08 - were small, single storey retirement homes, operated by two different RSLs. Since CS07 was also the only social housing case within the sub-sample of ten, it was thought that a comparison of CS07 with other RSL dwellings in the wider sample might provide better understanding of this otherwise isolated case.

The physical characteristics of these cases (dwellings and heating systems) are summarised in Table 5-3 below. This table reveals that the common features of the social housing cases are:

- small size – gross floor area ranging from 34 to 52 m^2;
- reported and measured low hot water usage – 4 out of 7 households reported only using hot water from the DHW cylinder for washing up (due to the presence of electric showers);

- presence of wall mounted electric fan heaters located in bathrooms in cases CS02, CS03, CS04 and CS05, and fan convectors fed from the primary heating circuit and located in bathrooms and/or kitchens in CS06, CS07 and CS08);
- SPFs in the range of 2.3 to 3.0 – note, however, that the initial estimate of SPF for site CS07 was 1.5, but the revised value was 2.7, as described in Table 5-3.

Table 5-3. Physical characteristics of the five well performing cases, suspected metering issues and discrepancies found on inspection of data

ID	SPF4		HP type	TFA (m2)	Declared net capacity (kW)	Heat emitter	DHW source	Suspected metering data anomalies (based on raw data)	Suspected metering data anomalies (based on observati on or occupant narration)	EPC	
	Preliminary and unpublished	Representative estimate								Estimated SH demand (kWh/year	Band
CS02	2.3	2.3	ASHP	50	5.5-7	Rads	HP, electric shower	None observed	None observed or narrated	5,276	D
CS03	2.4	2.4	GSHP	50	6	Rads	HP, electric shower	Did not pass sample B2 quality criteria due to missing data (electricity input when no heat output)[58]	None observed or narrated	3863	D
CS04	3.0	3.0	GSHP	52	6	Rads	HP, electric shower	Did not pass sample B2 quality criteria due to heat recorded for DHW but no electricity in	None observed or narrated	4828	D

[58] But see Appendix C for further information on all heat pumps not included in sample B2.

CS05	2.6	2.6	GSHP	52	6	Rads	HP, electric shower	Did not pass sample B2 quality criteria due to heat recorded for DHW but no electricity in	None observed or narrated	4643	D
CS06	2.8	2.8	ASHP	34	5	Rads+ hydronic fan convector	HP	None observed	None observed or narrated	7099	D
CS07	1.5	2.7	ASHP	41	5	Rads+ hydronic fan convector	HP, kettle	Electricity input when no heat output during 01/11/13 – 30/11/14	None observed or narrated	4161	E
CS08	2.4	2.4	ASHP	34	5	Rads+ hydronic fan convector	HP	Did not pass sample B2 quality criteria due to electricity data missing	None observed or narrated	4338	D

There is limited variation in the physical characteristics of these dwellings. CS02 had an ASHP whereas cases CS03, CS04 and CS05 were GSHPs, all of which consisted of integrated HP and DHW cylinders located inside the house. All four dwellings (CS02-05) had external wall insulation applied to previously filled cavity walls.

CS06, CS07 and CS08 had filled cavity walls with externally sited ASHPs feeding packaged hot water cylinders (with all pumps and valves pre-plumbed, together with with HP flow temperature controls), mounted on platforms in cold roof voids. All dwellings in the social housing group with the exception of CS07 had an EPC rating of D – CS07 was rated E.

CS03, CS04 and CS05 were configured in a single short terrace. The GSHPs in these three dwellings had ground loops in separate boreholes. They were also fitted with MVHR systems mounted in the roof voids. CS02, on the same estate, was fitted with an ASHP and an MVHR system that appeared not to be working. The occupant mentioned that somebody had come around and closed the outlets as they were "blowing cold air".

CS04 had had a mould issue above the front door (across the top of ceiling) that had subsequently been treated. At the time of the site visit, the MVHR was on all the time.

CS05 had had mould issues in the bathroom when it was previously used more intensively. The occupant was told to use the MVHR and keep the windows closed. The occupant habitually switched the MVHR on when having a shower and then off afterwards to avoid draughts from the MVHR. CS06, CS07 and CS08 were either mid-terrace or semi-detached bungalows in a single estate in another part of the country. Each of them had an ASHP installed with radiator heating and hydronic fan convectors in kitchen and/or bathroom. The occupants all complained that when they were operating, the fan convectors made them feel colder rather than warmer, and as a result, they were not used.

Three out of the four houses with MVHR reported draughts when the systems were switched on[59]. CS07 was also observed to have a poorly fitted and draughty front door. These were among several features that appeared to contribute to the occupants' obvious dissatisfaction with their HP.

CS02, CS03, CS04 and CS05 had small independent electric showers fitted in the wet room. The HP, by way of its packaged hot water cylinder, supplied hot water to the kitchen sink and wash-basins in the toilet. These dwellings had no bath fitted. Occupants reported using their electric shower daily. During CS02 interview, it was found the electric immersion heater associated with the HP had been turned on without the occupant's knowledge. With very low consumption of hot water, the heat input to the 175 litre hot water cylinder[60] would have been limited to that needed to offset standing losses, and most of this heat would have been provided at close to cylinder thermostat setting. Depending on the precise value of the cylinder thermostat setting, it is possible that the greater part of this heat would have been provided by an immersion heater. This would substantially explain the low efficiency (monthly COP near to 1) for DHW supply in these dwellings.

Figure D 3 toFigure D 16 (Appendix D) summarise the physical monitoring data for the seven social housing cases. Clear differences in DHW profiles can be observed between cases CS02, CS03, CS04, and CS05, which have and use separate electric showers, and CS06, CS07 and CS08, in which the shower is supplied with hot water from the HP.

CS07 was the only ASHP installed in the RSL dwellings in the sub-sample. Despite initial compressor failure and poor system insulation and installation, it had a representative SPF of 2.7. Comparison of CS07 with other RSL cases revealed a number of other physical factors that might influence SPF. In this sector, limited space (35-55m^2 gross floor area) may have been a factor behind the choice of hydronic fan convectors instead of radiators in kitchens and bathrooms (CS06, CS07, CS08). Occupants experienced the air movement produced by these systems as cold drafts, and tended to shut them down. This will

[59] One interpretation of the interview data is that the key to appropriate use of MVHR systems is more effective occupant education and training. However, the authors' suspicion is that many of the problems reported by occupants could be ameliorated by improved design, installation and commissioning of MVHR systems, and attention to air tightness.

[60] This cylinder appears larger than necessary for a 2 person dwelling. A recent study of hot water demand (EST 2008) suggests that such a dwelling would use less than 100 litres of hot water per day.

have reduced the total heat transfer capacity of space heat distribution systems, probably resulting in reduced SPFs. (There was a similar tendency to shut down MVHRs in CS02, CS03, CS04 and CS05). In addition, the amount of heat needed from the HP would have been further reduced in those dwellings fitted with independent electric showers (e.g. CS06, CS07, CS08), potentially further reducing HP efficiency (see figures in Appendix D). Further reductions still in CS03 (SPF=2.3) and CS07 (SPF=2.7) may have arisen from occupants' social and behavioural responses to their systems (see Section 5.5).

5.4.7 Summary of analysis of physical system performance

The starting point for analysis of physical system performance was the assumption, based on thermodynamic principles, that the goal of highest SPF would be achieved by ensuring the smallest possible difference between source and sink temperature i.e. ΔT, through the quality of HP design and installation, and that the most visible indication of this on site would be the quality of planning and insulation of pipework associated with the HP.

It has been found that those cases that performed less well, that is with SPFs below 3, either had external units sited far away from dwelling (e.g. CS09) or potential for restriction of air flow through an ASHP external unit (CS07). Regardless of SPFs actually recorded, it is clear that efficiencies will have been reduced where buffer vessels, immersion heaters and associated pipework were poorly insulated and sited outside the thermal envelope of dwellings, in uninsulated garages, outhouses, or lofts (CS01, CS20 and CS07 respectively).

Examples of unmetered heat losses from distribution pipework between heat pump condenser and heat meter(s) might have been prevented if aesthetic objections could have been overcome and installation quality improved. Four out of the five well-performing cases (CS18, CS13, CS19, amd CS14) support the idea of an association between that well-insulated systems and higher SPFs. However, the counter-examples of CS16 (a poorly-performing but well insulated system and dwelling) and CS20 (a well performing and moderately well insulated system with a long external piperun), show that system heat loss is not the only factor influencing SPF.

Putting aside uncertainties introduced by metering issues, it appears that well insulated pipework may not be the only factor affecting SPF – dwelling heat loss and overall heat demand appear also to be important. Lower SPFs are seen in less well-insulated dwellings: CS07, CS09, CS12 all have EPC ratings D or E. The unusually high SPF value recorded for the ASHP installed in CS20 (SPF=3.5) may have been the result of a heat pump providing space heating only. The analysis of load factors in CS16, CS14 and CS18 suggests that heat pump performance can be compromised by lower than expected heat demand.From this brief description, it is clear that the magnitude of such effects and the pathways by which they become apparent will depend on the detailed configuration of the heating installation (including the heat pump), and of the monitoring system and in particular, on the siting of the heat meter or meters that are used to measure the heat pump's output and efficiency. However, many of these conditions were not so easily observed and the qualitative analysis of the above cases was undertaken with restricted physical data.

5.5 Exploring social and behavioural factors influencing performance

To achieve a comprehensive understanding of HP performance, one has to go beyond system design and physical configuration. This section focuses on social and behavioural context in which these systems operate, starting from the foregoing analysis of physical factors, and drawing on the social and behavioural components set out in the Analytic Matrix (Appendix B). In the course of analysis of previous sections, metering issues affecting 3 out of 5 of the poorly performing cases became better understood, and the SPFs of these 3 cases were revised, thus putting them into the well-performing group. Therefore, the first cut of the analysis that follows is aimed at understanding the remaining poorly-performing cases, CS12 and CS16. This is followed by an analysis of the two well-performing cases, CS14 and CS19 that have no obvious metering issues. Finally, behavioural responses of occupants of CS07, which following detailed analysis has been judged to perform well, are explored within the context of social housing.

5.5.1 Social and behavioural responses in poorly performing cases with metering issues – CS12 and CS16

CS12 and CS16 were both owner-occupied. CS12 was a detached house of 106 m^2 built in 2008/9 under an affordable housing scheme, while CS16 was a recently built farm house of 314 m^2. CS12 had a single occupant whereas CS16 had a couple with long-staying guests during the monitoring period and a couple of dogs.

In response to the interviewers' questions regarding thermal control and ventilation, the occupant of CS12, said the room thermostat was set between 17-18°C (the sunroom being the only room kept at 13-14°C), and reported this is 'rarely overridden'. In winter, the windows were seldom opened whilst the trickle vent in the living room was opened but only for short periods, as it could 'feel draughty very quickly'. Bedrooms and bathroom were aired every morning for 5 minutes.

While the majority of the occupants reported that there had been no change in the controls of their HP during the monitoring period, as touched-on in Section 5.4.2, CS12's booster had, probably accidentally, been turned on by a plumber (see Section 5.4.1), but it was not until a 'huge bill' arrived that the occupant realised there was a problem. It is difficult to establish the causal relationship between CS12's heating practices and the physical and thermal environment from the interview data. The observed low internal temperature might have been a life-style choice (as a single occupant) or a response to a slowly dawning realisation of the size of the electricity bills. Occupant CS12 said that the energy bill was around £1144/year.

On the surface, CS12 and CS16 have little in common except poor SPF4 scores. However, on closer examination of lifestyles and heating practices, CS16 displayed some characteristics that resembled those of CS12. Inhabiting a 314 m^2 farm house built only four years before the interview (2012), with an EPC rating of A, and a GSHP assessed as 5 star, the occupants were surprised to learn, in the course of the case study, that their HP had an SPFH4 of 1.7. But they had themselves noticed, within a year of its installation, that the HP, 'uses too much energy, the [energy bill] goes up hugely during the winter quarter.' The occupants' estimated annual bill was approximately £1900. This high energy bill seemed to have triggered changes in occupants' heating practices, which they described as follows:

> "…up until last year, we used to heat most rooms to 20-21°C, [but] not on high temperature during the night. The HP would come on in morning and afternoon, and setback to [about] 16°C. [We] are trying out different control methods to work out what is going on. Currently [this year] the HP is on frost protection (used for background heating really) in most areas of the house because it uses too much energy." (CS16)

The householders described how, after receiving the high bill, they decided to hire someone to monitor their HP to find out whether there was a problem. At the same time, they consciously decided to use the HP only as background heating and tried out different ways to heat the house. These included: turning down most of the room thermostats to 16°C (exceptions were the hallways and ensuite, which were set at 21°C); having their electric oven turned on at its "snooze" setting (110°C) to provide background, resistance heating in the living room-kitchen; and using two wood burners (one in the snug and one in the lounge) to supplement the heating every night in winter (and during the day if it was cold). Moreover, the dwelling was a farmhouse and the occupants' life as farmers might also help to explain how lower temperatures could be tolerated. At the time of interview, occupants were observed wearing warm clothing[61] inside the house. It was clear that they and their two dogs spent most of their days in-and-out of the house. Despite sophisticated zoning, their external doors were opened and shut quite often, making precise control of temperature in the house difficult. This, coupled with a rather high electricity consumption resulting from frequent use of appliances such as a tumble drier, a dishwasher and a washing machine as well as electric power showers, makes it less surprising that their electricity bill was high. Perhaps, in the light of a growing awareness of the consequences of their lifestyle, the occupants had given up trying to control their internal temperature using room thermostats and were instead 'experimenting' with using secondary heating devices such as the two wood-burners and the oven mentioned above. Some of these changes in heating patterns appear to have taken place after the end of the monitoring period, in particular in the winter 2015/2016, and at the time of the visit, it was still early for the householders to know whether recent adaptations had reduced their bills. But it is likely that

[61] Clothing insulation values (Clo values) are a recognized as affording thermal comfort – see for example, ISO EN 7730:2005 Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

underlying energy use behaviours in this dwelling, such as the use of the Aga, the power showers, tumble dryer and the wood burning stoves, would have pre-dated the interview, and would have affected the use of the HP during the monitoring period. All of this begins to explain why the HP delivered less than 10,000 kWh/year, less than 40% of the 26,269 kWh/year estimated by the EPC assessor for this house.

The load factor analysis of CS14 and CS16 and CS18 presented earlier (see Figure 5-13) suggests that a >60% reduction in heat demand roughly halves SPF, and as a result, probably achieves only a 25% reduction in electricity demand. This single example illustrates, perhaps better than any other case, the potential for unexpected consequences that are inherent in the non-linear behaviour of HPs in dwellings. It is difficult to be sure of the antecedents of the poor performance of CS16's heat pump based on snapshot observational data. However, it appears that it may have emerged from a dynamic process of life-style and heating practices that affected heat load, triggered by the occupants' perception of high-energy bills. In the light of the evidence, two competing hypotheses can be entertained:

1) The metering error hypothesis: the SPF value of 1.7 is incorrect, and the heat pump is efficiently providing heat as demanded, and the occupants have no obvious grounds for dissatisfaction.
2) The heat load hypothesis: the low heat load of the dwelling causes the heat pump to operate less inefficiently. The high energy bill is physical evidence of electricity consumption, part of which can be explained by the HP operating inefficiently at low load, and part, by the implied consumption of electric resistance heating[62].

The potential for complex interactions can also be illustrated by bringing in at this point the problems experienced by CS17. It is clear from the interview data, that amongst the 9 owner-occupiers in the sub-sample, only two, CS17 and CS19, had in-depth knowledge or experience of HPs prior to deciding to install their own system. According to the interview data, the male occupant of CS17 was a physicist. Estimates of SPF4 for CS17 were consistently in the region of 3.1, and there was no obvious metering error. This case therefore represents an opportunity to explore the range of responses open to an occupant with technical knowledge and understanding of heat pumps.

A year after the HP (a 12 kW system) was installed, the householders received "a huge electric bill" following a surge in voltage, which had put the HP temporarily out of order. Having been alerted by the electricity bill, they then discovered that the integral "immersion heater[63]" had come on automatically. They remarked:

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[62] The occupants of CS16 stated that they used their electric oven, a double Aga, on its 'snooze' setting, to provide background heating. A brief on-line search suggests that at this level, the oven might consume around 600 Watts continuously, equivalent to some 5500 kWh/year (roughly half as much heat as the actual output of the HP), at a cost of perhaps £700 - see http://www.agaliving.com/aga-range-cookers/aga-running-costs (accessed 22/10/16). It is likely that the total annual electricity consumption of the Aga would exceed this by at least another 1000 kWh/a, to support cooking.
[63] Occupants' words. This system had an internal resistance heater.

"two years ago, there was a big surge in voltage; I didn't know if the pump was damaged or something else had happened. [The servicing technicians] did some diagnostics, had to follow [the manufacturer's] instructions, they were basically blaming each other. The house was freezing. We had not appreciated how cold it can get with no heat. The immersion heater must have come on automatically; we didn't notice until after a number of days. I checked the smart meter and was surprised with the huge amount of electricity spent; it took three weeks to fix the problem and during that time we kept going with the wood burner and heated the water occasionally with the immersion heater…" (CS17)

The latter part of the above remarks illustrates that the occupant of CS17 was aware of the presence of a resistance heater in the system that had caused the high-energy bill but nevertheless acted in the short term just like CS14 and CS16, coping with the breakdown by using secondary space and hot water heating. But in the longer term, CS17's priority was to identify and then turn off the integral HP booster heater, rather than turning down the temperature setpoint. Without such knowledge, occupants CS14 and CS16 instead appeared to have taken control into their own hands (so to speak) by turning down the heating.

5.5.2 Social and behavioural responses in well performing cases without overt metering issues – CS14 and CS19

Amongst the well-performing cases, CS14 (SPF4 = 3.5) and CS19 (SPF4 = 4.1) were deemed to have no overt metering problems. It is then useful to take a closer look at the knowledge and control strategies of these occupants.

C14 was a newly built 293 m^2 bungalow with two occupants. The heating system was zoned to provide independent control of temperature in all rooms. The occupants had set their room thermostats at different temperatures (most of them between 18 and 20°C) and did not subsequently change them. The much-used living room was set at 20-21°C while the guest room was set at 15°C (although in a separate building above garage). In winter they had their windows and trickle vents shut, and only opened the bathroom window when having a shower. They kept the internal doors of the cooler guest room section shut. Normally, they went on holiday for one month in summer and for one month in winter, and would shut down the HP during these periods. When they had visitors, or when it was particularly cold, they would light up the wood burner in the lounge. They did not apparently use their programmer to control water heating, other than by advancing the programme if they needed more hot water, e.g. when visitors were around. They recalled that there had been a major problem with the HP after installation. Leakage from the ground loop was detected by observing the level of fluid in the ground loop reservoir in the plant room. They dug up one of the two boreholes and thought that they had fixed the leak, but the fluid level kept going down, so they had to dig up the second borehole as well. It turned out that both boreholes were leaking. Although one of the occupants had some technical background, he did not seem to have full knowledge of how to run the HP. When asked if he had changed the operation of the HP or whether he and his wife had made any adjustments to their behaviours after the HP was installed, he replied "No, but [he] would like to have it simulated to find what the optimum system is; it is a slow reacting system, [so one] cannot try something and see immediate results." In conversation with the investigator, he displayed an active interest in knowing how efficiency might be improved. He observed that there was a 1°C difference when he had moved the indoor temperature sensor from the external wall of the utility room to inside the utility room, seemingly suggesting this might make a difference to the efficiency of the system, as this sensor was involved in modulating the output of the HP.

Although this HP achieved an SPF of 3.6, the occupants were the only household in the well-performing group who declined to express satisfaction with their system (they were neutral - neither dissatisfied nor satisfied). This seems to have been influenced by the costs of their energy bill (average £130/month, i.e. approximately £1560/year), which was higher than the occupants expected.

CS14 can be compared with CS19. CS19 stands out as one of the well performing cases in the sub-sample of ten. It was a dwelling of 95 m2 with an EPC rating of C, the oldest part of which had been built, with 500 mm thick stone walls, in the 1820s. The occupant of CS19 was a physicist and widower who had been living on his own since 2013 (he had previously lived in the house with his wife). Although the performance of the dwelling was constrained by its age (a part extended and renovated early 19th Century farmhouse), the occupant had planned the installation of his HP over a long period. Apart from designing the system and overseeing the installation of the HP carefully, as mentioned in Section 5.4.3, he had also found a way to manage the system to his own satisfaction. He explained:

> " …In the first 6-8 months (or even less), I tried to control it as a boiler, with the HP there is a choice of 2-3 heating periods and different temperatures for these periods. There are also different modes available, i.e. auto, holiday, frost protection etc. It turned out that it is less expensive to run [the system] continuously". (CS19)

He said that he had "fiddled" with the controls on rare occasions only and that he did not initially know what the heat settings were as the HP programmer showed just abstract icons (forming a scale); he eventually found out that this abstract scale represented return flow temperature. Since the system had stabilised, he had never changed the HP settings and never turned it off, even when on holiday.

He was very satisfied with his HP. He said it was no [more] fiddly, and produced a better temperature profile if it ran continuously. This had also been appropriate because his late wife had been particularly sensitive to temperature changes. He commented:

> "[It] works well as long as you don't run it in the traditional manner, just leave it on, it does a good job, easier to control than oil boiler once it is set up." (CS19)

The electricity bill for CS19 is £900 per year of which approximately half relates to the HP and the remainder to lights and appliances.

High energy bills were suggested in Section 5.6.1 as a possible trigger of occupants' behavioural responses to their system. However, when comparing all four cases above, it appears that occupants' perception of whether an energy bill is high or not is largely based on expectations since the poorly performing cases CS12 (106 m^2) and CS16 (314 m^2) were paying £11/m^2 and £6/m^2; while the well-performing cases CS19 (92m^2) and CS14 (293 m^2) were paying £10/m^2 and £5/m^2 respectively. The larger dwellings seemed to have a nearly factor of 2 advantage over the smaller ones, as one would expect. Yet, occupants of both CS16 and CS14, regardless of the performance of the heat pump, felt that they had paid too much or a bit too much for electricity, with the former minimising their use of the system and the latter maintained a 'wait and see' or 'neutral' stance when asked whether they were satisfied with their heat pump. CS14's disappointment with their energy bill, while genuine, suggests an unrealistic expectation. Their annual electricity bill is close to the UK median, for a dwelling that is about 3.5 times larger.

The occupant in CS12 was paying £1 more per square meter for electricity than the physicist in CS19. Yet again, their enjoyment of thermal comfort couldn't be more different with CS12 apparently living with heating setpoints of 17-18°C, while CS19 operated his heat pump at a constant room thermostat set-point of 21-22°C.

5.5.3 Comparison of CS07 social and behavioural responses with CS06 and CS08

Amongst the social housing group, CS07 was initially thought to be the poorly performing case, with an SPF4 of 1.5. When subsequent reanalysis showed that a more representative estimate of the SPF of CS07 would be 2.7, it became clear that the three cases in the same estate were also of a similar performance: CS06 had an SPF4 of 2.8, and CS08 2.4. It is therefore possible that exploration of the experiences of CS06 and CS08 alongside with CS07 might shed light on the specific issues observed in CS07.

All the three cases were situated in a social housing estate, which was one of a cluster of small single-storey dwellings managed by the same RSL, with similar building characteristics and heating systems. All had approximately 50 m^2 floor area, and all three HPs were produced by the same manufacturer and were installed around March, 2012. All had radiators controlled via a lounge thermostat, and fan convector(s) connected to the radiator circuit and fed by the HP system fitted in bathroom and/or kitchen.

Compared with occupants of CS06 and CS08, occupant CS07 stood out as a retired engineer who appeared to have some technical knowledge relating to HPs. CS06 stayed at home due to health conditions, and the occupant of CS08 was an elderly person whose daughter visited her every other day.

It is not known how much the initial estimate of SPF (1.5)[64] on the invitation letter to CS07 influenced the occupants' responses to the interview. When asked for his opinion on the quality of the installation, the male occupant remarked that 'HP technology is not rocket science'. The attitude of both CS07 occupants towards the HP appeared to be extremely negative. It transpired that the couple had experience of heat technology and had seen this kind of heat pump before. He remarked that they were just an 'outside refrigerator'.

Compared with HPs installed in the private sector, HPs in the social housing sub-sample were installed in cramped and much needed cupboard space or with hot water cylinders in small lofts, and digital displays that were by-and-large inaccessible. Consequently, the ability of occupants to utilise control devices such as thermostats and programmers might have been curtailed. Among these cases, room thermostat settings varied from 30°C (CS06), 21°C (CS08) down to 17°C at night (CS07)[65].

From the interview data, occupants of both CS06 and CS08 appeared to be aware of their heating patterns and to be able to control their room temperatures through the limited interface available to them - mainly by pressing the 'up' and 'down' buttons on their digital programmable thermostat. Living on his own, the occupant of CS06 was, at the time of the interview, convalescing after an accident. By way of keeping himself warm, he reported leaving the HP 'on all the time' and setting the room thermostat up to 30°C. His HP was programmed to come on between 7:30 am and 11:30 pm in the heating season (October-March)[66]. Sometimes, he would set the system to come on at 8:30 or 9 am if he wanted a 'lie in'.

The occupant CS08 reported that the thermostat and probably timer were on around 6am but, as the occupier stated, she 'doesn't know when it's off'. She thought that perhaps it was on all day. She said that she left the thermostat[67] on at 21°C all the time. However, in winter, she would occasionally put it up to 23°C, usually around tea-time after she had opened her windows, presumably to air cooking smells, then

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[64] Based on the *preliminary and unpublished* dataset (November 2013 – October 2014), the SPF4 for the HP in CS07 was 1.5 but based on Sample B2 (i.e. period with the most complete electricity and heat data) SPF4 rises to 2.7, which is above the median for an ASHP.

[65] Detailed information on thermostat settings in the social housing can be found in Section 4.5.1. and Table D 9 (Appendix D).

[66] Presumably what the occupant meant by leaving the HP on 'all the time', was that there was always a power supply to the HP. But whether it produced heat or not at any given time would have been determined by the combination of programmer and room thermostat. The investigators noted the presence of TRVs on one or more radiators, but not the setting of these devices. But it is likely that their maximum setting would have been less than 30°C, and so the internal temperature in the dwelling would not in fact have been controlled by the room thermostat. It is unclear how much of this complexity would have been apparent to the occupant.

[67] The EPC states that the system was controlled by the programmer, TRVs and a bypass. It appears the EPC assessor had overlooked the room thermostat.

she would put it back to 21°C. The hot water was on the timer, set to come on between 3 and 5am and between 3 and 5pm.

There had apparently been a string of problems associated with the HPs in these three houses about a year after they were installed. All three cases reported that interventions such as replacing the fan of the outdoor unit and adding wall insulation caused untold disruption and discomfort. For example, the CS06 occupant told how the 'generator' (probably the outdoor unit) had 'exploded'. He said that the RSL had told him that the generator was faulty and needed to be replaced. He recalled that at the time the house was 'freezing and [that] 2 bars of the electric fire were used' to keep warm. Subsequently, there had been a blockage in the hot water cylinder and lounge radiator, and the 'heating went off [again] in winter'. In addition, the fan convector in the bathroom had broken down. His friend found something wrong with the thermostat setting and re-adjusted it. The occupant also saw a 'damp patch' coming out of the outdoor unit, causing the patio to be quite slippery. The occupant appeared unaware that the damp patch resulted from condensation dripping from the evaporator and from defrosting. The dip in electricity in February 2013 in Figure D 12 (Appendix D) probably reflects the story told by CS06.

The occupant of CS08 told a similar tale. One year after HP installation, around February or March 2013, the HP broke down. She was told that the 'motherboard had gone', and 'the technicians came and changed the whole lot'. This was around March 2013: they said it would take 2-3 weeks for a replacement, then went off and then they said it would take another 4-5 weeks'. The occupant ended up staying at her daughter's during that time. After that, she had experienced no further problems until she complained of water dripping from the outdoor unit. Then, she had to wait 7 months for a drip tray to be installed to catch water coming out of the outdoor unit. The officer from the RSL said that there was a drain pipe but that it was not connected.

The CS07 occupants also recalled that there were many problems with their HP started approximately 12 months after it was installed, and that it eventually 'burnt out'. The male occupant remarked:

> "In around February, 2013, the RSL brought a new fan unit in and the technician reset the whole thing. There was another one [technician] that came and dug it up and said it [was all] good but it still does not heat the house, every night at 5pm the heating would go off." (CS07)

The male occupant of CS07 said that the installer could not resolve this problem but said everything 'looked OK'. However, the occupants found that they had no space heating after one of the occupants had a bath. They suspected that the bath had drained all the water out of the cylinder and the HP then switched to supplying hot water, because this was set as the priority. Trying to find a reason for the failure of heating to come on, the technician then suggested that the standing lamp was placed right next to the thermostat, thus causing the system to turn-off. The occupant of CS07 said the HP eventually 'burnt itself out'. He reported that the reason given by the technician was that the flow temperature was set too high.

The male occupant of CS07 reported that their DHW heating pattern had changed after the replacement HP was installed. Before the replacement, they used to heat up the cylinder twice a day (9-10 am and 3-5 pm), but they found that the HP could not provide sufficient DHW and SH at the same time. In response, the technician changed the programmer so that the hot water came on only once a day between 1-3am, when it would have been unlikely that the HP would have also been providing SH. The SH was set to come on between 5am and 9pm at 21°C, and setback to 17°C at other times. However, he noticed that it took at least '4 hours' i.e. not until 9 am, for the dwelling to reach 21°C. He and his wife realised that the heating could not come on quickly - 'no quick fix'. For this reason and to save energy, they put the thermostat setting down slightly when not at home and they never put it any higher than 21°C.

Although no changes of control behaviours were reported by occupants of CS06 and CS08 after the disruptions, there is evidence to suggest that their enhanced awareness of the immersion heater or booster and the expenses incurred if it were used to provide DHW or SH, affected how they interacted with the system. It was clear that the CS06 occupant was aware of the existence of the immersion heater and that its use could be costly. He said that he had never used it 'unless in an emergency'.

Both occupants in CS07 were completely unaware of the existence of the immersion heater. When the investigator pointed it out to them, they said that they had never used it. They attributed the breakdown of the HP to the high setting of the DHW temperature (66°C) as they believed that it was set to 'override' the immersion heater. They referred to the instruction manual which stated that:

> 'if there was an immersion heater, the DHW temperature should be set at 60°C. But if there was no immersion heater, it should be at 66°C.' (CS07)

This suggests that CS07 had a misconception of how the HP works, or of the relationship between the immersion heater and the HP, which may have been reinforced by an incorrect statement in the instruction manual.

In the course of the interview, the occupants expressed deep dissatisfaction with their HP. Not only had there been a lot of problems associated with it, but they also found themselves paying a high bill in the first year i.e. £782 in 2013. The bill was lower at £572 in 2014 and up to the time of interview (close to the end of 2015), they had paid £620. They said that, 'if they set the temperature higher, they won't be able to pay the bill'. The occupants seemed to have developed a number of behavioural strategies for keeping warm at 'lower cost'. They remarked that although they had an electric fire, they never used it, even when the HP had broken down, because it 'would cost too much run'. Because the house was draughty, they shut their lounge door to keep warm. When they wanted to use the computer in the bedroom, they would put several layers of clothing on because it was cold in this room. In terms of the use of hot water, they reported they would normally have two showers per day as well as washing dishes. However, they were not confident the HP would provide sufficient hot water to cover their needs. Remarking on how they did not use hot water from the HP for dishwashing as they 'wouldn't know what the situation would be', they described how they managed their daily hot water usage. Because the kitchen tap was furthest away from the tank, 'it [would] take several minutes to reach the tap. Using the hot water from the HP for dish-washing is not only wasteful but also would drain all the hot water out of the tank, so 'to be safe' they 'boiled a kettle instead, [even though] it costs a lot'.

Figure D 14 (Appendix D) shows modest hot water heating demand between September 2012 and February 2013 and associated electricity input roughly a factor of three less – but both with very high seasonality. Then, from March 2013, at about the time the replacement HP was installed, both hot water heating and electricity input fell to close to zero. This change may be associated with an unmetered immersion heater taking over the function of hot water heating.

The most obvious feature is a spike in electricity input for space heating between November 2013 and March 2014, leading to a monthly COP of less than 1. The high electricity consumption however does not appear to coincide with the period of interruption as reported by CS07 occupants.

The CS08 occupant narrated similar problems. She found, in November 2015, that her immersion heater was on and had been running without her being aware of it. She recalled:

> "The RSL put in a new kitchen and bath [around Feb, 2014]. There was a power cut, then the electric was on and off for three weeks due to renovation. We [the occupant and her daughter] noticed there were two lights in the cupboard but were not sure what that was until the electricity bill showed a huge increase." (CS08)

They couldn't get anybody to understand the problem: one particular technician was knowledgeable but the rest were not. The technician found no fault in the system but thought the whole system had reset itself and the immersion heater had come on[68]. CS08 asked the council for a refund but was refused. Because of this mishap, the normal payment of direct debit of £45 per month had been increased to £75/month to cover the accidentally high consumption brought on by the immersion heater[69].

The monitoring data for CS08 (Figure D 15 and Figure D 16 or Appendix D) shows two anomalies. The first one between September 2012 and March 2013, is almost certainly associated with the failure of the outdoor unit. The second is the emergence of a new profile for electricity and heat output between September 2014 and March 2015 (when the monitoring ended). It is unclear whether the latter was

[68] An external reviewer confirmed separately that this was possible with some HP systems.
[69] It is not clear how long the problem persisted but it was later resolved.

associated with the installation of the new kitchen and bath that the occupant describes as having taken place in February 2014, i.e. the occupant thought the booster heater might have been left on by mistake by the renovation team.

Despite the fact that after discounting the period of interruption, CS07's HP was estimated to have had an SPF4 of around 2.7, the problems with 'faulty' HPs and various interventions appears to have affected this household more than CS06 and CS08. Taking the revised SPF at face value, occupants of CS07 should have enjoyed similar comfort and satisfaction as CS06 and CS08, but instead, they suffered cold draughts and discomfort, felt that they had paid too much for too little, and that they were at risk of not being able to pay at all. They would have preferred to have had their 'more controllable' Economy 7 storage heaters back and constantly compared their system with the gas central heating system of their relatives across the road.

The experiences of the above occupants suggest that a combination of physical, social and personal factors are at work to produce responses that could influence not only the 'performance' of the HP but also the occupants' thermal comfort and satisfaction with this technology. Simply, factors such as the common knowledge that electric heating is costly, the perception that the HP could not sufficiently and/or simultaneously provide both SH and DHW, and the reality of a high energy bill, have the capacity to trigger behavioural responses such as that of CS07, setting a lower thermostat temperature to avoid a high energy bill, and relying on electric kettles, or other forms of secondary electric resistance heating, thereby defeating the objective of introducing the HP in the first place.

A HP as a heating system is very different from common gas central heating, or other oil or electric heating (i.e. storage heaters) systems. Good design, installation and initial commissioning of the system are important, as these physical arrangements prefigure the trajectories of occupants' responses to the heat pump. In the case studies presented above, one can observe several different examples of how occupants' technical backgrounds might have contributed to their embracing or rejection of this technology. The two extremes are represented by CS19 and CS07 respectively. Although no single simple and direct pathway to performance can be traced through the above exploration, it is clear that a HP is a complex piece of technology, and that occupants' understanding and management of it plays a vital part in its performance.

6 Methodological strengths and limitations

This field study has utilised the multiple case study method to address some of the issues raised by the statistical and technical analysis of HP performance. Case studies are used for a variety of subjects, but this appears to be the first evaluation of a heating technology at this level of detail.

The study has also provided an opportunity to develop a broader understanding of the HP performance beyond thermodynamics and to reveal a phenomenon that is clearly socio-technical in nature. The richness of the results produced is evident. The method reaches the parts that statistics alone cannot reach, generating a concept of performance that is nuanced and hypotheses that have potential to guide further research. The fundamental strategy adopted in this work was to use physical observations to guide selection of cases, and to constrain analysis and interpretation of interview and other data collected on site.

As far as the authors are aware, the application of the case study approach in this way to understand the technical performance of a technology in a multi-disciplinary context is unique. Methodologically, the field study research design was compromised because of its subordination to the statistical analysis. The short time frame for project completion has meant that the study was implemented as a mixture of sequential explanatory study and a concurrent study in relation to the statistical study of performance. This has made comparing data and triangulating results as well as their interpretation difficult.

Apart from design weaknesses, this study has revealed some practical issues around the implementation of mixed methods. Awareness of these issues might help researchers or evaluators who wish to use this method in a future to improve the quality of the evidence gathered, and thus in turn improve the repeatability of such a study. These weaknesses include:

- The limited time allocated for site visits - it was difficult to gather both physical and social data in only two hours;
- Managing expectations of occupants - these ranged from not wanting us to record the interview or to take photographs, through to expecting investigators to solve problems of poor performance during the site visit;
- Difficulty accessing cylinders and controllers, e.g. when located in limited spaces e.g. attics or small cupboards;

- Potential unreliability of data. The interview data in this retrospective study required occupants to recall events and dates two to three years prior to the interview.

- Unavailability of crucial documentation about systems and sub-systems e.g. ground loops, underfloor heating systems and detailed building specifications that are necessary for calculation of individual room heat losses and to corroborate interview data.

A fundamental problem with socio-technical case studies is that occupants' statements cannot necessarily be taken at face value. Memories fade, particularly with respect to precise timing of events. More importantly, occupants' interpretations of events are unlikely to be expressed in precise technical language and be based on misconceptions about their heating systems. Under these circumstances, the task of the researcher is to report what has been said, without placing more weight on it than it can bear.

Despite these limitations, this field study has provided a vast amount of data of many different types. The limited time and resources available for this report mean that it does not do justice to the data collected.

7 Summary and conclusions

The case and cross case comparison of the field study relied heavily upon data generated by site visits and site schematics, electricity consumption data and MCS certificates, together with EPCs. Uncertainties regarding data quality and sufficiency, together with the dynamic nature of heat pump performance, affected all stages of case and cross-case analysis. Monitoring issues unfolded throughout the course of analysis, affecting the intended criteria of sub-sample selections i.e. well and poorly performed heat pumps, thus making causal inference difficult. Changes in the sampling of the physical data resulted in changes to the SPFs that most usefully represent three of the five poorly performing heat pumps; and these changes were corroborated by the occupants' accounts, as well as photographic evidence. In consequence, the analysis process changed from comparing and contrasting groups of well and poorly performing cases, to comparing cases on a gradient of performance. Conclusions drawn from this analysis, particularly those that relate to performance, should therefore be considered as tentative, pending further investigation.

7.1 Heat pump performance

Based on a set of socio-technical assumptions, the analysis began with an initial set of hypotheses. The first of these was of a relationship between system insulation (external and internal), planning of pipework, and performance. The procedure then was to attempt to use case comparisons to test and/or verify this hypothesis, drawing on all of the available data. Analysis of the five well-performing cases, CS13, CS14, CS18, CS19 and CS20, suggested that well-insulated systems tended to be associated with higher SPFs. This was further confirmed when the estimate of SPF for CS15 (a well insulated case) was revised from 0.7 to 3. But it was challenged by CS16 - a well insulated system and dwelling, but with an SPF of 1.7 - leading to a much more complex analysis that involved comparison of heat load and performance of similar types of dwellings in the sub-sample.

It is generally recognised that heat pumps are likely to perform better if dwellings, heat pumps and heat emitters are well matched. In the absence of detailed surveys of case study dwellings, EPCs and MCS certificates were the only source for estimates of heat demand for analysis of cases. However, discrepancies were found between the data collected on site visits and EPCs. Specifically, in the sub-sample, it appears that EPCs may have been based on underestimates of the insulation standard of some of the dwellings (e.g. CS07, 09, 12, 19, 20). For example, CS19's solid floor was mistakenly assumed to have no insulation.

Practically, the installation of heat pumps in poorly insulated dwellings is challenging because of the resulting size of heat emitters. Local defects in the thermal envelope potentially add an extra layer of complexity, seen most clearly in CS07 as the result of an ill-fitted front door. Regardless of the performance of the heat pump, such defects make it difficult to maintain comfort in the dwelling, and may directly and indirectly increase annual energy bills for occupants. In this context, it is possible that occupants may conflate problems arising from systems, such as MVHR, installed at the same time as heat pumps, with the performance of their heat pump.

Section 5.4.1 presented an analysis of load factor and monthly COP for three comparable newly built dwellings, CS16, CS14 and CS18, of similar sizes, and with EPC ratings A, B and B respectively. This suggests that the issues at play are not purely technical. In CS16, an A rated dwelling built in 2011, heat load was evidently a socio-technical composite, and the efficiency of the heat pump in this case was influenced by a complex web of life-style choices (an electric Aga, power showers, use of wood-burners) and perceived high energy bills. Both CS09 and CS16 highlight the importance of the understanding not only the physical factors that contribute to the performance of heat pump but social and behavioural responses of occupants that might affect both performance, thermal comfort, and user satisfaction.

The role of electric resistance heating is, unsurprisingly, a theme that runs throughout this analysis. In general, it is observed that resistance heating can be triggered both by physical and social factors. Specifically, automated or integrated resistance heater units, and the unexpected and in some cases, undetected switching on of booster or immersion heaters (CS08 and CS12) can increase resistance heating, in turn reducing SPF and increasing bills. This is particularly problematic where occupants are unaware of the presence of such systems or lack knowledge of their potential effects (e.g. CS02, CS12, and CS16).

There is ample, if circumstantial, evidence within this report to suggest that resistance heating is associated with higher energy bills. While these bills might or might not be an accurate reflection of occupants' use of electricity, occupants do react to them. In some of the cases (e.g. CS07, CS08, CS12, CS17), occupants reported various mishaps - malfunctioning heat pumps or boosters being turned on by installers or as a result of storm-induced power surges – that may have contributed to high energy bills. Amongst some of these occupants, awareness of the consequences of resistance heating seems to have helped them to deal with issues in a more positive way, e.g. CS17 by getting technical help from installers or manufacturers, rather by turning down the heat, and enduring thermal discomfort (CS07, CS12). Conversely, some occupants adopted ad hoc energy saving strategies - using an electric Aga as background heating (CS16), using a kettle as an alternative to the HP for heating hot water (CS07) – which may have set off a negative cycle of behavioural responses to physical systems that may have increased their use of electricity, and in CS16, appears to have lowered the efficiency of their heat pump.

Moreover, even in well performing HPs, there is evidence of electric resistance heating at work – see CS14 and CS18. The implication of this may be that even better performance could be achieved with improved control of boost and immersion heating. Manufacturers might wish to consider how control systems might be designed to alert occupants to the operation of immersion heaters and integrated boosters, so that they can either make appropriate adjustments themselves, or seek advice and help to put the system right.

A key insight into issues associated with retrofit of heat pumps into existing systems is provided by CS19 and CS20. In CS19, considerations of cost, practicality and resilience resulted in the retention of an existing oil-fired boiler and its integration with the new heat pump resulting in a bivalent heating system. CS20 suggests the potential for simplifying HP design, installation and operation, by providing water heating separately. This strategy appears to have resulted in operational stability and very high SPF for an ASHP, though one with limited applicability, and with the potential to increase overall capital cost, overall electricity consumption and load on the grid in the winter.

There is some evidence to show that occupants who were technically knowledgeable (the sample included two physicists[70], CS17 and CS19) did better. CS17 actively managed the system on an on-going basis. CS19 was perhaps more interesting still: after a period of experimentation, the householder chose to operate the system continuously (including when he was away), and as a result enjoyed better thermal comfort and greater satisfaction with minimal effort. However, this finding should not be generalised to all properties. Future studies could investigate the most appropriate control methods for different household preferences and dwelling types.

With the exception of CS07, CS14 and CS16, most occupants were satisfied or very satisfied with their heat pumps. The case studies revealed the complexity of the notion of satisfaction, which included the level of thermal comfort felt, running costs, ease of use, environmental impact, technical integrity, noise levels and controllability of the system.

The case that stood out was CS07. Much of the scientific value of this case lay, paradoxically, in the deep dissatisfaction of its occupants, which prompted the decision to extend detailed case analysis to all social houses in the case sample. Although none of the seven social housing cases were assessed as poor performers, four appeared to exhibit significant resistance heating for most of the monitoring period, despite relatively predictable heat demands due to simple built forms and demographics. Despite significant disruptions (HPs in CS06, CS07 and CS08 had experienced break downs), six out of seven occupants were satisfied with their new heating systems, because they considered them to be cheaper and less troublesome than the electric storage heaters they had had previously.

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[70] The proportion of physicists in the population as a whole is roughly one in 400. The *a priori* probability of a randomly selected sample of 50 people containing two physicists is less than 1%.

This should serve to encourage RSLs who wish to provide renewable heat to their housing stock. However, the occupants' experiences of initial problems with their heat pumps, which resulted in periods of high electricity bills, should be taken seriously. There is a risk that initial poor performance, particularly if associated with slow and ineffective response to complaints, entrenches a level of dissatisfaction that is subsequently difficult to change. This maybe exacerbated by feelings of powerlessness and the consequences of fuel poverty in this vulnerable segment of the population.

The performance of HPs defined by SPF is subject to a double contingency: on one hand the interactions between the physical and the social that influence performance, and on the other, issues around remote monitoring practices and technologies, and technical/scientific judgement by which performance is quantified. Despite the complexities and contingencies, this study has revealed that resistance heating and heat load are two significant issues that require attention if performance of HPs in operation is to be improved. These two issues, though at first sight physical in nature, emerge from physical and social substrates that cannot be easily disentangled. Though constrained in terms of both resources and time, this study has generated a number of insights and hypotheses which may provide the focus for future studies.

7.2 Lessons for future case studies

This report illustrates the ability of case studies to add significant value to field trials of HPs and other energy technologies. The case studies reported here shed light on design and installation of HPs, installation of monitoring systems, operational issues, incidence and nature of faults, and occupants' satisfaction with their systems.

The value of case studies lies in the close examination and detailed understanding of individual cases – a case study is not a small field trial. The flexible nature of case study methodology lays the research team open to the unexpected to a greater extent than other approaches. In the present study it enabled issues – such as the effect of load factors on SPF, the complex nature of occupant satisfaction and the presence of a gas supply in four of the case study dwellings - to emerge in ways that would have been unlikely or impossible through statistical analysis of data collected by remote physical monitoring alone.

A critical decision in the design of field trials is the number of cases that are to be included. This must be considered together with the issues that are to be explored and the resource that is available. One of the mistakes often made by researchers new to case studies, is to take on too many cases, sometimes with the aim of undertaking statistical analysis within the sample of cases in pursuit of a narrow interpretation of generalisability.

Much of the work on this case study was undertaken by an architect and a heating system engineer, with support of an experienced social scientist. But it also required other members of the consortium, whose main focus was analysis of monitoring data, to provide supporting data and analysis. The resource implications of such support were underestimated in this study. The research team set out to study twenty cases, with one additional case undertaken as a pilot. But resource limitations meant that detailed analysis was initially undertaken on a sub-set of just ten cases.

Case studies can support large scale, predominantly quantitative, statistically oriented field trials in at least two ways. If undertaken during the installation of monitoring equipment, they can help to improve the quality of both metadata and data collected by remote monitoring systems. If, as in the study reported here, they are undertaken after the onset of physical monitoring, they can make use of insights from monitoring data to suggest lines of enquiry for site visits and subsequent analysis. In this study, the value of such insights was limited by the quality of monitoring data available. High quality monitoring data is as important to mixed methods case studies as it is for the conduct of large scale, predominantly quantitative, statistically oriented field trials of new energy technologies.

One of the lines of inquiry of this case study was to explore the relationships between dwelling heat load, heat transfer capacity of the heat distribution system, and heat pump capacity. It transpired that to fully achieve this would have required significantly more resource and time on site than was available. There is a possibility that longer site visits would affect the number of households that would be willing to engage with a future research team. It is possible that this could be mitigated by requiring recipients of subisidies for new technologies to indicate their willingness to engage with a future research project, should one be commissioned. This should include the option of additional contact with dwelling occupants to resolve questions that emerge after an initial site visit.

The above lessons for case studies can be summarised as follows:

- socio-technical, mixed methods case studies are likely to add significant value to any field trial of new energy technologies;
- depending on the design of the field trial, and specific objectives case studies can be undertaken either during the installation of monitoring equipment, or after the onset of physical monitoring;
- a third, more ambitious option would be to undertake longitudinal case studies, which follow individual cases from recruitment into a programme, through design, installation and occupation – if adequately resourced such an approach has the potential to provide very rich insight into the multiple factors at work in the performance of energy technologies;
- case studies should examine numbers of cases appropriate to research objectives and available resources – except in very unusual circumstances, no more than twenty;

- the value of case studies is likely to be significantly enhanced by the availability of high quality physical monitoring and energy bill data.

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Appendix A – Communication to Case Study households

A1 Cover letter to private householder

A2 Cover letter to social landlord

A3 Invitation letter to private householder or social tenant

A4 Information sheet

A5 Consent form

A6 Topic guide

A1 Cover letter to private householder

RE: DECC Study of Heat Pump Performance (Renewable Heat Premium Payment Scheme)

Dear [NAME]

I am writing on behalf of Penny Dunbabin, Senior Scientific Officer of DECC's Technical Energy Analysis Team. We would like to thank you for taking part in the DECC study of heat pump performance as part of the Government's evaluation of the Renewable Heat Premium Payment (RHPP) Scheme. Following a period of data collection and analysis, we are now in a position to inform you, and others who took part in the research, of the initial results of investigations and in particular how your heat pump compared to others that were supported by RHPP funding.

Please see attached for:

- a summary of your heat pump's performance
- an invitation asking you to provide consent for the investigation of your heat pump installation for research purposes.

Many thanks for help in advance.

Kind regards,
[NAME]

A2 Cover letter to social landlord

RE: DECC Study of Heat Pump Performance (Renewable Heat Premium Payment Scheme)

Dear [NAME]

I am writing on behalf of Penny Dunbabin, Senior Scientific Officer of DECC's Technical Energy Analysis Team. We would like to thank you for taking part in the DECC study of heat pump performance as part of the Government's evaluation of the Renewable Heat Premium Payment (RHPP) Scheme. Following a period of data collection and analysis, we are now in a position to inform you, and others who took part in the research, of the initial results of investigations and in particular how your tenants' heat pumps compared to others that were supported by RHPP funding.

Please see attached for heat pump performance summaries for each one of the following properties monitored:

[PROPERTY 1]
[PROPERTY 2]
[PROPERTY 3]

Forwarding attachments to tenants

Should you consider it to be appropriate, we would greatly appreciate it if you could forward the attached summaries ASAP to all properties mentioned above to:

- inform tenants of their heat pump's performance and
- invite them to provide consent for the investigation of their heat pump installation for research purposes.

Should you not be able to contact some/all of your tenants above, we would be grateful if you could also let us know by contacting Penny Dunbabin at penny.dunbabin@decc.gsi.gov.uk

Many thanks for help in advance.

Kind regards,
[NAME]

A3 Invitation letter to private householder or social tenant

Department of Energy & Climate Change
3 Whitehall Place,
London SW1A 2AW

Email: penny.dunbabin@decc.gsi.gov.uk

www.decc.gov.uk

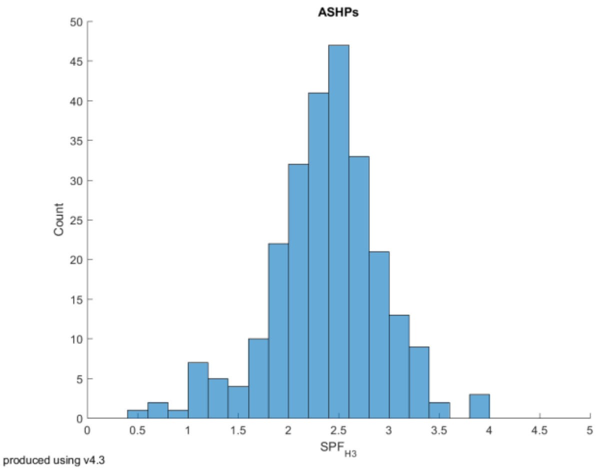
[NAME]
[ADDRESS]

[DATE]

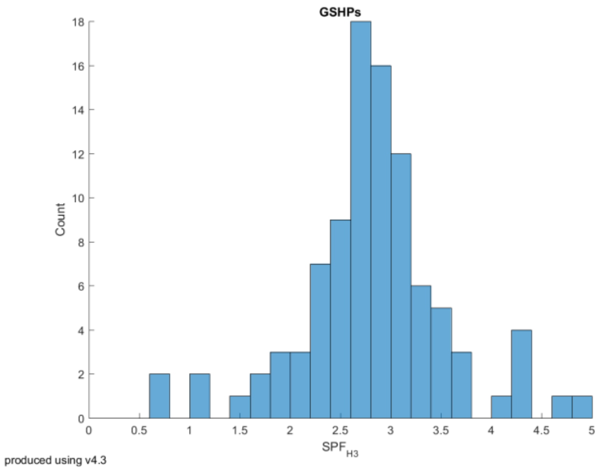
Dear Householder

Thank you for taking part in the DECC study of heat pump performance as part of the Government's evaluation of the Renewable Heat Premium Payment (RHPP) Scheme. Following a period of data collection and analysis, we are now in a position to inform you, and others who took part in the research, of the initial results of investigations and in particular how your heat pump compared to others that were supported by RHPP funding.

We monitored a total of 703 heat pumps, of which 230 were in privately owned properties and 473 properties in the Registered Social Landlord sector. In total, we monitored 530 air-source and 173 ground-source heat pumps. Good quality data was obtained for 351 heat pumps.



Air-source efficiency (SPF_{H3})



Ground-source efficiency (SPF_{H3})

The distribution of annual heat pump efficiencies in the trial is shown in the figures attached. An efficiency of 2 means that for every one unit of electricity used, two units of heat are provided (one from the electricity and one from the air or the ground). An efficiency of 3 means that for every one unit of electricity used, three units of heat are provided, one from the electricity and two from the air or ground.

The efficiency of your heat pump was [SPF3] over the period 01/11/2013 - 31/10/2014. Your [HEAT PUMP TYPE] was in the [% RANGE] of the 351 heat pumps, for which we have good quality data.

Please note that this efficiency is a combination of the efficiency for SH (from radiators or underfloor heating) and the efficiency for DHW heating (for showers, taps, etc). For comparison, the efficiency of a new gas or oil boiler is estimated at about 0.85.

The efficiency of your heat pump depends on a number of factors, including the quality of the basic product, the way it has been installed and the way in which it is used and operated. An efficiency in the lower end of the range of measured values does not necessarily mean that your heat pump is working incorrectly. This may be due to choices you have made about your installation and the constraints of your home and existing heating system (e.g. radiators). If you are unsure whether your heat pump is working as it should you can talk to your installer.

Our study also examined the common reasons for poor performance, which are mostly related to:

- High flow temperatures (heat pumps are more efficient when they supply low temperature heat at a continuous rate and for a long period, rather than when they supply high temperature heat). Large, modern radiators, hydronic fan radiators or underfloor heating allow the use of lower temperature heat and make the heat pump more efficient. Some householders have chosen not to upgrade their radiators and, as a result, the heat pump supplies heat at a higher temperature and lower efficiency.
- Excess use of the immersion, rather than the heat pump, to heat the DHW. This is usually due to incorrect set up or incorrect use of controls.
- Incorrect set up of weather compensation, which means that the heat pump may supply heat at a higher temperature than required when the weather is relatively mild.

One of the requirements of the RHPP programme was that installers must be registered with the Microgeneration Certification Scheme (MCS) or an equivalent scheme. If you are unhappy with your heat pump's performance, for example if it was not what you were expecting based on what your installer told you, or to find out more about how you could improve it, we suggest contacting your MCS accredited installer if you have not already done so. Contact details should be on the documentation you received when your heat pump was installed. If you are unsatisfied with their response you can also consider using the MCS complaints process to resolve issues with the installer, further information can be found on the MCS website: http://www.microgenerationcertification.org/about-us/contact-us.

Your consent is required for research purposes:

As part of the study, we would like to investigate a small sample of heat pumps. This would entail a visit by two researchers from University College London, who are under contract to DECC. The researchers would examine the installation and operation of the heat pump and radiators and ask you a number of questions about your patterns of use, satisfaction with the system etc. A separate study, involving additional visits of the same nature may be planned via a Reputable Academic Body. All visits will take place between 01/11/2015 – 23/12/2015. Would you be prepared to get involved through (a) DECC and (b) a Reputable Academic Body?

If you are willing to participate, please contact me, Penny Dunbabin, at:

penny.dunbabin@decc.gsi.gov.uk.

We would like to thank you for your participation in this study.

If you have any queries about the contents of this letter please submit these by email for the attention of Penny Dunbabin at penny.dunbabin@decc.gsi.gov.uk.

If you have questions about the RHPP more generally, please contact rhi@decc.gsi.gov.uk.

Yours faithfully

Penny Dunbabin

Technical Energy Analysis Team

Department of Energy & Climate Change

A4 Information sheet

Information Sheet for Participation in
Site Visits and Interviews as part of the Renewable Heat Premium Payment (RHPP) scheme project on behalf of the Department of Energy and Climate Change (DECC)

<u>You will be given a copy of this information sheet.</u>

Title of Project

Analysis of data from heat pumps installed via the Renewable Heat Premium Payment (RHPP) scheme to the Department of Energy and Climate Change (DECC)

Research Ethics

This study has been approved by the UCL Research Ethics Committee (Project ID Number: 6268/002)

Researcher's Details

Name	Ms Eleni Oikonomou
Work Address	UCL Energy Institute, Central House, 14 Upper Woburn Place, WC1H 0NN
Contact Details	020 3108 5967

Research Project Description

The UCL research team, on behalf on behalf of DECC would like to invite you, ……………………………………. to participate in the folllowing research project.

As part of the project analysing data from heat pumps monitored through the Renewable Heat Premium Payment (RHPP) scheme, the Department of Energy and Climate change (DECC) have appointed a research team from University College London (UCL) and University of Westminster (UoW) to undertake a number of case studies (sites visits and interviews) in dwellings previously monitored as part of the DECC RHPP project and to compare their responses with the monitored performance. The subject matter that the survey is attempting to illuminate is socio-technical.

The specific aim is to produce case studies that:

- investigate the influence of energy use, lifestyle, and adaptive behaviours of occupants on performance;
- investigate the influence of technical performance on satisfaction and
- improve our understanding of the overall performance of domestic heat pumps – that is to find out why some heat pumps perform well and others poorly.

Should you agree to take part in this study, the interview and site survey will be conducted on a mutually agreed date between 18/11/2015 and 18/01/2016, by a team consisting of a social researcher, and a technical researcher, who will investigate the heat pump and its controls as well the experiences of occupants living with this technology. Both researchers will present photo IDs upon arrival. The visits are expected to last between two and three hours. The survey and interview will be structured in four parts, as follows:

- **briefing session** - researchers will explain why they are there and what are they going to do; participants will be provided with the trial information sheet and agreement with the option for them to give their signed consent to participate;
- **confirmation of details** - you will be asked to confirm some personal information (e.g. name, address, household size, contact details) and some general questions will follow (e.g. how long have you been living in the house and why did you choose this technology);
- **walk through** - some information on the house configuration, structure type and conditions (e.g. room dimensions, thermal characteristics, identifying warm/cold rooms), the equipment installed in the house and their operation (e.g. heat pump system and its monitoring equipment*, controls and frequency of use) will be collected either via observation, taking pictures or asking you directly.
- **sit down session** - you will be asked a final set of questions relevant to their habits, lifestyle and use of heating (e.g. energy use, thermal comfort, occupied hours).

* *The heat pumps and their monitoring equipment have been previously installed by another institution, which had it's own ethics approval procedure in place.*

Specific participant benefits

You may benefit from the case study visits, as researchers may be able to provide you with some insight on the performance of your heat pump and possibly suggest how you could improve the performance of your heat pump. The information collected will be included in a report to DECC, which may be published. You will be sent a copy of those parts of this report that contain information that has been collected about you or your home. If the report is published, you will be sent a copy of the whole report.

A5 Consent form

Participant's Statement

I ……………………………………………….. (print name)

☐ have read the notes written above and the Information Sheet, and understand what the study involves.

☐ understand that if I decide at any time that I no longer wish to take part in this project, I can notify the researchers involved and withdraw immediately.

☐ consent to the processing of my personal information for the purposes of this research study.

☐ understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.

☐ agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study.

☐ understand that my participation will be taped recorded and I consent to use of this material as part of the project.

☐ understand that some exterior and interior photographs of the building fabric and equipment will be taken and I consent to the use of this material as part of the project.

☐ agree to be contacted in the future by members of the RHPP research project team who may wish to invite me to participate in follow-up studies.

☐ understand that the information I have provided will be included in a report to DECC, which may be published. I will be sent a copy of those parts of this report that contain information that I have provided. If the report is published, I will be sent a copy of the whole report. Names and addresses will be changed in the report to protect my privacy. But it may still be possible for individuals involved in the installation of my heat pump system to identify me from the report.

☐ agree that my non-personal research data may be used by others for future research. I am assured that the confidentiality of my personal data will be upheld through removing all personal information from publications.

Date:

Participant's name: Researcher's name:

Participant's signature: Researcher's signature:

A6 Topic guide

1 Briefing section

Explain why researchers are here and what they are going to do. Participants will be provided with the trial information sheet and agreement with the option for them to give their signed consent to participate.

- Introductions and brief chat. Reassurance that there are no wrong answers and that how much they know about the HP installation is not important.
- Reiteration that the interview will be recorded, a walkthrough will be conducted and photos may be taken. Permission will be sought for all of these aspects of the interview.
- Explanation of the arrangements for ensuring anonymity and confidentiality.

2 Confirmation of details

Confirming personal details and gathering general information about household

2.1 Contact Information

Name	…
Address	…
Contact number	…
Email address	…

2.2 Household Characteristics and Decision Making

Household characteristics refer to the monitoring period only

Household size	…
Household composition	Children / Adults / Elderly
Tenancy	Private landlord / Private tenants / Social tenant
Occupant(s) background	…
Time living in property	…
Any changes in the number of people living here during the monitoring period?	New baby / adult children living home / multiple tenancy / etc.

- *[Private householders only]* Could you tell us why and how you came to install your HP?
- *[Tenants]* Was the HP here before you moved in? If not, were you asked whether you would like to have the HP installed? When was this?

3 Walk-through

Gathering information on house configuration, structure type, internal conditions, equipment installed and their operation. Information will be collected via observation, taking pictures or asking the occupants directly. Allow around 45 mins for this section.

3.1 Dwelling characteristics

Just before starting the walk through – confirm the following. Note that most of the information needed to complete Government's Standard Assessment Procedure (SAP) for the Energy Performance Certification (EPC) of dwellings will be collected by direct observation using a separate SAP checklist (see 'RdSAP_checklist.xlsx attached).

Property type	Mid-terrace / end-terrace / detached / flat
Number of rooms	…
Number of bedrooms	…
When was it built	…
What is it build of	Brick / stone / concrete / other
Wall insulation	…
Roof insulation	…
Floor insulation	…
Glazing type	Single / double / triple / other
Draught presence	…
Other problems	Damp / mould / internal air quality issues / unusual smells

3.2 Room by Room / Measure by Measure exploration

- Would it be ok for you to take us round your property? It would be great if you could tell us a little bit about each room and show us the HP installation. Would it be ok if we take some photographs and measurements of the room and radiator sizes?

Room by Room

- Were the radiators changed when the HP was installed?

- How do you find the radiators? (too hot, too cold etc.) – If they find them too hot, too cold, what do they normally do?

- How much do you / the other occupants use this room?
    - Every day for a number of hours
    - Every day but only very briefly
    - On average, less than once a day – why?
- Please could you indicate on this scale how the room normally feels (winter/summer)?

Hot	Warm	Slightly warm	Comfortable	Slightly cool	Cool	Cold

    - [If too warm/much too warm] What do you do to cool down? Explore the use of fans, opening windows, portable air conditioning.
    - [If too cool/much too cool] What did you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV.
- Which (if any) windows in this room do you open?
    - Why?
    - Do you do it habitually (e.g. every morning)?
- Is there any issue with damp / condensation / mould / smells in this room?
    - Is this all the time or just when you are using hot water etc.?
    - How do you cope with this?
- Excluding the main heating system, do you use any other heating equipment in this room?
    - How often is it used?
    - Why do you use it?

3.3 HP characteristics and controls

Collect information when viewing the HP installation. The interviewers will collect any additional information needed to complete the Microgeneration Certification Scheme (MCS) assessment by direct observation. MCS is a nationally recognised quality assurance scheme for microgeneration technologies, such as HPs. Our technical aim is to check whether the entire central heating system specification meets the relevant installation standard applicable at the time of the contract. Occupants will be shown the MCS checklist (see MCS_checklist_01.pdf and MCS_checklist_02.xls attached) and will be informed of the additional information collected.

HP type	Air-source / ground-source
HP model	…
HP power	…
Circulating pump type	...
Circulating pump setting	…
Heat emitter type	Radiators / underfloor / fan-assisted radiators Were these installed when the system was installed? Yes / No / Unknown
Previous fuel	Gas / Electricity / other

- Have you got an idea of the installation cost?
- Did your use of the heating system change after the HP was installed?
    - how?
    - in terms of hours of heating? (from when to when)? Ask for SH and DHW controls.
- Do you use any other source(s) of heat other than the main heating system? Please say what.
- Are there any renewable energy/passive systems installed?
- Tell us about how you control your HP and heating system?
- Could you show me how you operate/control your HP?
    - Have you changed the control settings at all?
    - If so, how? *[Opportunity to record settings and find out what the householder can change. Find out if there is a winter setting and if so, whether this involves the use of direct resistance heating systems such as a built-in electric cassette or immersion heater (if present)? Do the occupants know if the system includes weather compensation, and can they show the interviewers how they use it? Has the householder disabled any controls? The interviewers will observe the thermostat and programmer settings.]*

Control type	Weather compensation / other
Ease of use	Easy / difficult
Electricity tariff	Standard / Economy 7 / Economy 10 /other

- Could you tell us about how you were instructed or shown how to use the HP?
    - *[If given instructions/training]* How was this done, e.g. own research, installer demonstration or written instructions? If written, have you read them?
    - *[If given instructions/training]* Could the instructions/training have been better? If yes, how?
    - *[If given instructions/training]* Overall, can you indicate on this scale how satisfied you are with the level of instruction you were given?

Very satisfied	Satisfied	Neutral	Dissatisfied	Very dissatisfied

- *[If the occupant was not given any instructions/training]* Would you have liked instruction or training?

- Overall, how satisfied are you with your HP overall? *[If not…]* Why not?

Very satisfied	Satisfied	Neutral	Dissatisfied	Very dissatisfied

- Have you had any problems with your HP so far?
    - *[If yes]* What was the problem?
    - *[If yes]* How did you/What did you do to deal with the problem?
    - *[If yes]* Do you feel you can resolve/control the problem yourself?
- Who would you get in touch if you were having trouble with your HP or thought there was a problem with it?
- Since the HP was installed, has there been any more work done in relation to the HP, the monitoring equipment (rectifying problems etc.) or the house itself (insulation, draught-proofing etc.)? If so:
    - Were you expecting this to happen?
    - What did this involve?
    - Did this cause any problems for you?
    - Has this changed the way you feel about the property?
- What advice would you give to other householders who are considering installing a HP?

4 Sit down session

Final set of questions relevant to habits, lifestyle and use of heating

4.1 Comparison with Previous Heating System

The interviewers should be aware of the possibility that the occupants may have lived somewhere else before and may have moved into their present home after the HP was installed.

- What heating system did this house have before the HP was installed?
  - *[If the occupants lived somewhere else before the HP was installed, ask them to talk about the heating system in their previous house]* What was the heating system in your previous house like?
- Compared with your previous heating system, could you tell us what you like or dislike about your current heating system?
  - Easy/hard to control?
  - Cheap/expensive to run?
  - Space heating/water heating [do you have enough hot water]?
- Overall, do you prefer the HP to your previous heating system?
  - Yes, why?
  - Feel no different
  - Prefer previous heating system, why?

4.2 Energy Use, Bills and Demographics

This section will help us understand how much energy is used and when.

- Do you keep your energy bills? Could you tell me what is the average cost of your energy bill per month or quarter (approximately)?
- Have you noticed a change in your energy bills from your previous heating system? If so, please describe. *[Note: oil customers would have bought in bulk.]*
- Which appliances do you think use most electricity in your house? *[If physical monitoring data were available, this could be explored at this point]*
- Does anyone in the house smoke at all? If so, do they do this outside/open a window?

- What do you use hot water for? How often do you do the following in a day? Are there any particular laundry habits?

Showers	How many per day? Is the hot water supplied by the HP? Yes / No	Duration?
Baths	How many per day? Is the hot water supplied by the HP? Yes / No	Duration?
Washing up	How many per day? Is the hot water supplied by the HP? Yes / No	Duration?
Other	How many per day? Is the hot water supplied by the HP? Yes / No	Duration?

- Do you or any of the occupants work?
    - *[If yes]* What do you/they do? Is it full/part time? Is it a fixed contract?
- Are you or any of the occupants away for long period of time? E.g. students at university, people away with work. Are there times when the house has more or fewer occupants? Did you have any frequent/long-staying visitors over the monitoring period?

4.3 Thermal Comfort

- How warm or cool do you like the house to be?
- Could you indicate on this scale how the property feels normally?

Hot	Warm	Slightly warm	Comfortable	Slightly cool	Cool	Cold

- *[If too warm/much too warm]* What do you do to cool down? Explore the use of fans, opening windows, portable air conditioning.
- *[If too cool/much too cool]* What did you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRVs.

- Could you tell us about how you use your windows?

- Open all the time – why?
- Open at least once a day – why? For how long?
- Rarely open – why not? How often and for how long?
- Never open – why not?
- When (day/night)?

5 Close interview

- Explain when we might next be in touch and leave contact details for them
- Thank them for their time and help

Appendix B – Analytical matrix

Source Climate =>outdoor unit		Sink Radiator + Target Temperature					
Observation	observation	Installation design Radiators sizes	Issues of configuration and decisions	Target Temperature (Physical factors)		Target Temperature (Behavioural factors)	
	)			Insulation:	Quan/Qual: Roof	Thermostat setting	Quan:
						Heating hours	Quan/
						Window opening, Pets	
				Airtightness	Quan	Smoking	No

					Others i.e. secondary heating	
Initial Commissioning (control setting):						
Setting for maximum flow temperature				Yes/No/Cannot be observed		
Weather compensation activated				Yes/No/Cannot be observed		
Adjustment of weather compensation				Yes/No/Cannot be observed		
Control of boost:				Yes/No/Cannot be observed		
Default factory settings				On/Off/observation/**Cannot be observed**		
Achieving ideal temperature difference: Yes/No/Don't know/observation						
Analysis based on a combination of schematics, monitoring data, and observations:						
Changes or variation in commissioning: matching flow temperature to heat loss:						

<table>
<tr><td colspan="8">Reported behavioural adjustment indicate:</td></tr>
<tr><td colspan="8">Previous heating experiences and behaviour:</td></tr>
<tr><td colspan="4">Active adaptive</td><td colspan="4">Passive adaptive</td></tr>
<tr><td>Understanding of technical operation of HP</td><td>Prevent heat loss</td><td>Reduce demand</td><td>Adjusting weather compensation curves to match comfort needs</td><td>Little to no understanding of technical operation of HP</td><td>Did not set heating programme

Programme set</td><td>Using only room thermostat in respond to comfort</td><td>Complete locked out</td></tr>
<tr><td colspan="8">When compared with previous heating experiences, has the occupant indicate an adjustment with understanding of the system or habitual actions based on previous experience?</td></tr>
<tr><td colspan="3">SPF</td><td colspan="2">Satisfaction:</td><td colspan="2">Comfort</td><td>Bill</td></tr>
</table>

Appendix C – Case Studies outside Sample B2

Table C 1. Reasons for excluding Case Studies from Sample B2

ID	Reason for exclusion from Sample B2	Estimated impact on SPF
CS03	Metering issue – electricity but no heat recorded for a a period	Loss of 1 month of DHW heat data. Likely to result in a small impact on annual SPF in this dwelling.
CS04	Metering issue – heat but no electricity recorded for a period	Loss of all data for several days. Several weeks with no DHW heat data, possibly consistent with holidays. Likely small impact on SPF.
CS05	Metering issue – electricity but no heat recorded for a period	Loss of all data for several days. Several weeks with no DHW heat data, possibly consistent with holidays. Likely small impact on SPF.
CS08	Metering issue – heat but no electricity recorded for aperiod	Loss of all data for several days. Several weeks with no DHW heat data, possibly consistent with holidays. Likely small impact on SPF.
CS10	Metering issue – 5 months of missing heat and electricity data (May to Oct)	One of two HPs on this site. Heat data Hhp for winter only, suggesting this is a space heating only HP – though there is also immersion heater Edhw data. This would suggest that the other HP is doing the hot water. **Potentially significant impact on SPF**.
CS12	Metering issue – electricity data missing, site not monitored properly	Monitoring system has a number of issues (see body of report). **Potentially significant impact on SPF**.
CS16	Metering issue – electricity input but no heat output for a period	All data missing for 10 days in November 2013. Likely small impact on SPF.
CS20	Missing schematic - missing DHW data could not be verified prior to site visit, where a SH only HP was identified	Likely small impact on SPF.

The overall conclusion is that although these sites were excluded from samples B2 and B2 cropped, the effect on SPF is likely to have been small in most cases. This is because the algorithm for calculating SPF only includes electricity and heat data for timestaps in which both are present.

Two cases, CS10 and CS12, are affected by more fundamental issues, which are discussed in the main body of this report.

Appendix D – Monthly mean COP, electricity and heat data for all Case Studies

Case Study 01

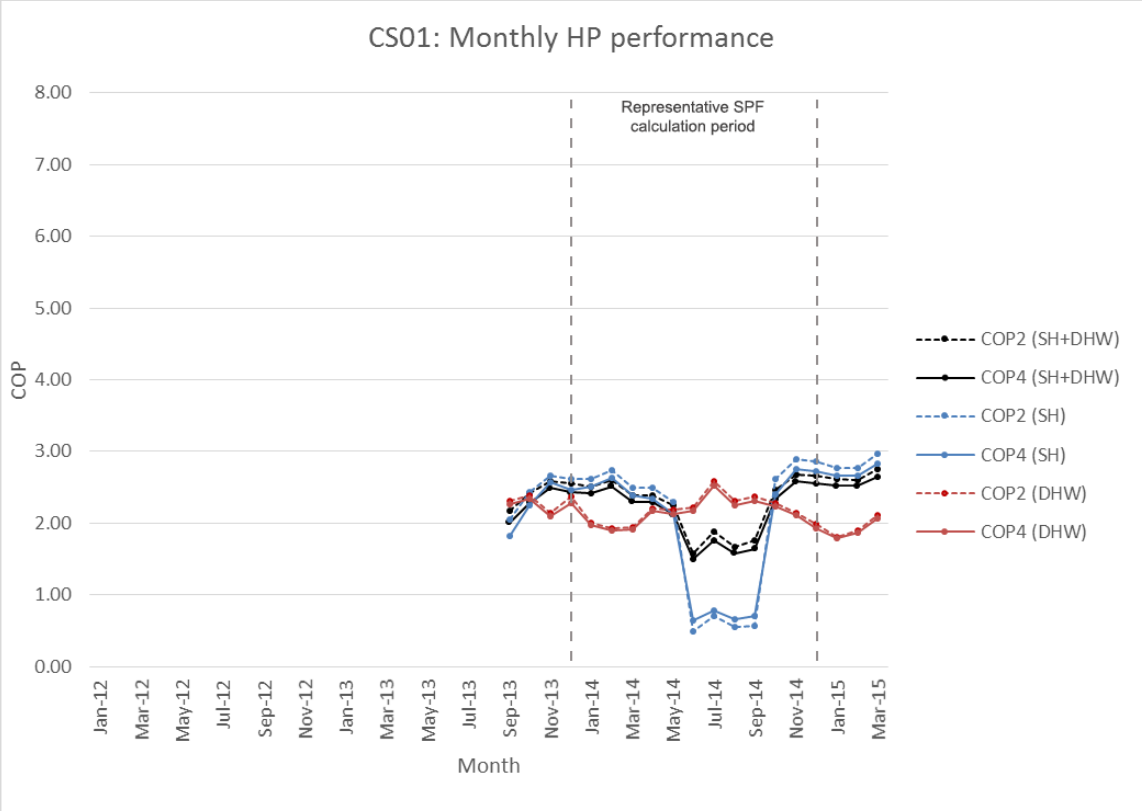


Figure D 1. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS01)

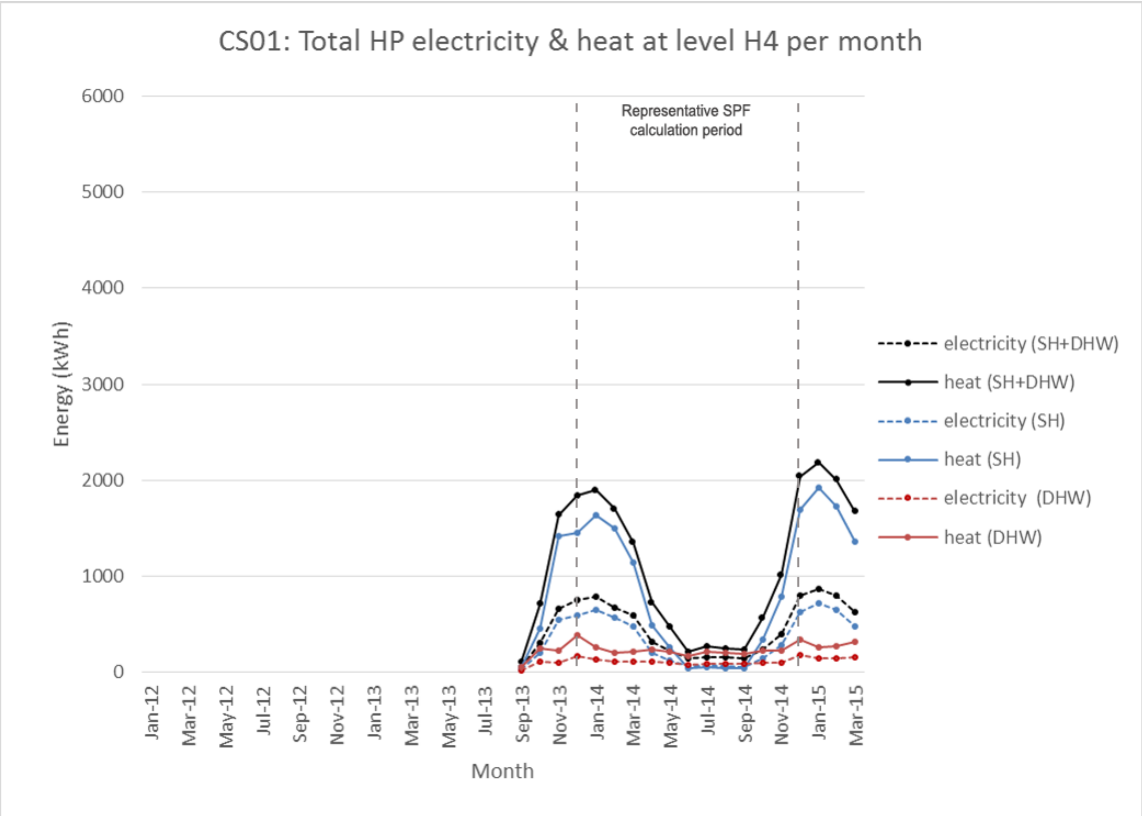


Figure D 2. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS01)

Case Study 02

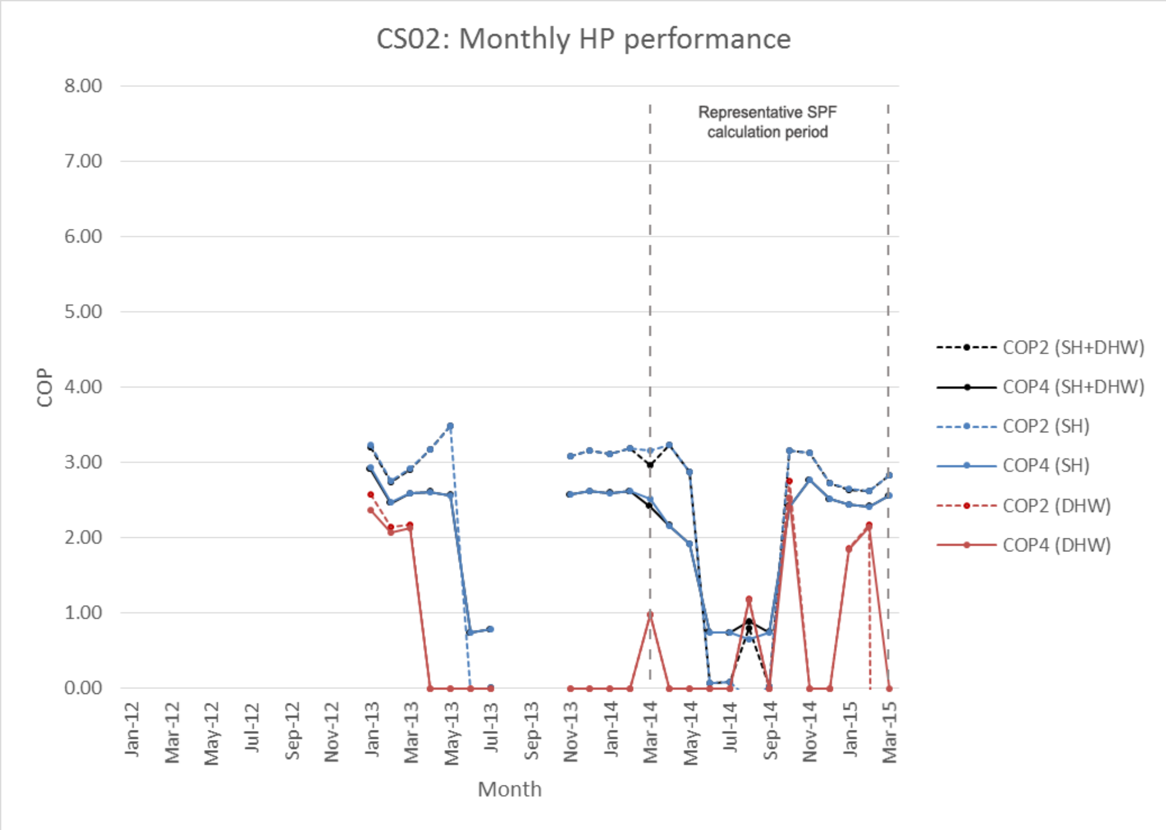


Figure D 3. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS01)

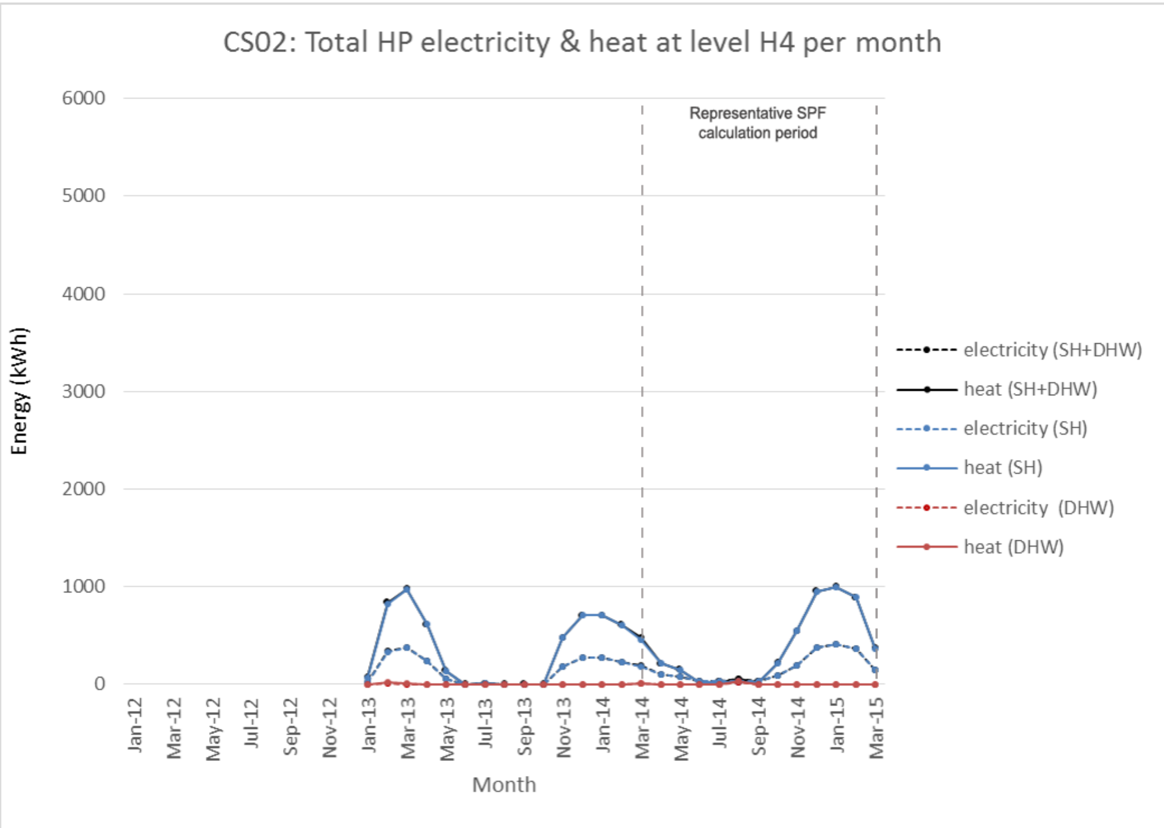


Figure D 4. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS02)

Case Study 03

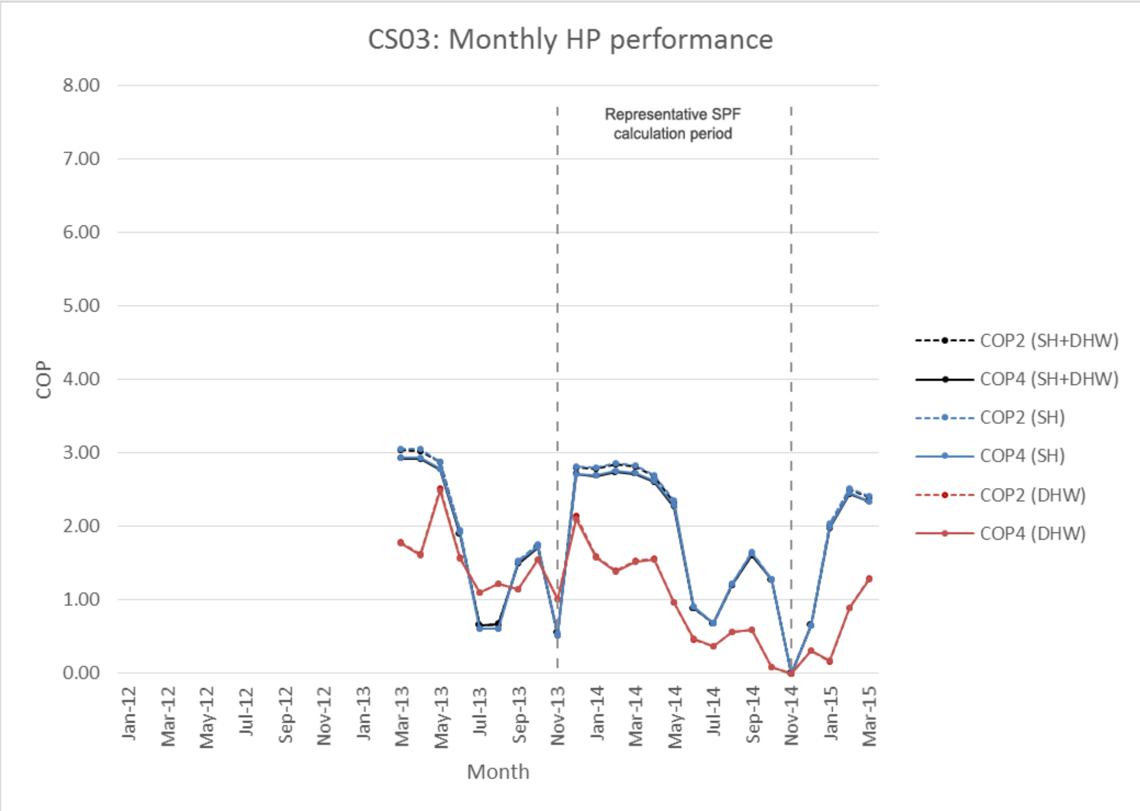


Figure D 5. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS03)

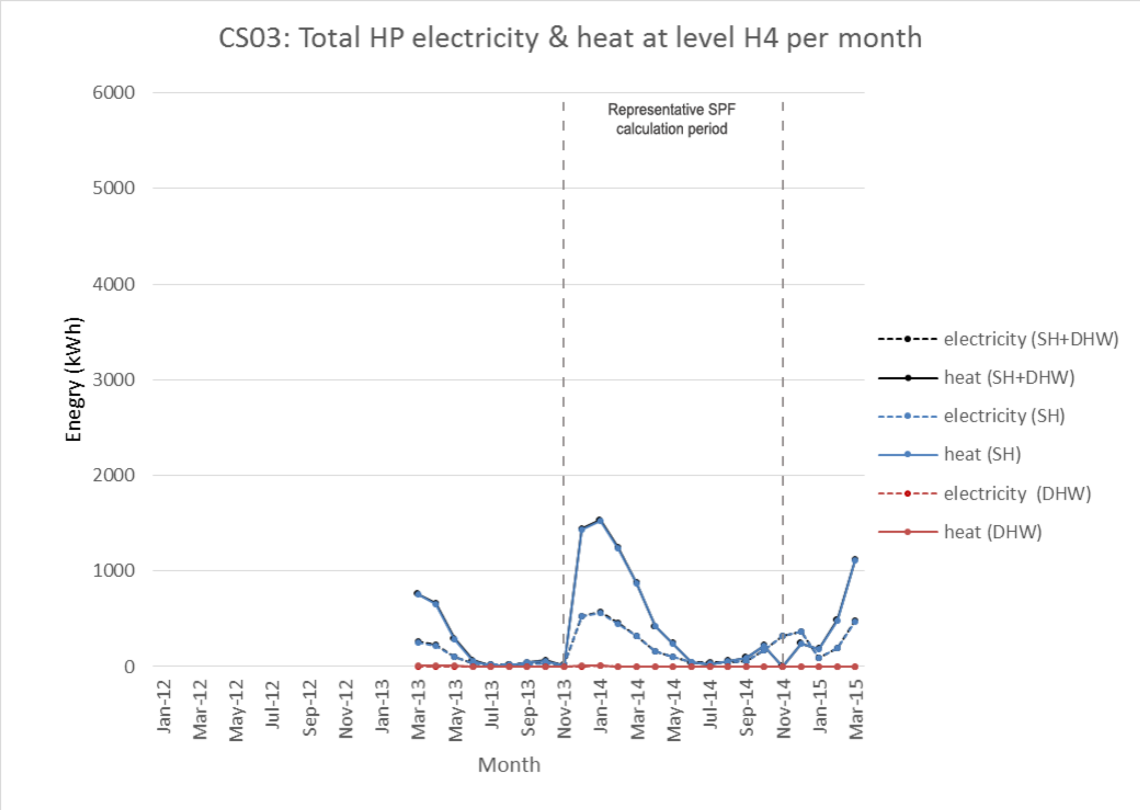


Figure D 6. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS03)

Case Study 04

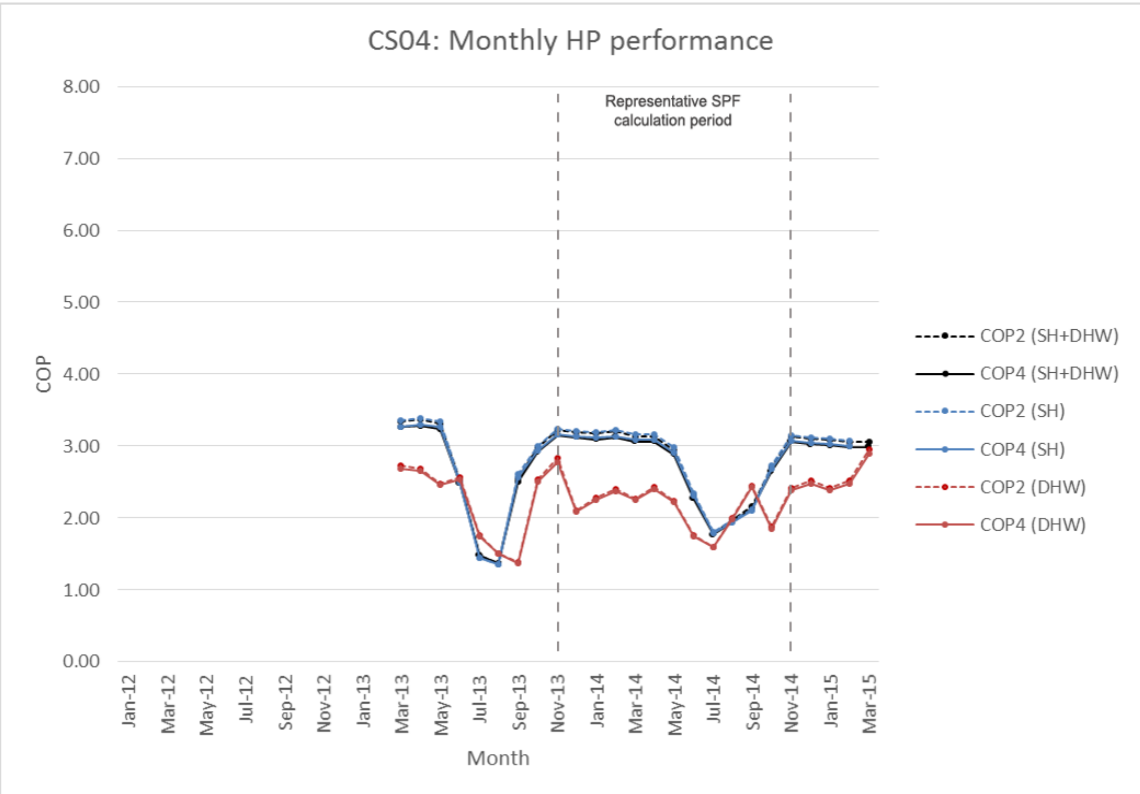


Figure D 7. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS04)

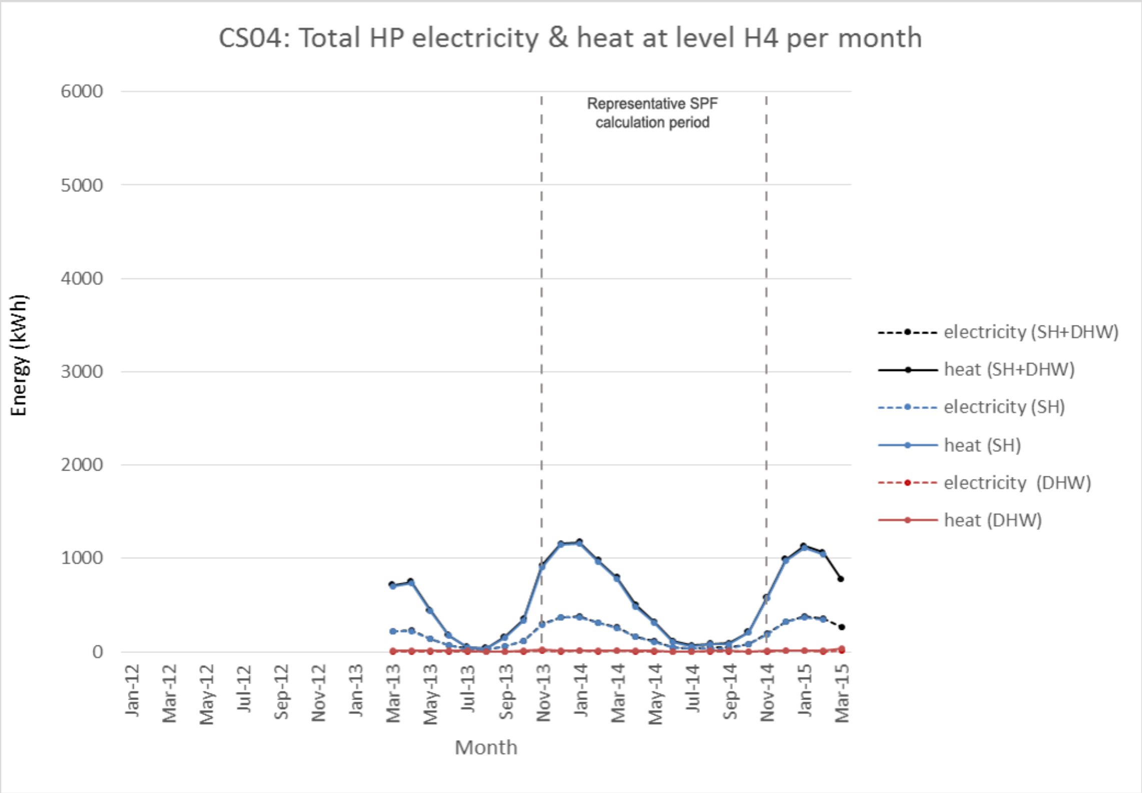

CS04: Total HP electricity & heat at level H4 per month
Representative SPF calculation period
Energy (kWh)
6000
5000
4000
3000
2000
1000
0
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
Month
electricity (SH+DHW)
heat (SH+DHW)
electricity (SH)
heat (SH)
electricity (DHW)
heat (DHW)

Figure D 8. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS04)

Case Study 05

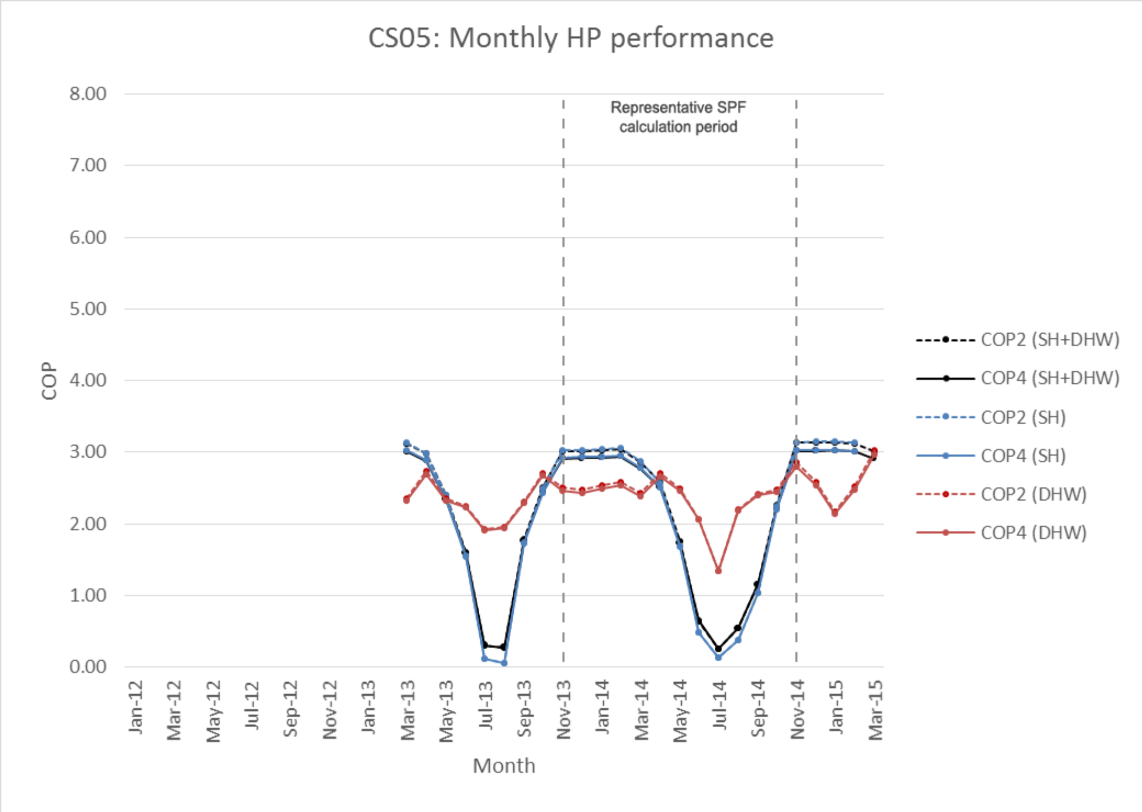


Figure D 9. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS05)

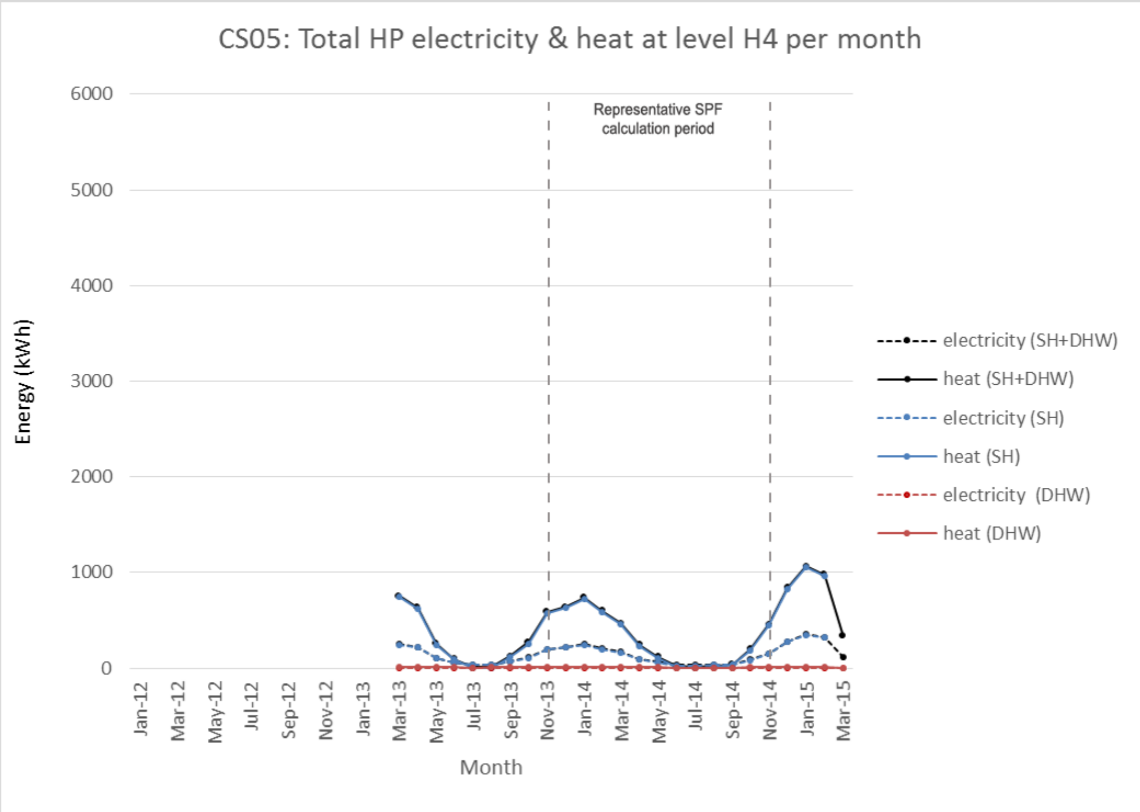


Figure D 10. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS05)

Case Study 06

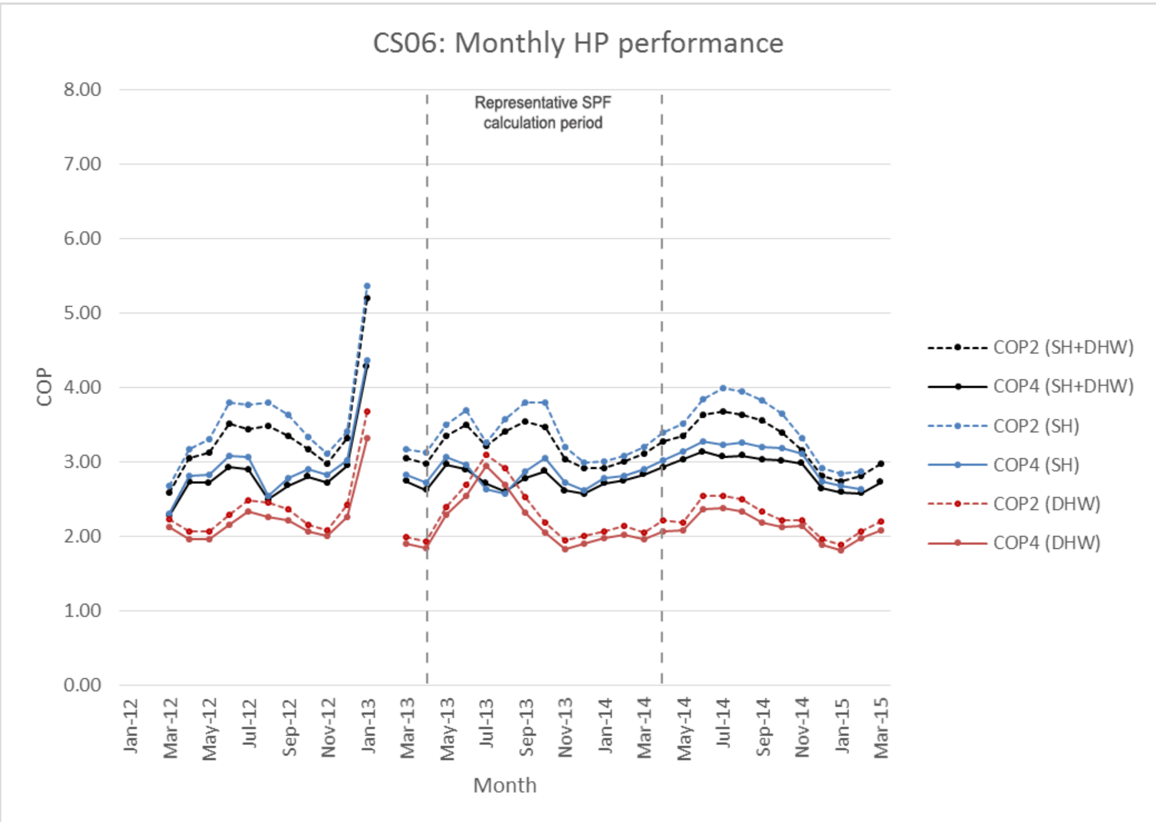


Figure D 11. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS06)

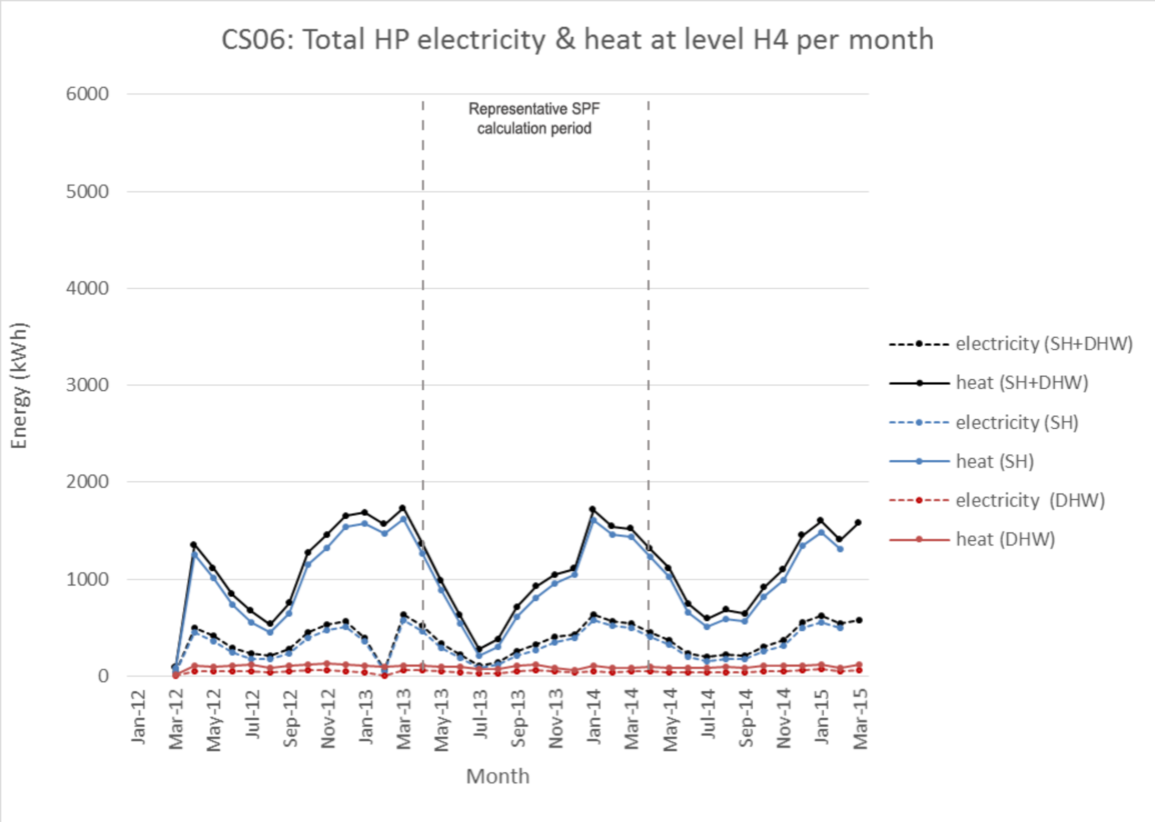


Figure D 12. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS06)

Case Study 07

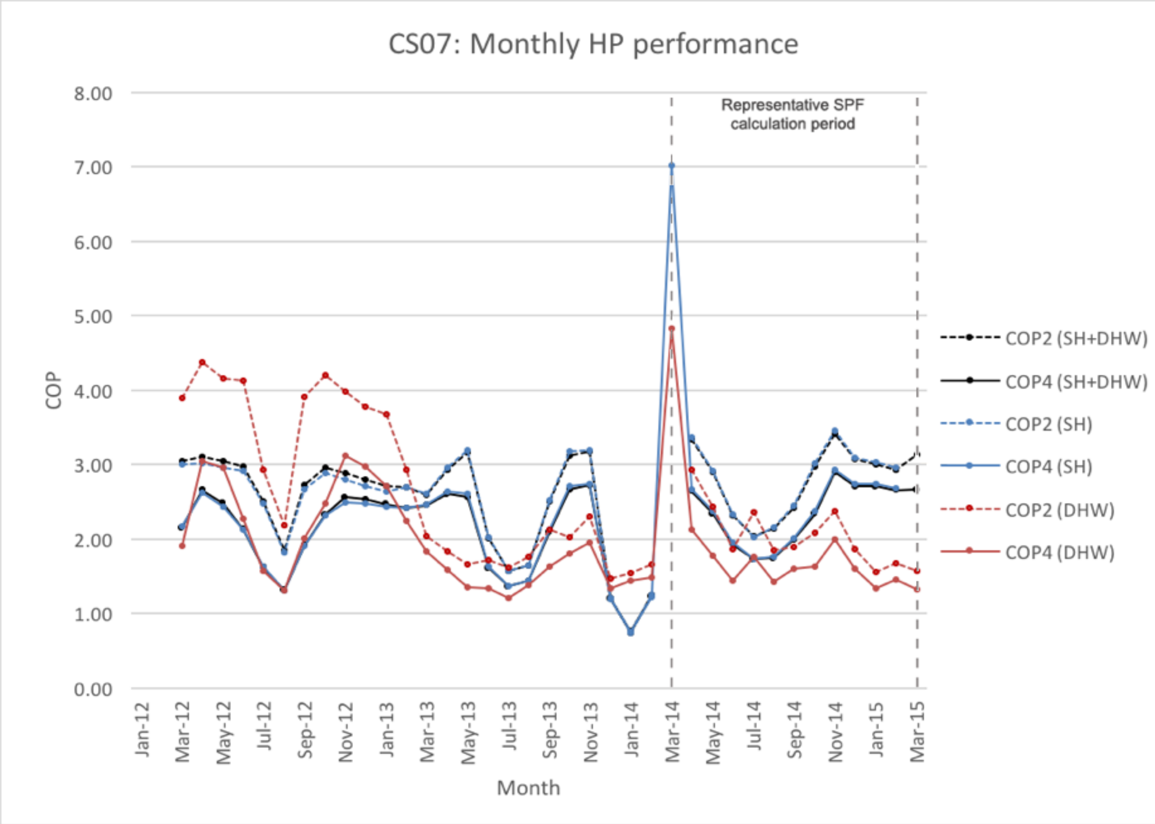


Figure D 13. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS07)

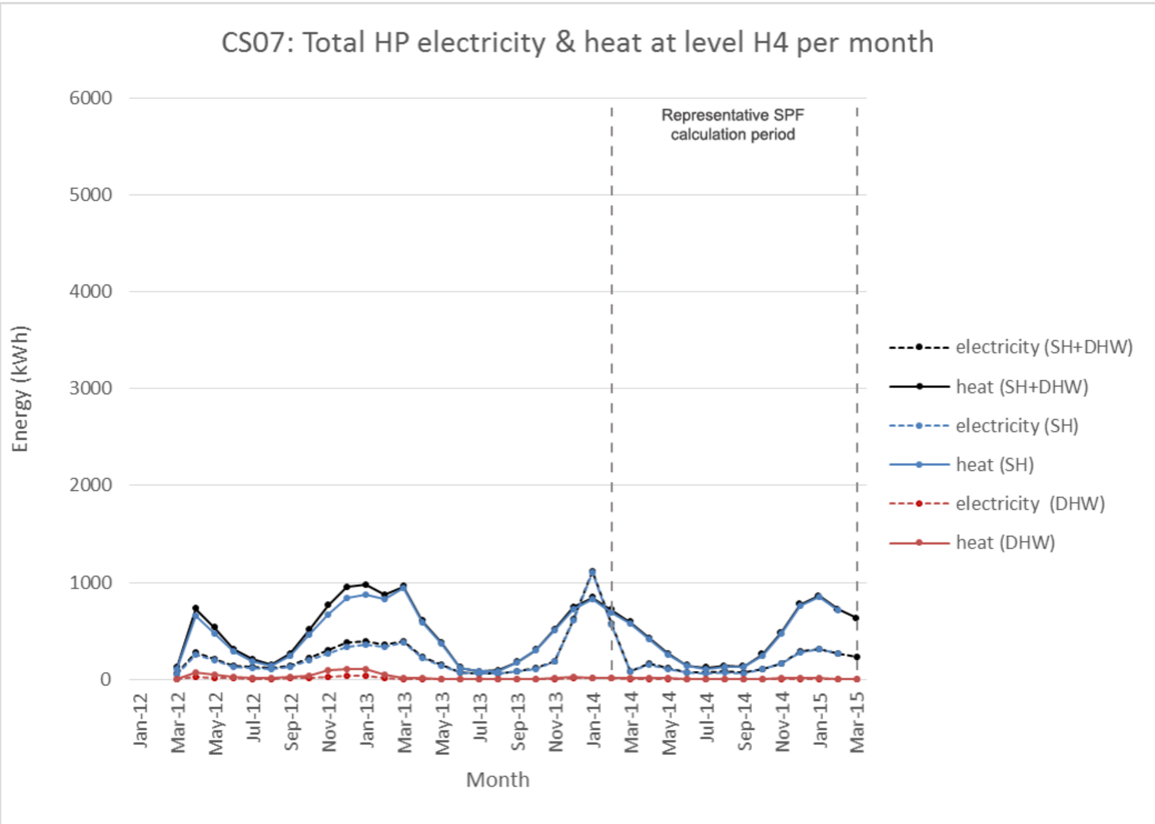


Figure D 14. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS07)

Case Study 08

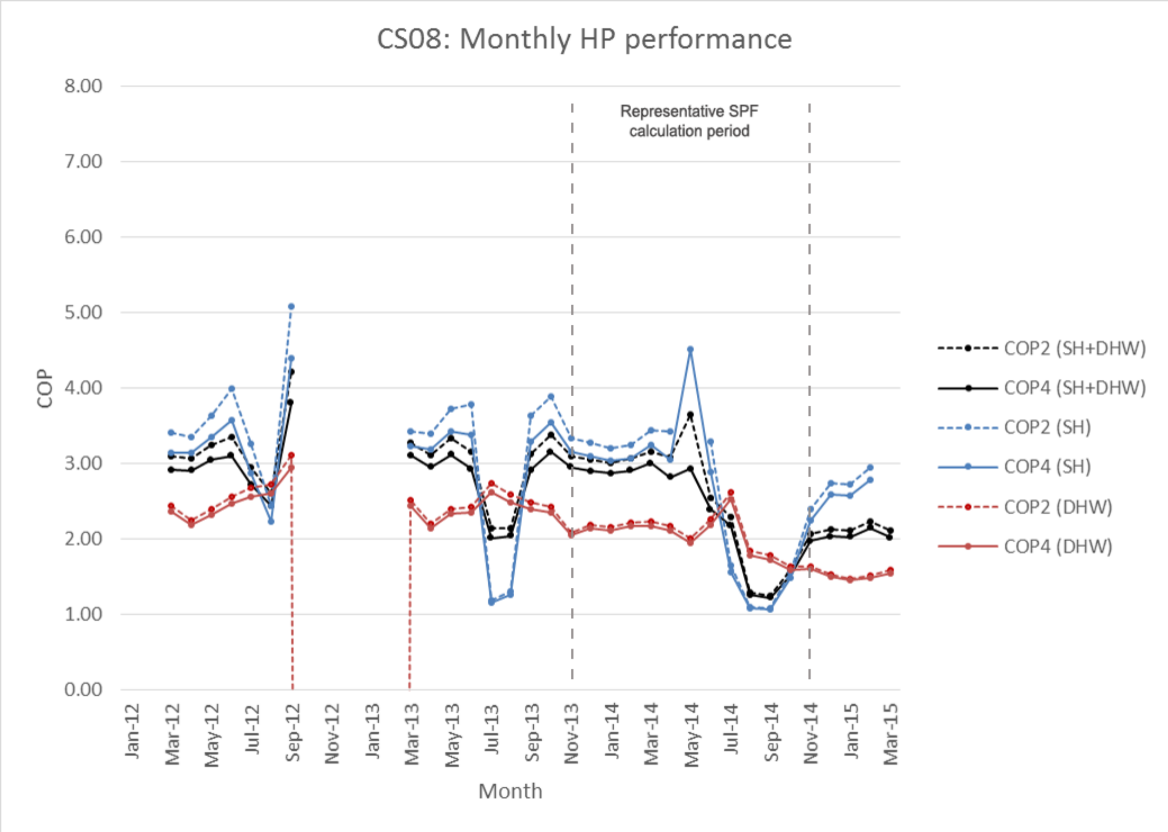


Figure D 15. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS08)

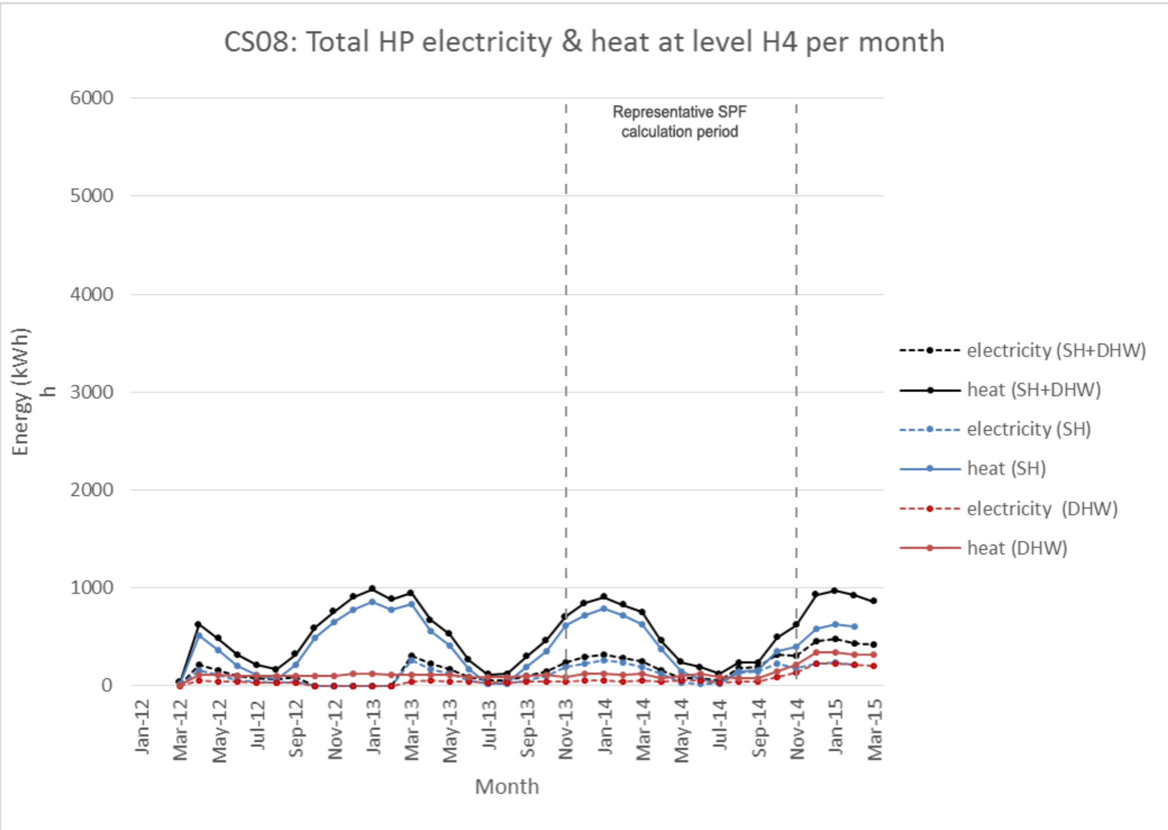


Figure D 16. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS08)

Case Study 09

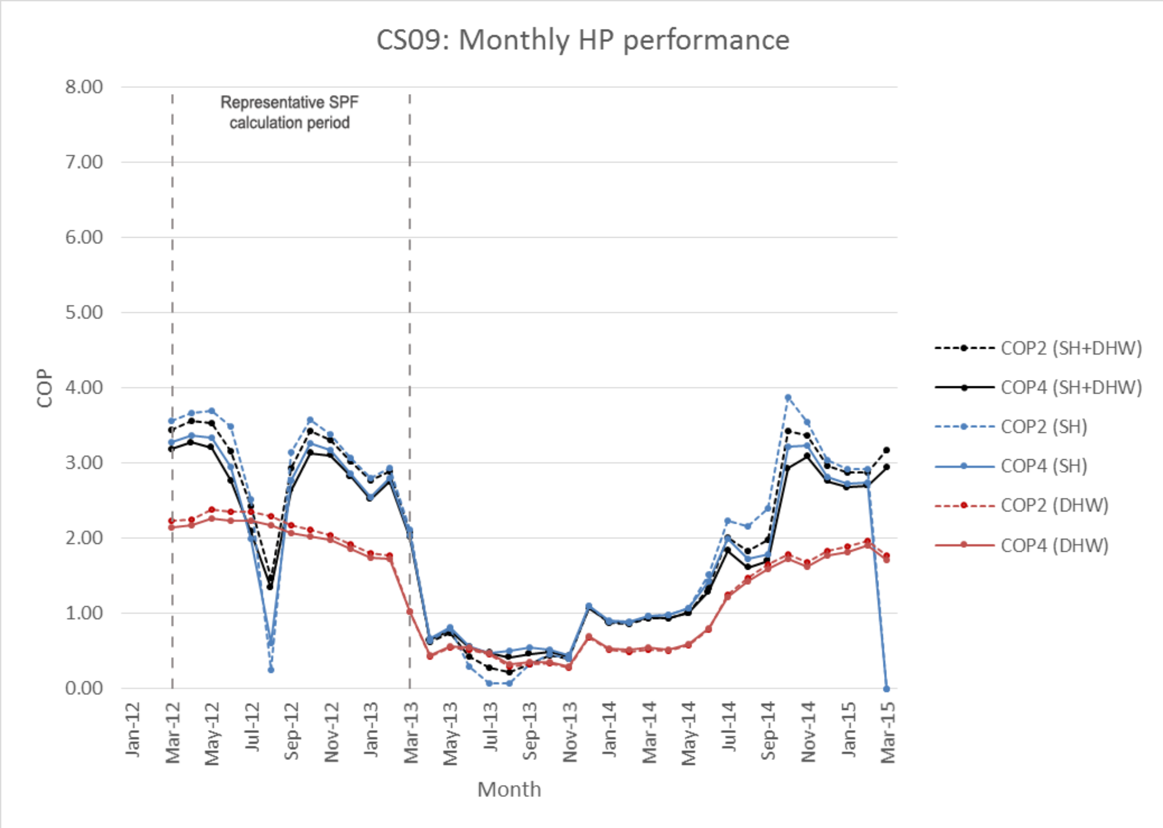


Figure D 17. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS09)

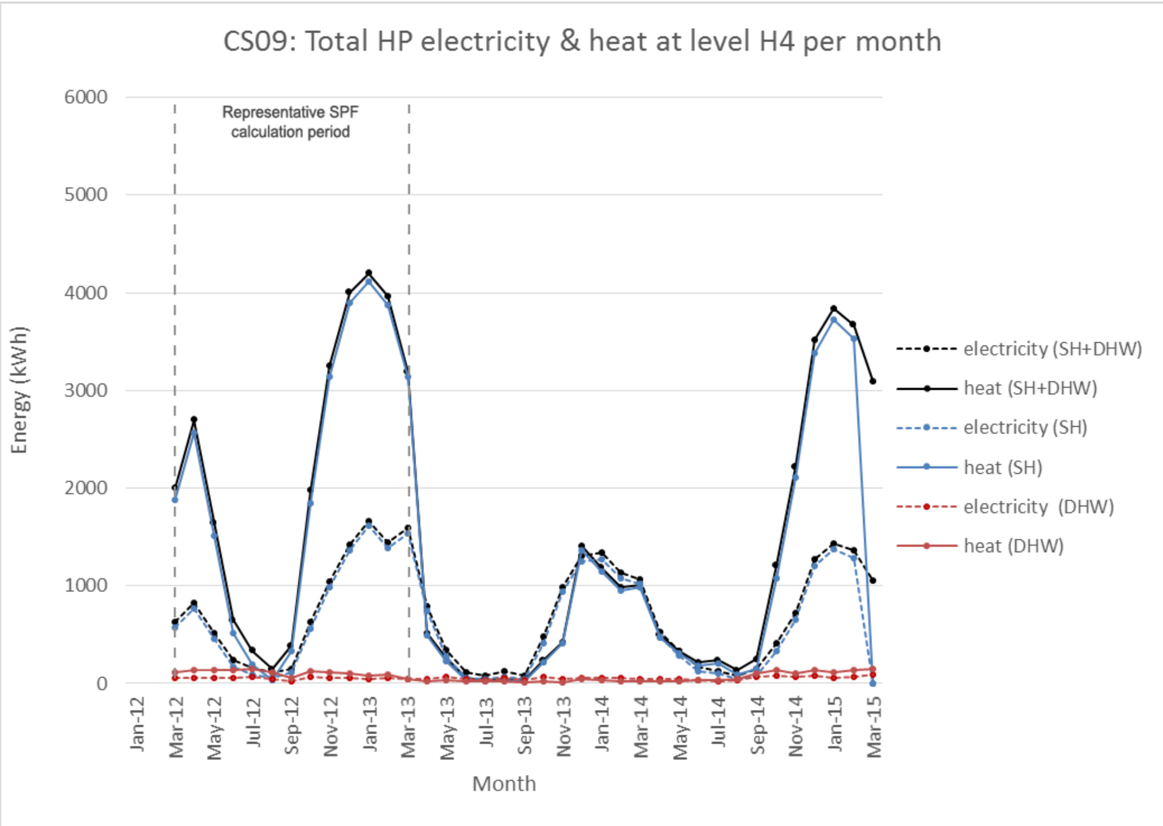


Figure D 18. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS09)

Case Study 10

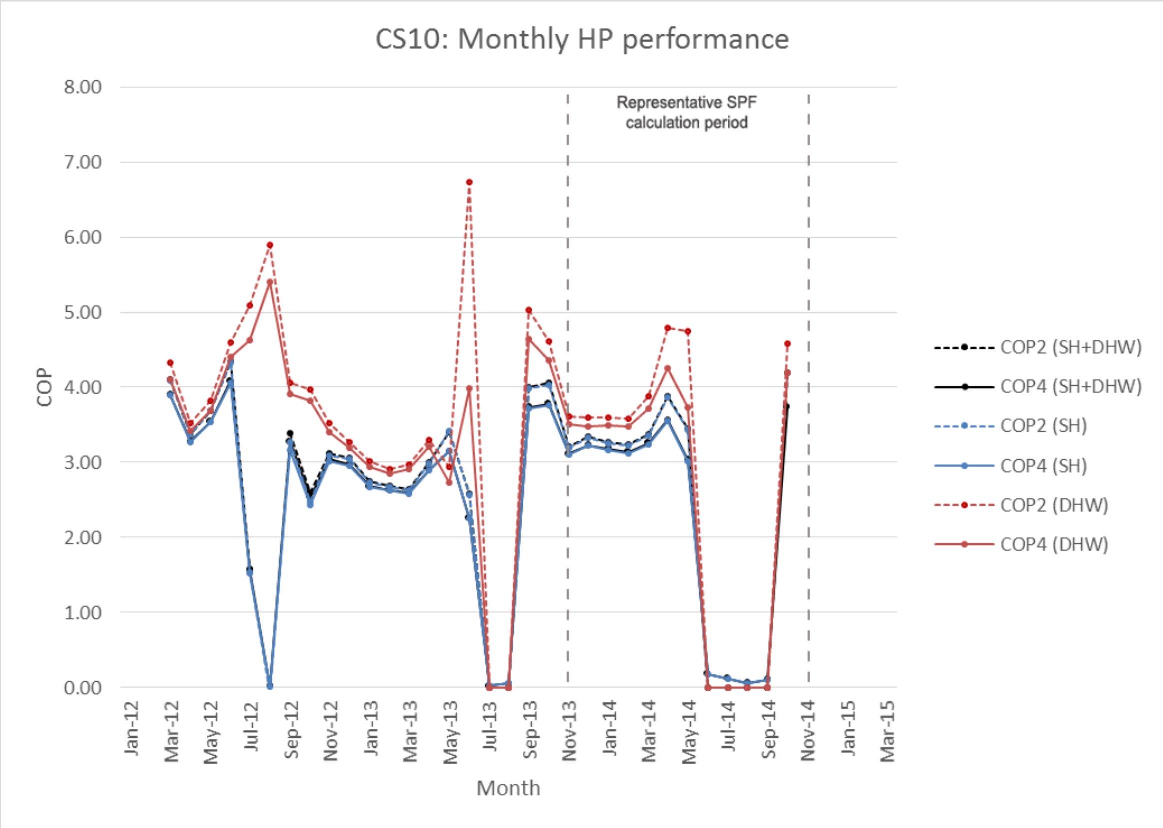


Figure D 19. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS10)

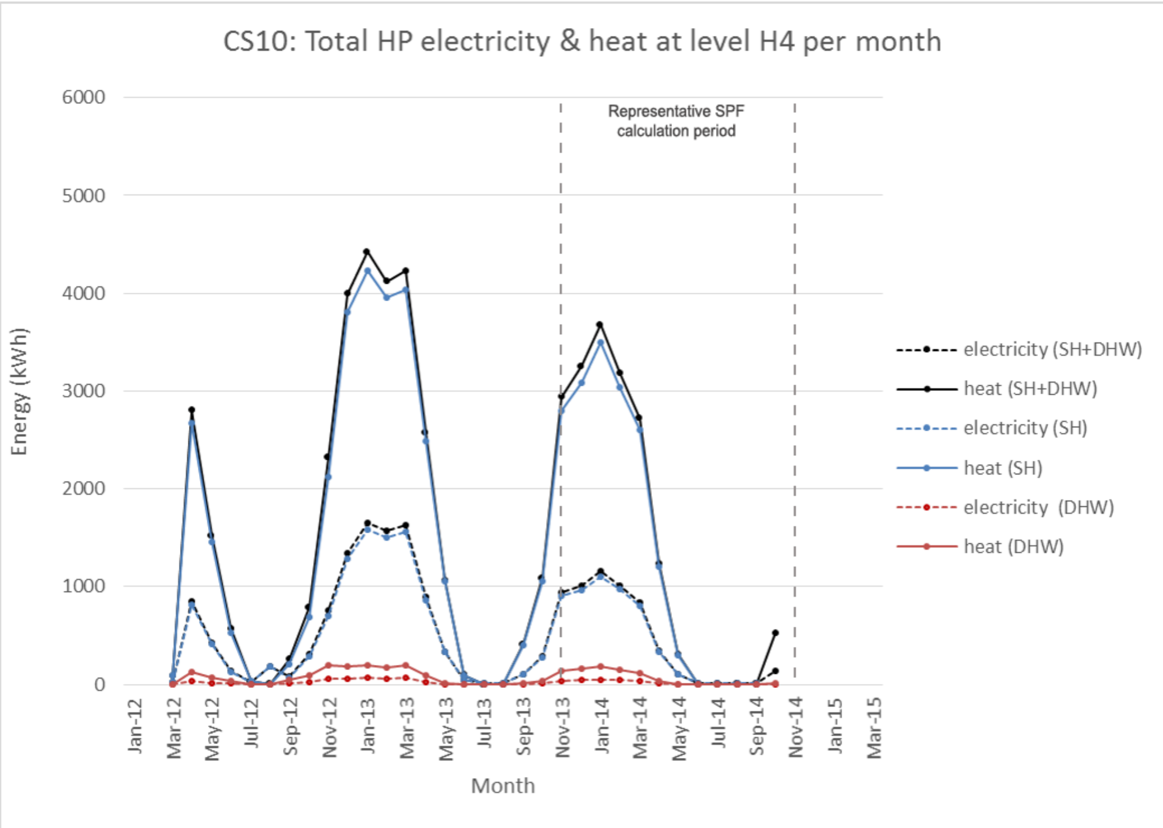


Figure D 20. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS10)

Case Study 11

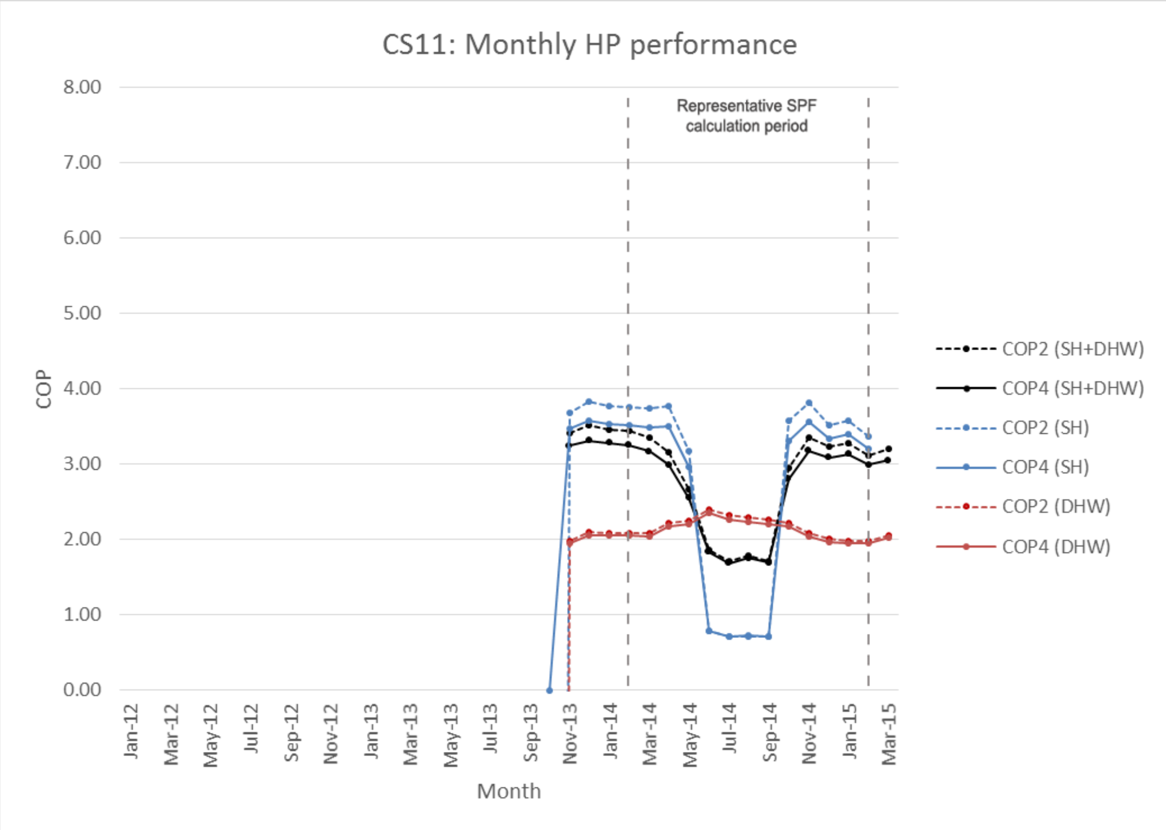


Figure D 21. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS11)

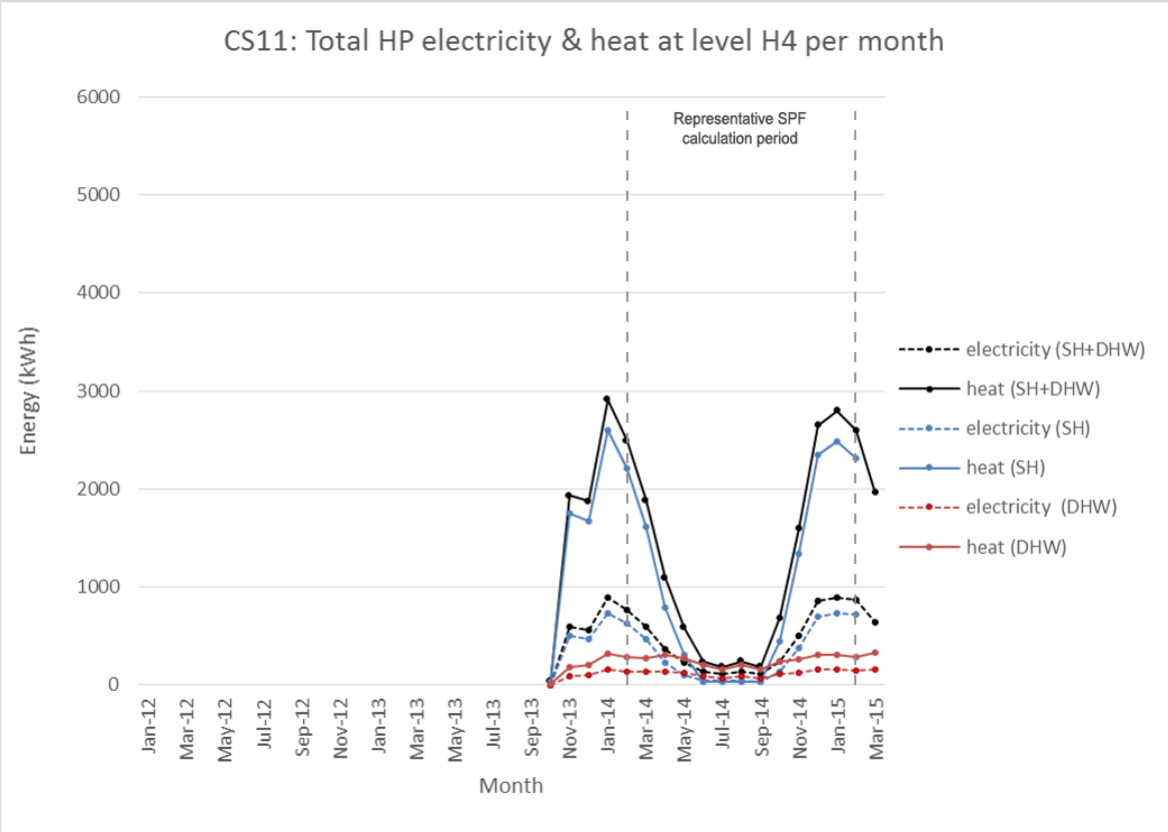


Figure D 22. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS11)

Case Study 12

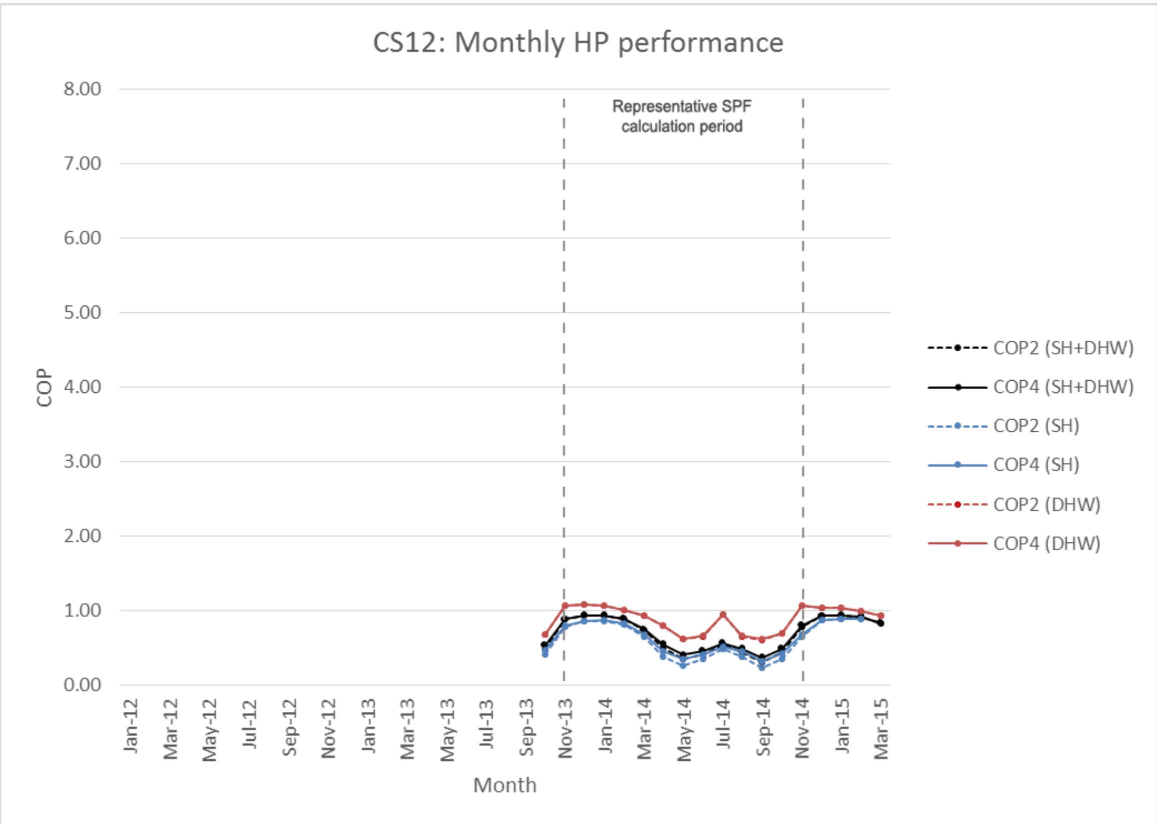


Figure D 23. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS12)

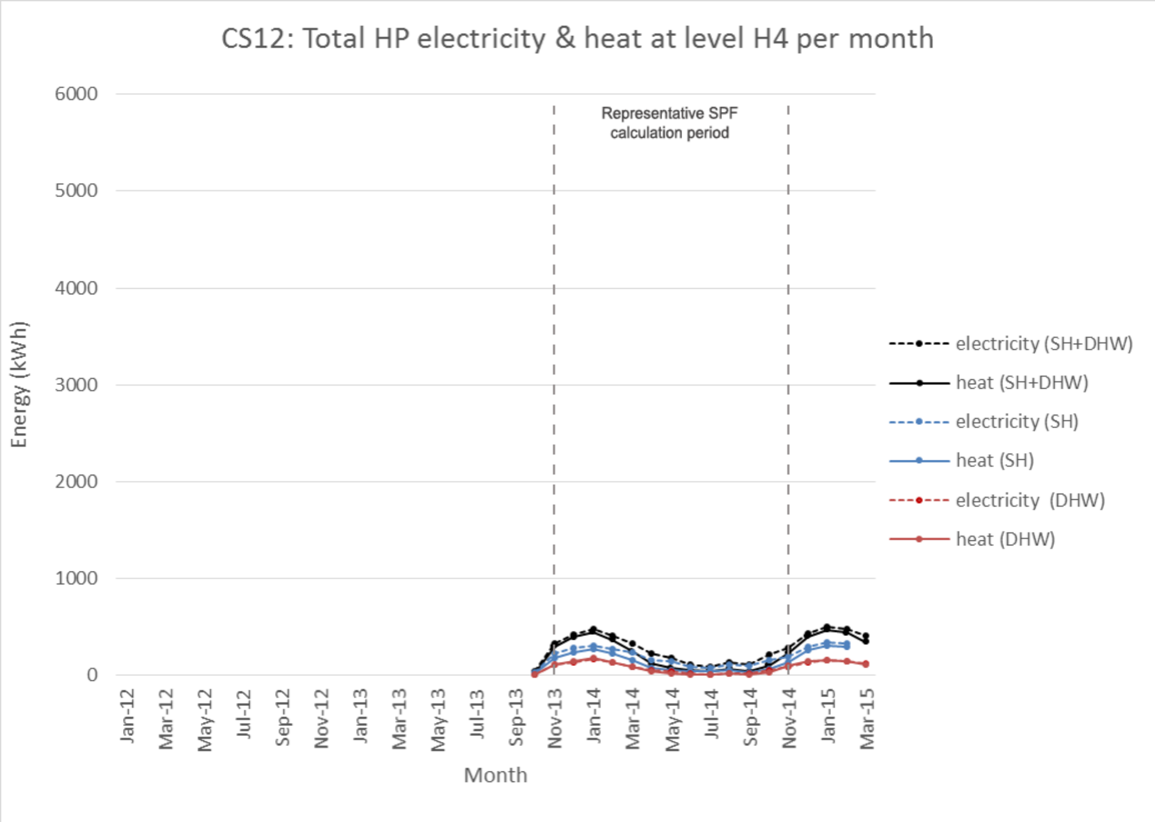


Figure D 24. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS12)

Case Study 13

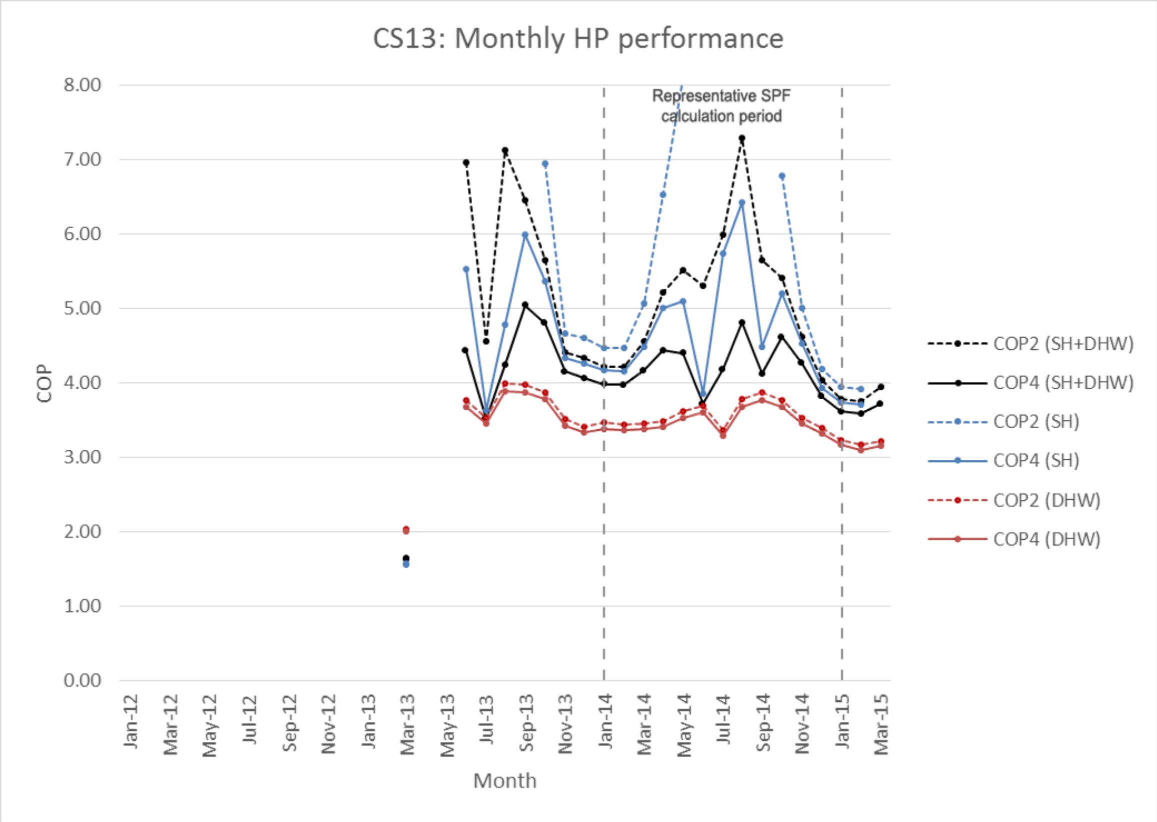


Figure D 25. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS13)

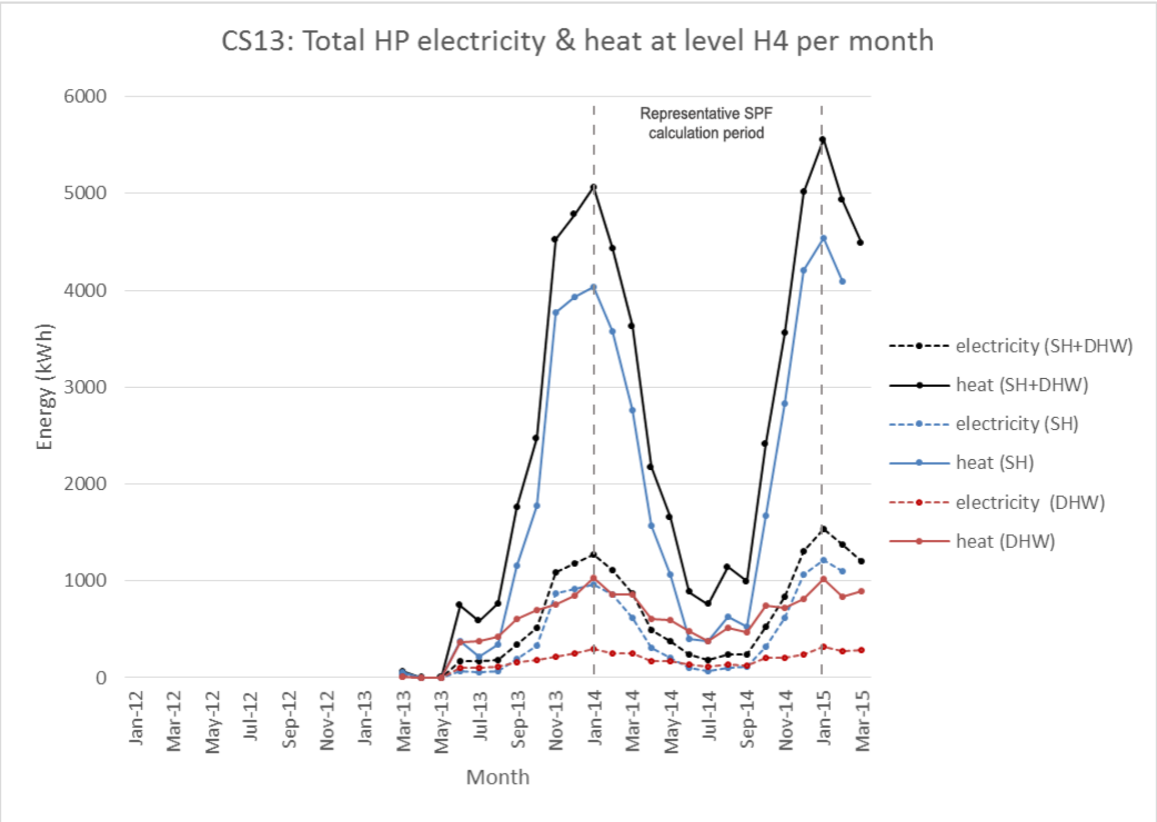


Figure D 26. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS13)

Case Study 14

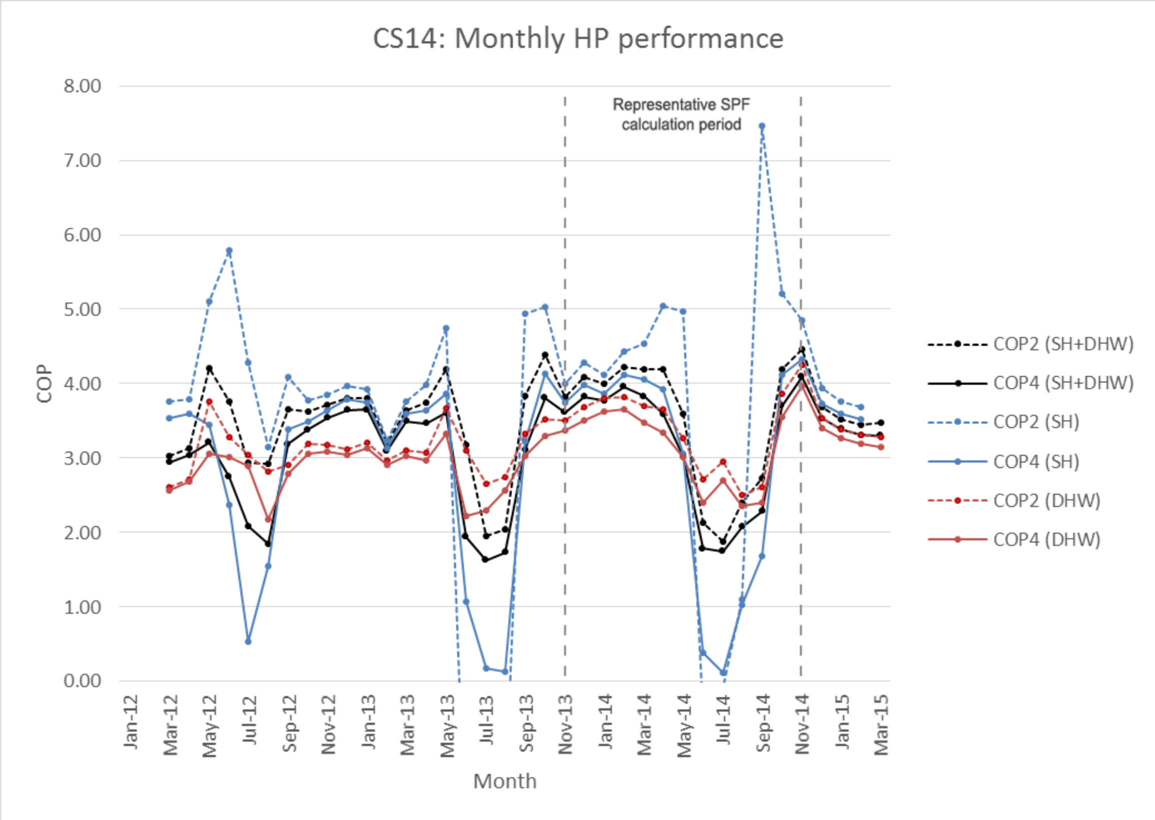


Figure D 27. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS14)

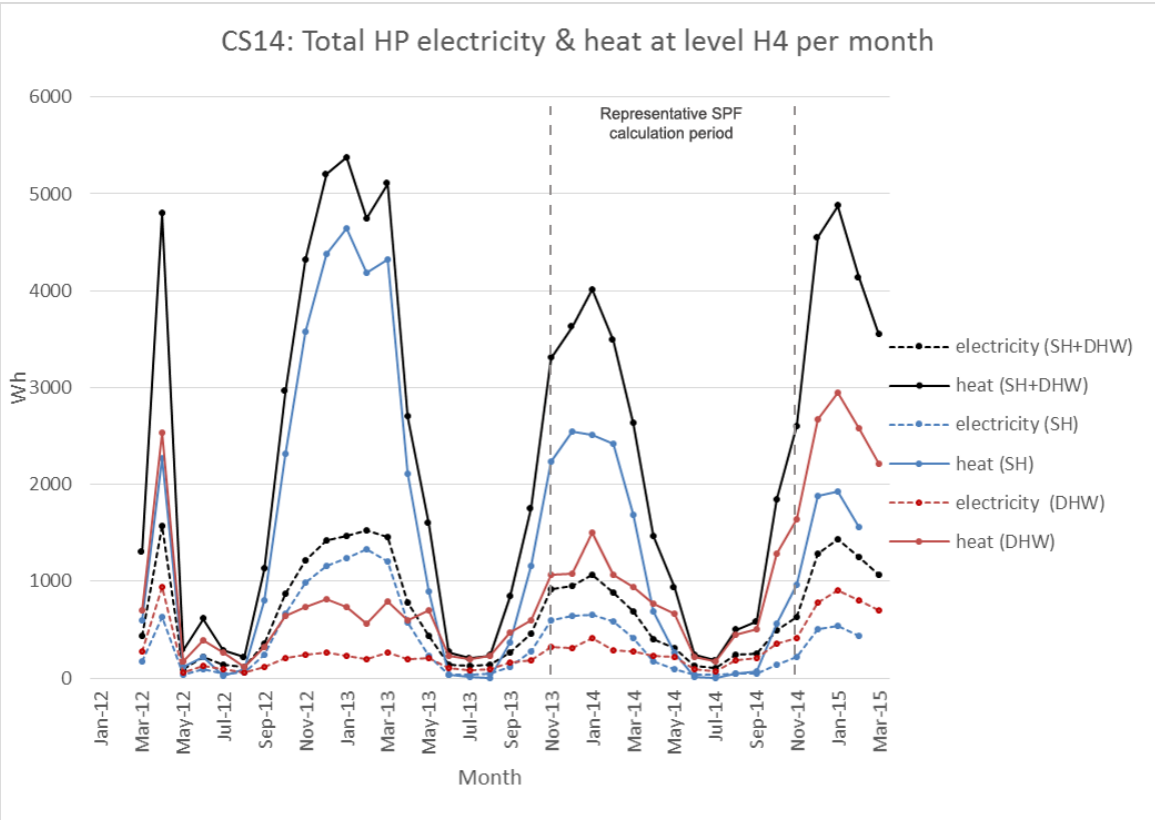


Figure D 28. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS14)

Case Study 15

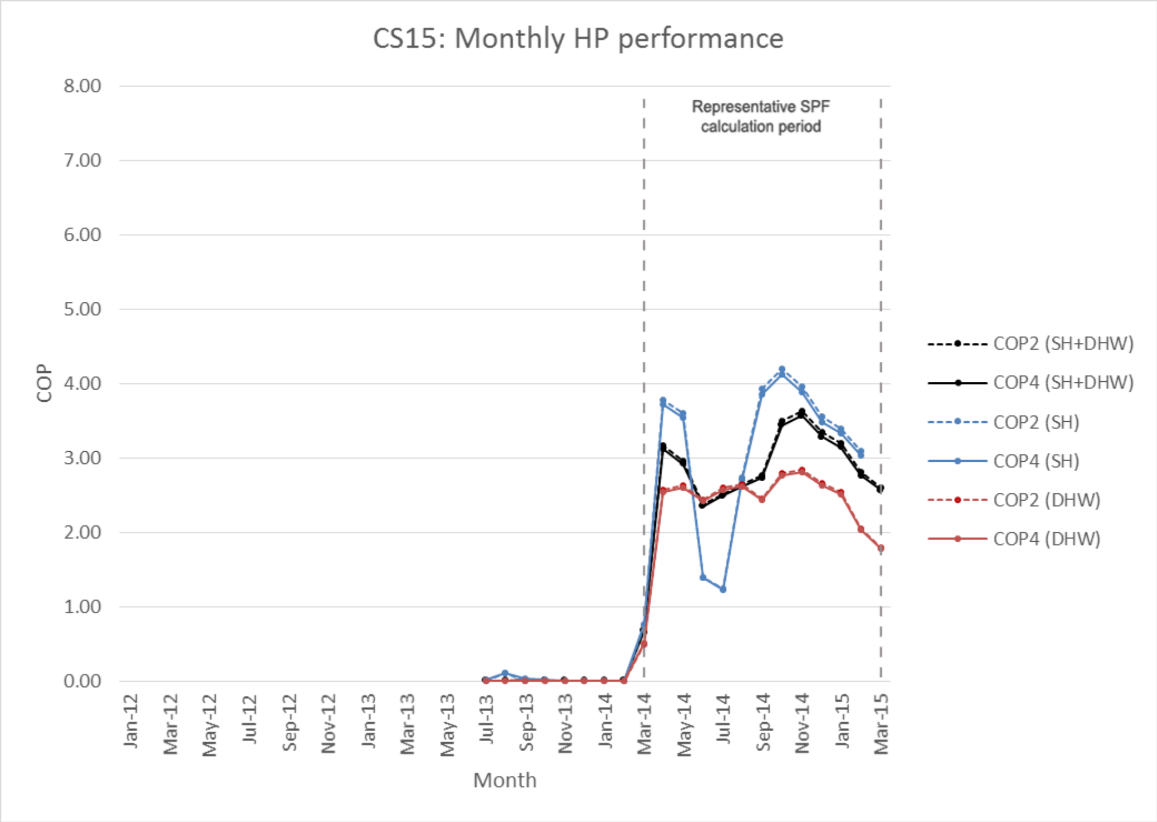


Figure D 29. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS15)

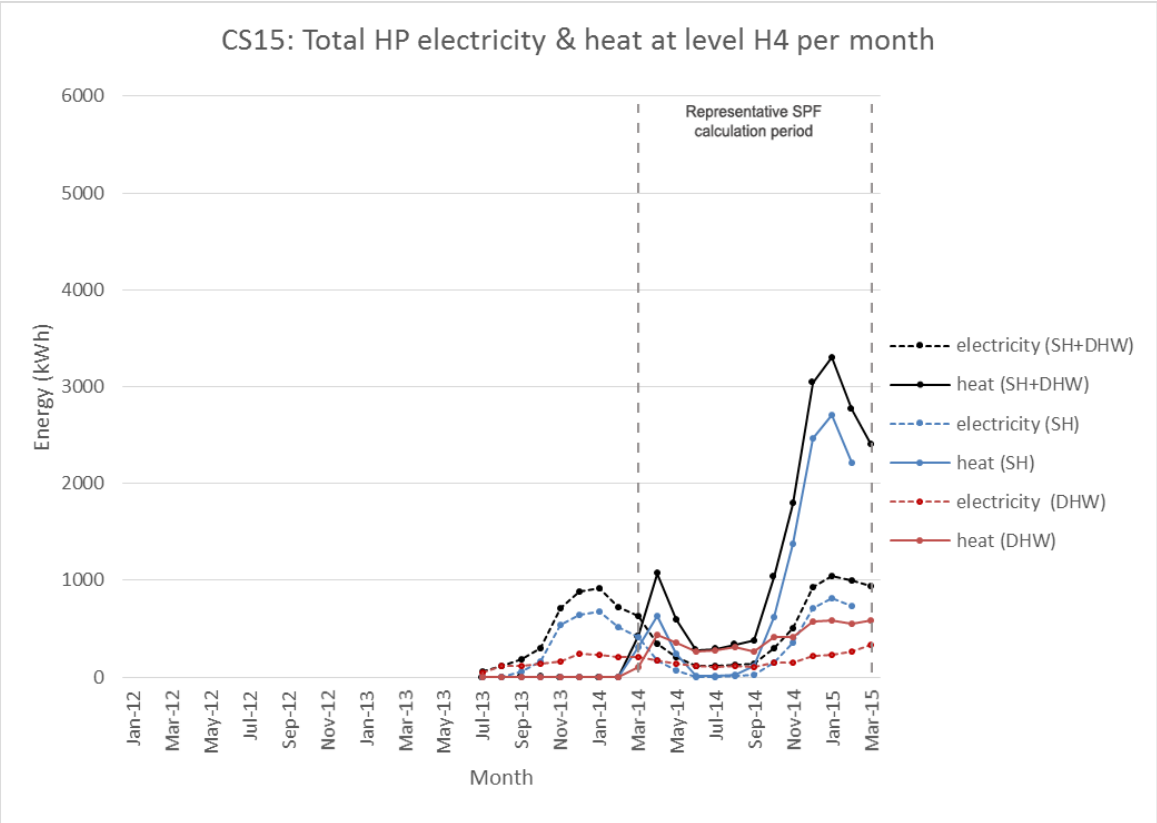


Figure D 30. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS15)

Case Study 16

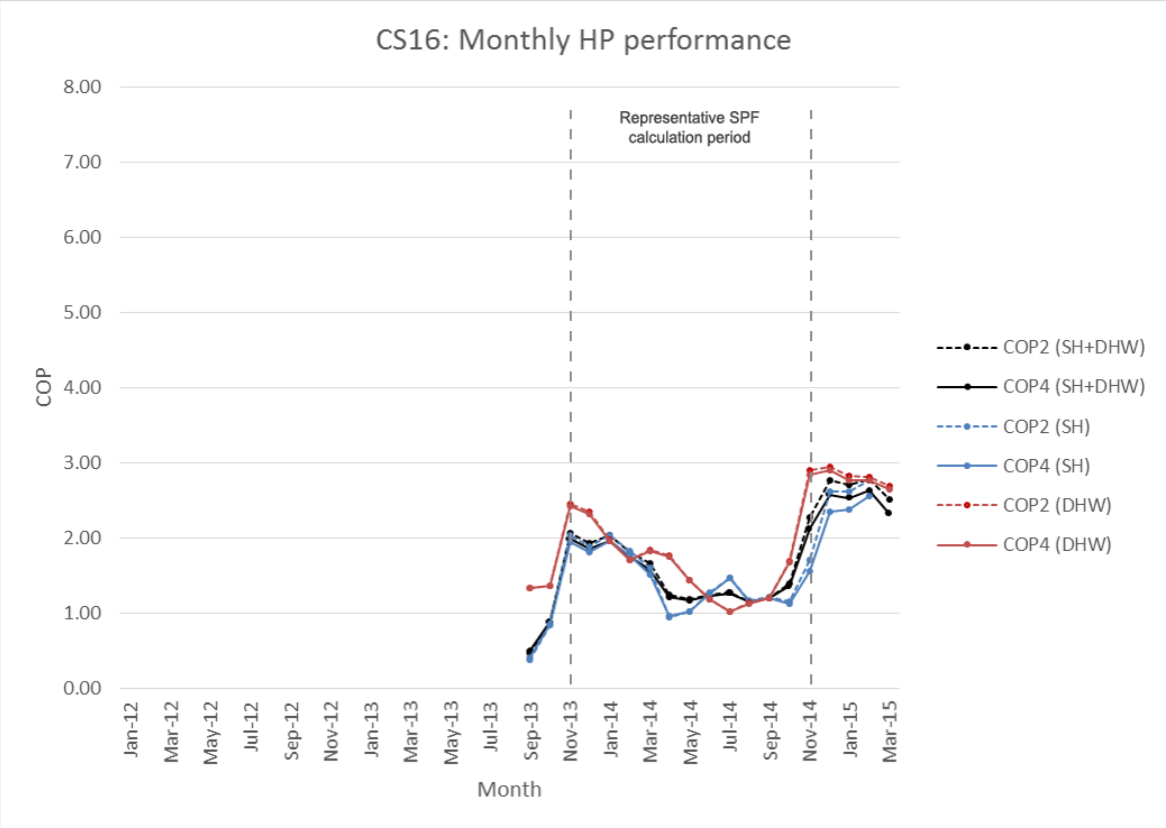


Figure D 31. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS16)

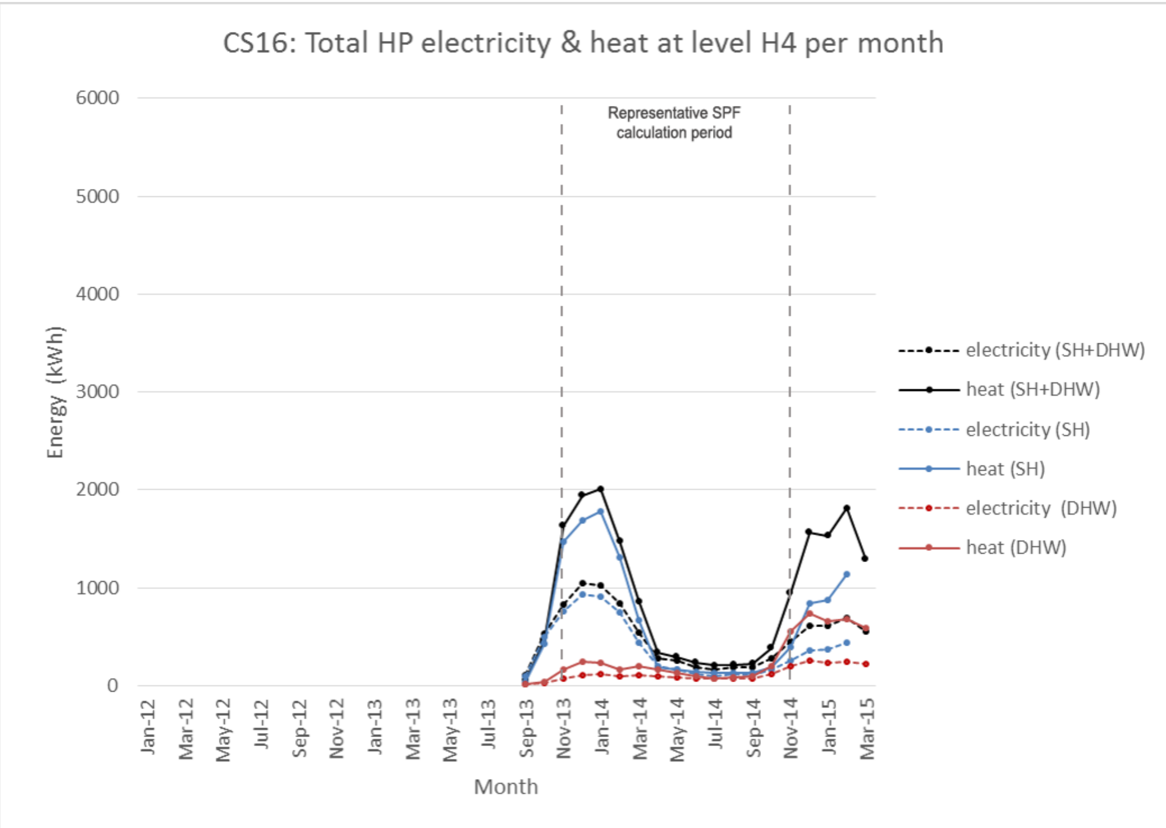


Figure D 32. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS16)

Case Study 17

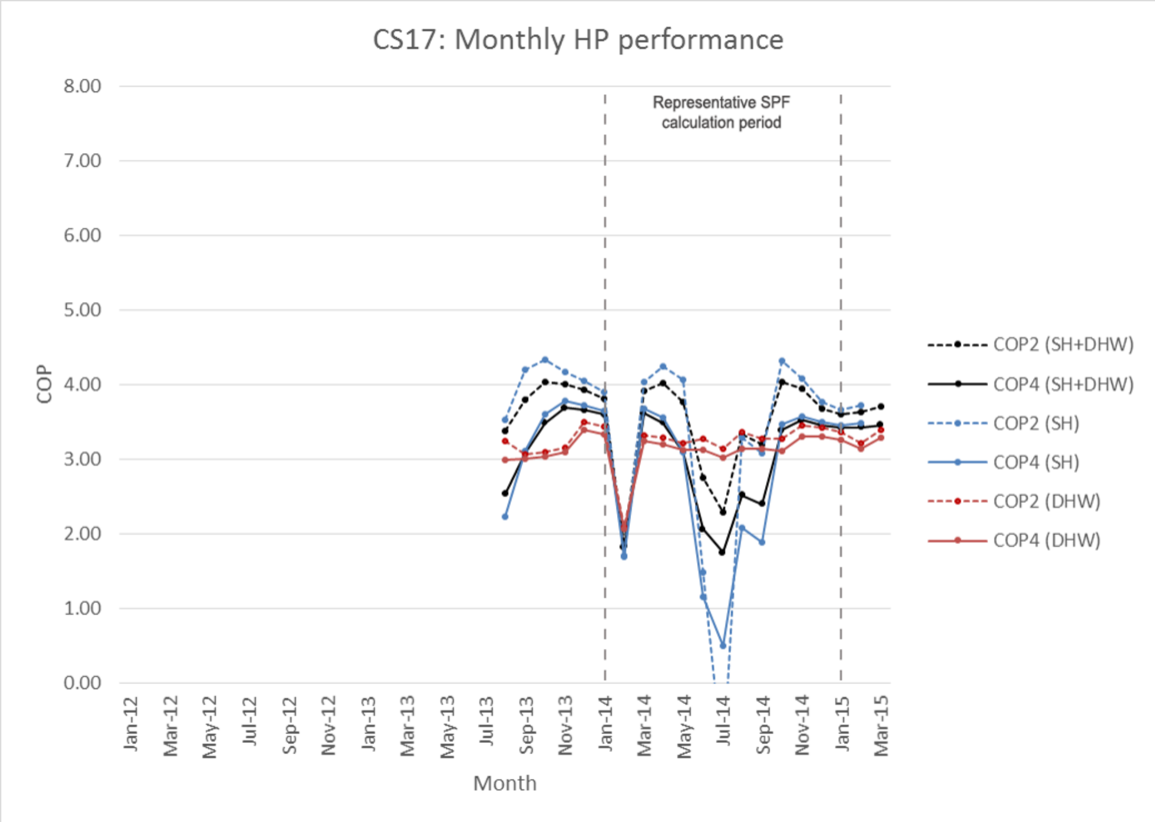


Figure D 33. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS17)

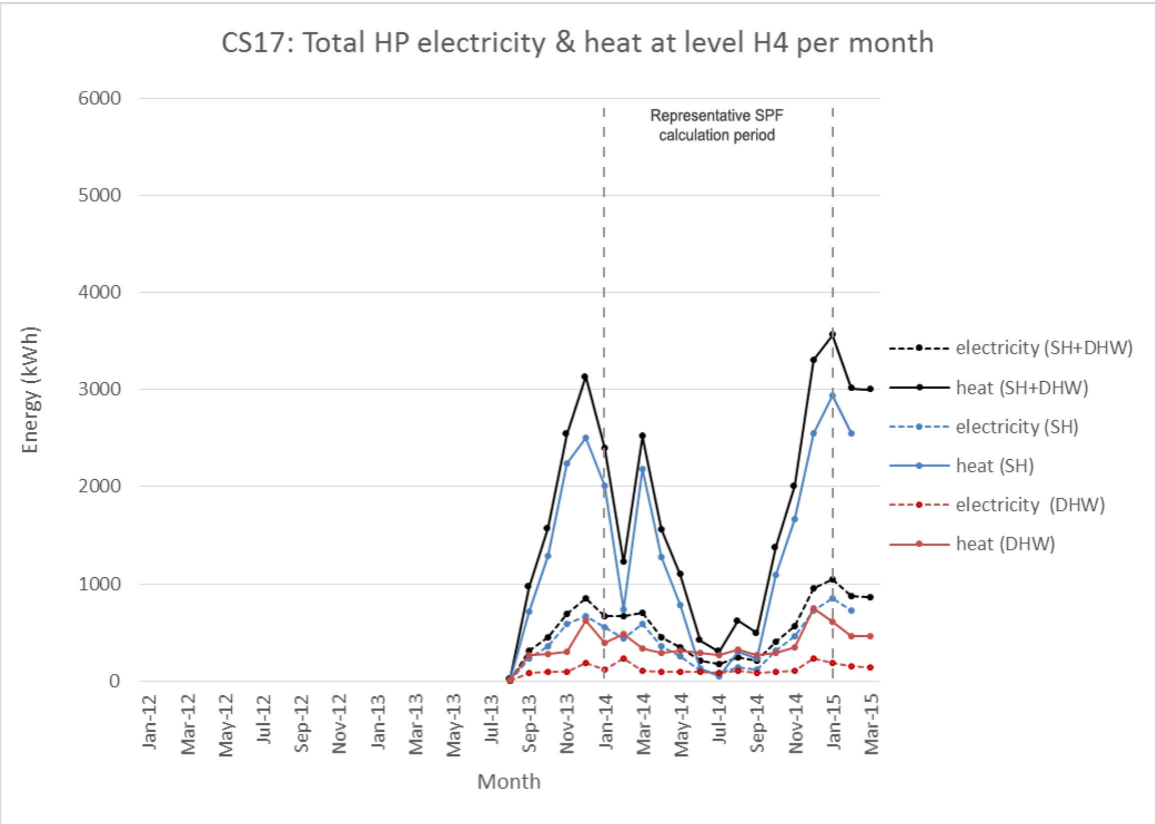


Figure D 34. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS17)

Case Study 18

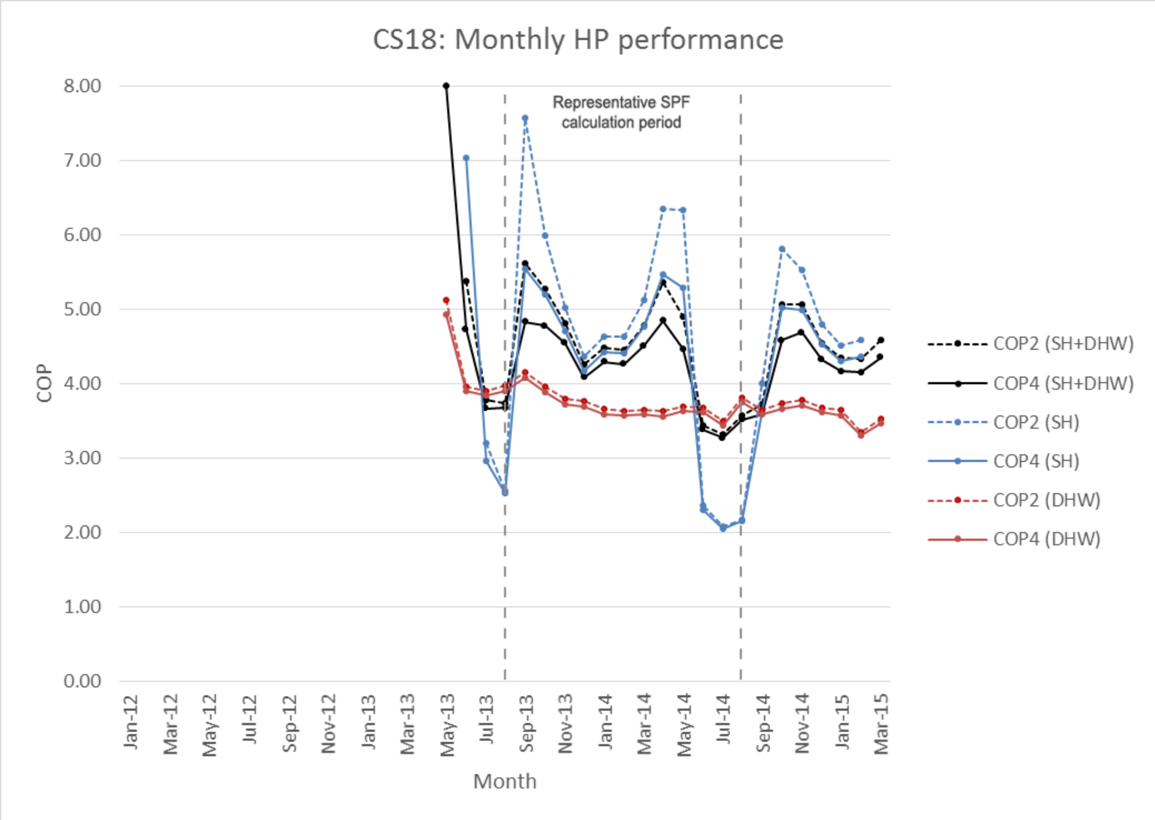


Figure D 35. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS18)

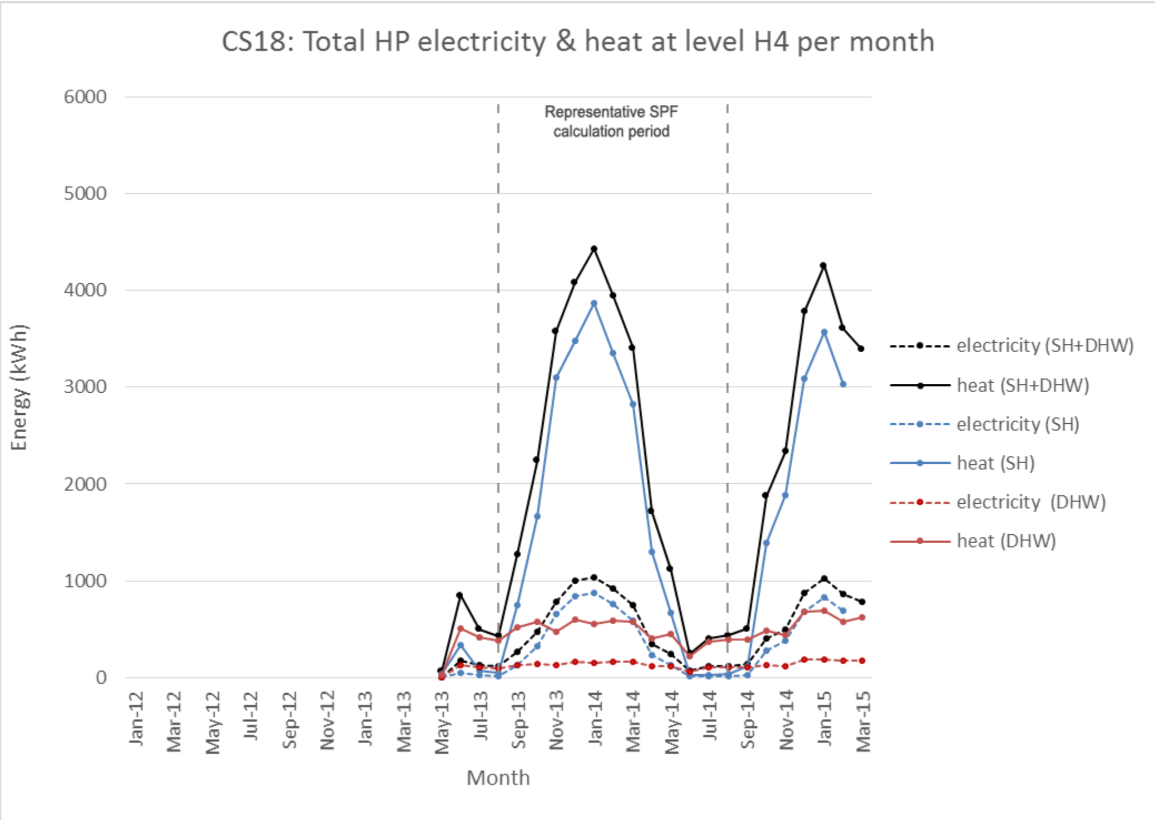


Figure D 36. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS18)

Case Study 19

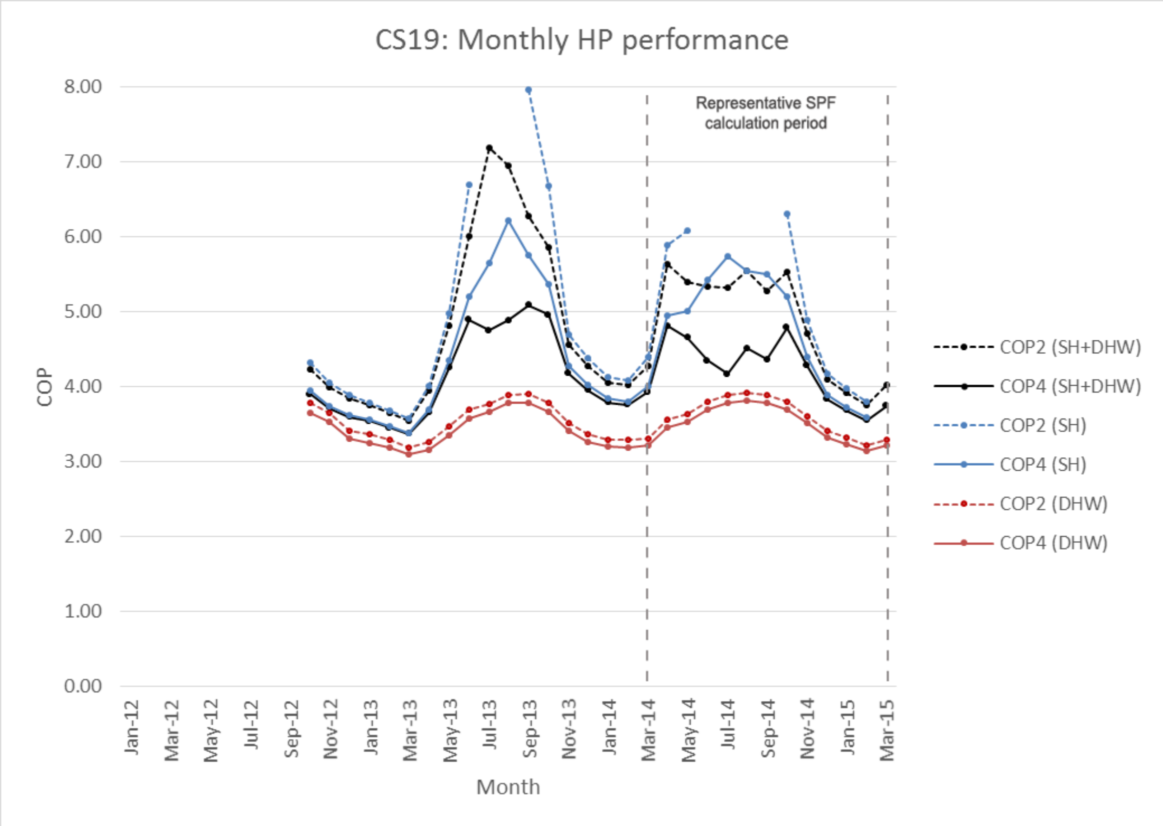


Figure D 37. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS19)

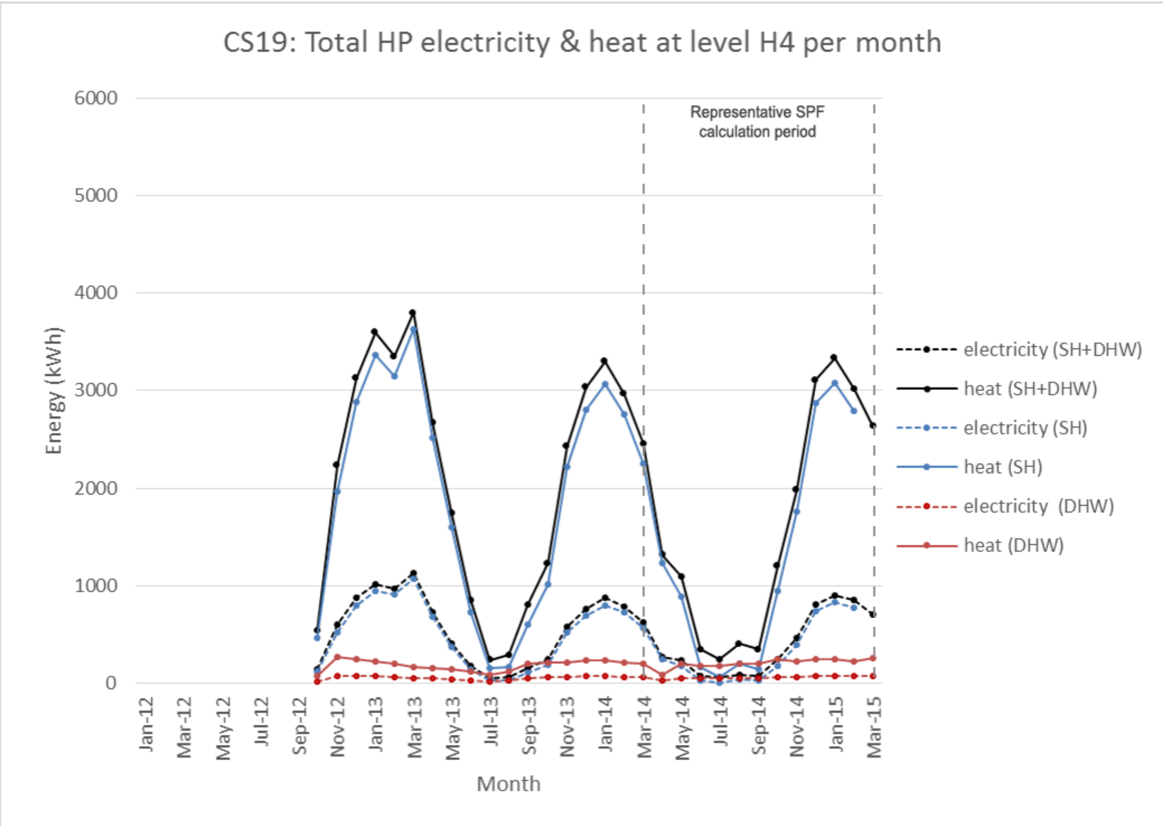


Figure D 38. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS19)

Case Study 20

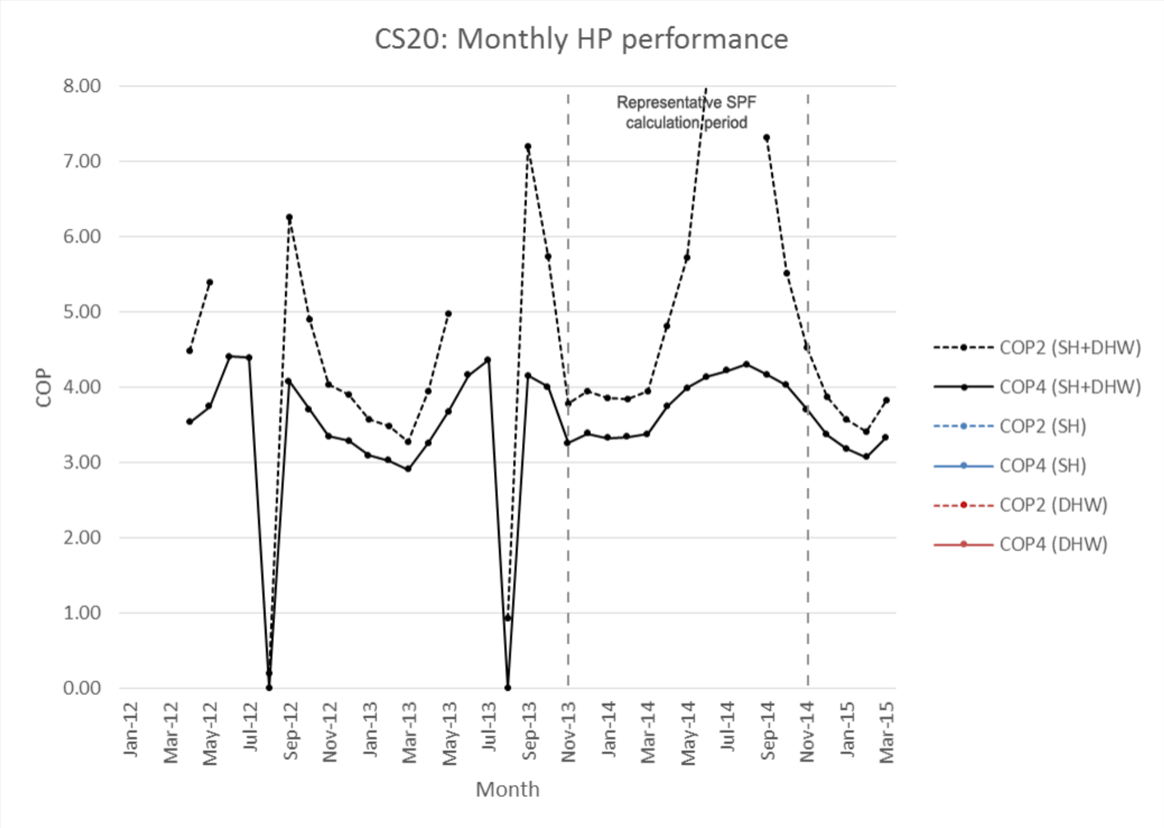


Figure D 39. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS20)

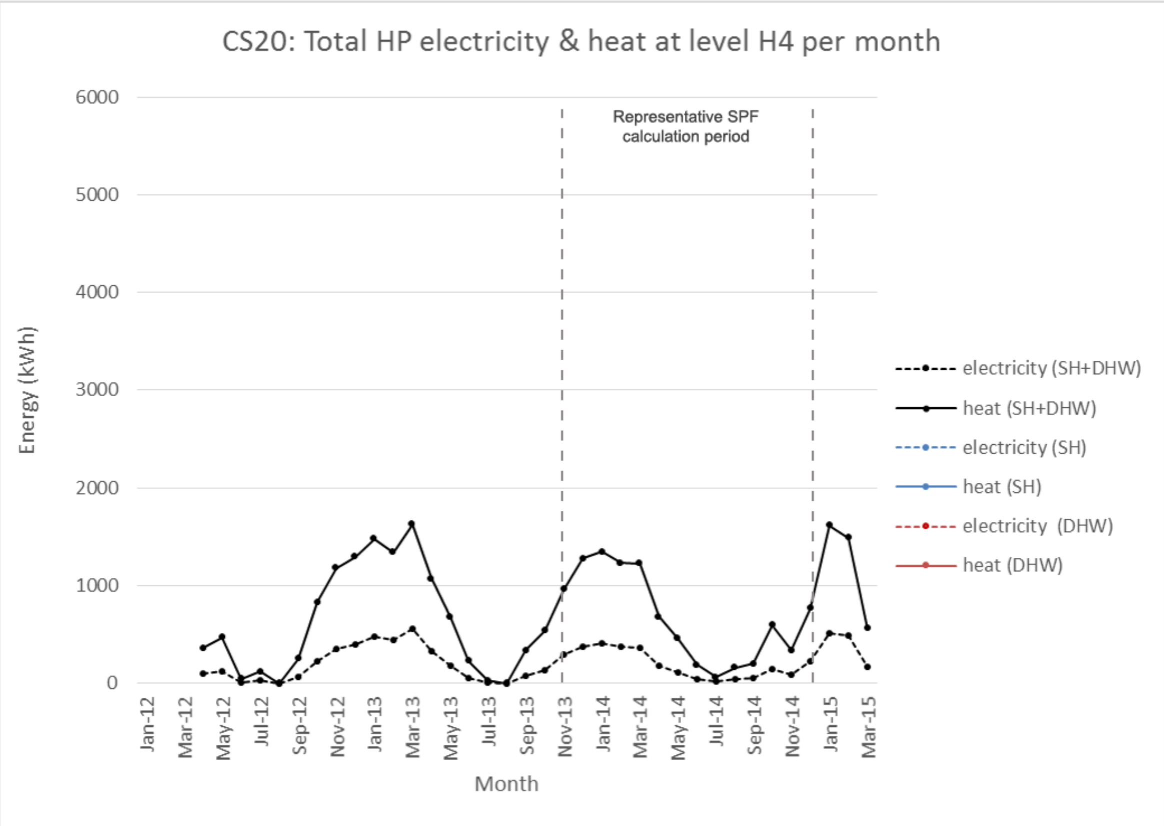


Figure D 40. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS20)

Case Study 21

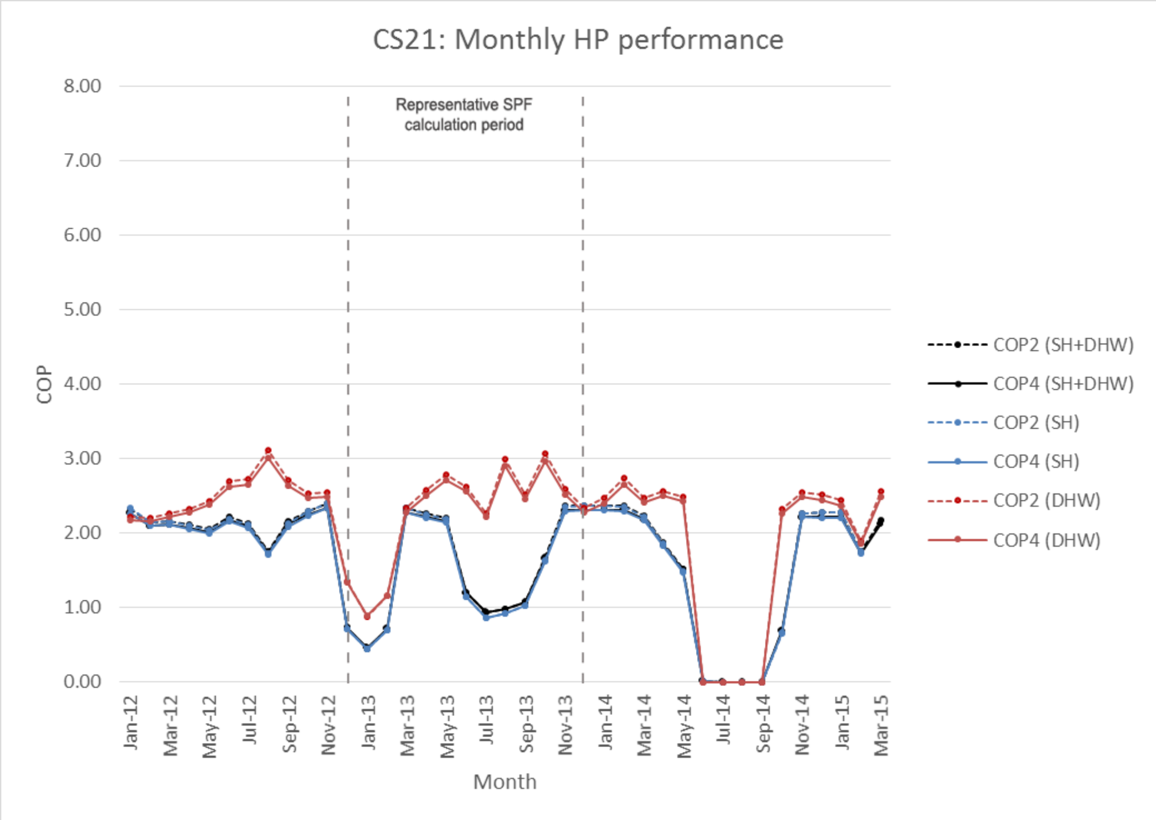


Figure D 41. Monthly COPs for SH, DHW and combined at levels H2 and H4 (CS21)

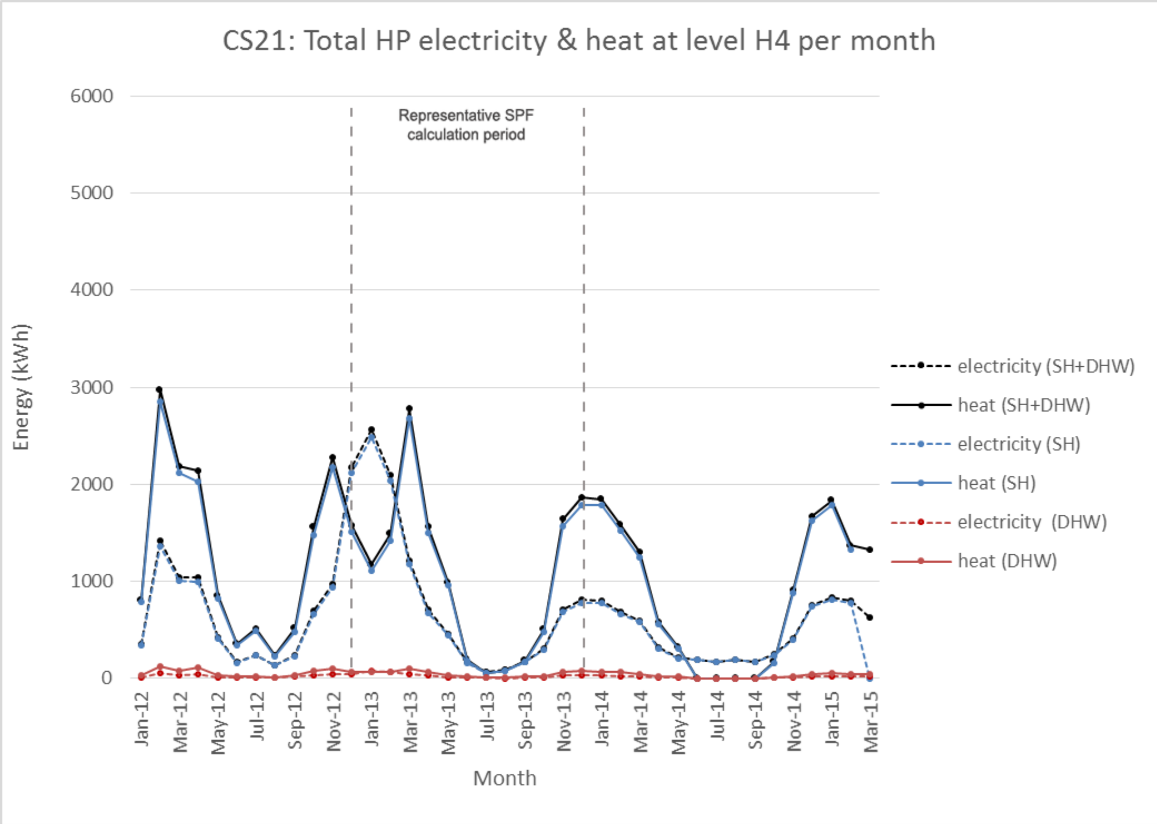


Figure D 42. Total monthly amount of electricity consumed and heat produced by the HP at level H4, for SH, DHW and both (CS21)

Appendix E – Detailed Case Study variables

E1 Social information and decision making

E2 Dwelling information and ventilation patterns

E3 Technical information on HPs

E4 Control and usage of heating systems

E5 Overall energy cost

E6 Occupant perception of comfort and satisfaction

E1 Social information and decision making

Table E 1. Household characteristics during the monitoring period

ID	Ownership	Number of adults	Number of children	Occupation status	Year moved in property	HP installation date	Occupants with a technical background	Amount of time home is occupied	Regularly away from home periods
CS01	Private	2-3*	-	Couple working from home	2012	Pre-2012	At least one	Most of the time	No or not long
CS02	Social	1	-	Retired	2011	2013	None	Most of the time	No or not long
CS03	Social	1	-	Retired	2013	2012	At least one	Most of the time	No, 8 weeks in 2015
CS04	Social	1	-	Retired	2009	2012	None	Most of the time	Up to 2 weeks /
CS05	Social	2	-	Couple (1 of the 2 working - temporarily off sick)	2011	2012	None	Most of the time	No or not long
CS06	Social	1	-	Inability to work	2007	2009	None	Most of the time	No or not long
CS07	Social	2	-	Retired	2010	2012	At least one	Most of the time	No or not long
CS08	Social	1	-	Retired	2011	2012	None	Most of the time	4-6 weeks / year
CS09	Private	2	-	Retired	1977	2012	None	Most of the time	2-4 weeks / year
CS10	Private	2	2	Husband working partly from home & stay-at-home-mum	2011	2012	At least one	Most of the time	No, 3 weeks in 2015
CS11	Private	2	-	Retired	1991	2012	None	Most of the time	6-8 weeks / year
CS12	Private	1	-	Inability to work	2013	2013	None	Most of the time	No or not long
CS13	Private	2	2	Couple working partly from home	2006	2013	At least one	Most of the time	4 weeks / year
CS14	Private	2	-	Couple not working by choice	2012	2012	At least one	Most of the time	8 weeks / year

CS15	Private	2	-	Couple (1 of the 2 working)	2014	2014	None	Most of the time	No or not long
CS16	Private	2-4*	-	Couple working from home (farmhouse)	2012	2012	None	Most of the time	No or not long
CS17	Private	2	-	Retired	2011	2011	At least one	Most of the time	Up to 3 weeks /
CS18	Private	2	1-2*	Couple (1 of the 2 working)	2013	2013	None	Evenings mostly	No or not long
CS19	Private	1-2*	-	Retired	1997	2012	At least one	Most of the time	5-6 weeks / year
CS20	Private	2	-	Couple working part-time	2005	2011	None	Most of the time	2-3 weeks /year
CS21	Private	1	-	Retired	2002	2011	None	Most of the time	No or not long

** Occupancy numbers varied throughout the monitoring period*

Table E 2. Decision making on the installation of HP in social ownership cases

ID	HP type	Previous fuel	HP already in place before tenant moved in	Option given to tenant by RSL	Tenant's preference / response to RSL	Tenant receives RHI payment
CS02	ASHP	Gas	NO	RSL asked whether tenant wanted a HP	Tenant was happy to have HP	NO
CS03	GSHP	N/A	YES	-	-	NO
CS04	GSHP	Gas	NO	RSL gave no option	Tenant didn't mind	NO
CS05	GSHP	Gas	NO	RSL gave no option	Tenant did not object	NO
CS06	ASHP	Storage heaters	NO	RSL gave no option	Tenant wanted gas	NO
CS07	ASHP	Storage heaters	NO	RSL gave no option	Tenants wanted gas	NO
CS08	ASHP	Storage heaters	NO	RSL gave no option	Tenant was told no gas could be supplied	NO

Table E 3. Decision making on the installation of HP in private ownership cases

	HP type	Previous fuel	HP already in place before tenant moved in	Motivation behind HP installation	Receives RHI payment
CS01	**ASHP**	N/A	YES	-	NO
CS09	**ASHP**	Oil	NO	Lower running cost, fits with PVs, RHI scheme, constant heat provided	YES
CS10	**ASHP**	Coal	NO	Lower overall cost, environmentally friendly, constant heat provided	YES
CS11	**ASHP**	Oil	NO	Recommended by trusted installer, no mains gas available, oil tank couldn't be refitted due to regulations	YES
CS12	**GSHP**	N/A	NO, new build	Attended green info day, no mains gas, looked at another house with HP	YES
CS13	**GSHP**	Oil	NO	Minimal running cost & energy footprint, environmentally friendly	YES
CS14	**GSHP**	N/A	NO, new build	Environmentally friendly, cost efficient, RHI scheme, long standing, low maintenance, no mains gas	YES
CS15	**GSHP**	N/A	NO, new build	Interested in HPs for own business purposes, tried out to understand technology better, no mains gas	YES
CS16	**GSHP**	N/A	NO, new build	Recommended by planning people, installer & friends, land available, efficient technology	YES
CS17	**GSHP**	Oil	NO	Desire to invest on renewable heating	YES
CS18	**GSHP**	N/A	NO, new build	RHI scheme, economically & environmentally sound choice	YES
CS19	**GSHP**	Oil	NO	Always interested in RES, cost effective solution (considering RHI scheme & PV's payback)	YES
CS20	**ASHP**	Storage heaters	NO	Installer & experts' recommendation, fits well with PVs	YES
CS21	**ASHP**	Oil	NO	Installer recommendation, RHI scheme, oil tank couldn't be refitted due to current regulations	YES

E2 Dwelling information

Table E 4. Dwelling characteristics as observed by researchers, narrated by householders or stated by RSLs and cross-checked with the EPC data available

ID	Property type	Floors	TFA (m2)	No. of beds	Age	Wall type	Roof type	Floor type	Window type	EPC band	EPC date	Draughts, damp, mould issues or air quality issues	Interventions since HP installation*
CS01	Detached	2	201	4	2011-12	Insulated brick + block wall	Pitched, insulated loft (300mm)	Carpeted, insulation unknown	Double glazed	C	26/09/12	Internal circulation draughts due to large glazing area	NO
CS02	Mid terrace	1	50	1	1945-64	Filled cavity + EWI	Pitched, insulated loft	Probably no insulation	Double glazed	D	05/02/15	MVHR blows cold air in (when on)	NO
CS03	End terrace	1	50	1	1945-64	Filled cavity + EWI	Pitched, insulated loft	Probably no insulation	Double glazed	D	01/04/15	NO	NO
CS04	End terrace	1	52	1	1945-64	Filled cavity + EWI	Pitched, insulated loft	Probably no insulation	Triple glazed (15-16 years old)	D	01/04/15	Draughts from MVHR (when on),damp/mould above front door (has been treated)	NO
CS05	Mid terrace	1	52	1	1945-64	Filled cavity + EWI	Pitched, insulated loft	Probably no insulation	Double glazed	D	10/02/15	Draughts from MVHR (when on), mould in bath when used more intensively	NO
CS06	Semi	1	34	1	1930s	Filled cavity	Pitched, insulated loft	Probably no insulation	Double glazed	D	18/03/15	Mould around bathroom window frame	Autumn 2015: CWI added
CS07	Mid terrace	1	41	1	1930s	Filled cavity	Pitched, insulated loft (>200 mm)	Probably no insulation	Double glazed	E	09/02/15	Draughts everywhere in the house, leaky front door, feels damp	Winter 2013: CWI and loft insulation added
CS08	Mid terrace	1	34	1	1930s	Filled cavity	Pitched. insulated loft	Probably no insulation	Double glazed	D	17/03/15	Damp around bathroom window and walls (has been treated)	2012-13: CWI added, bath + kitchen renovated

CS09	Detached	1	164	3-4*	1973	Partially filled cavity	Pitched, insulated loft (varied, 100-270 mm)	Uninsulated	Triple glazed, argon filled	D	25/03/15	NO	2012-13: one room converted to ensuite + study
CS10	Detached	3	293	5	Pre 1919	Stone wall, no insulation	Pitched, partial roof insulation(100 mm)	Underfloor heating areas insulated only	Double glazed (thinner in GF kitchen+toilet)	F	24/09/14	Draughts mostly on GF mostly due to unstripped doors, damp in plantroom due to external water pass	2013: roof insulation (utility+kitchen),underfloor heating insulation
CS11	Detached	2	178	4	1958 +extension	Filled cavity (new+ old walls)	Pitched, insulated loft (150mm)	Sunlounge floor insulated only	Double glazed	D	21/10/14	NO	NO
CS12	Detached	2	106	2	2008-9	Insulated brick wall	Pitched, insulated loft	Insulated floor	High performance double glazing	D	19/03/15	Some draughts due to wood burner air vents	NO
CS13	Deatched	3	252	5	1780s +extension	Highly insulated brick walls (new+ old)	Pitched, roof insulation at rafters	Insulated floor + in-between floors	High performance double glazing	B	30/06/12	Draughty front door, dry air issues	NO
CS14	Detached	1	293	3 (+1**)	2012	Insulated brick cavity	Pitched, insulated loft	Insulated floor	Triple argon filled	B	29/05/12	Slight draughts felt through glazed back wall only when windy	NO
CS15	Detached	2	262	4	2011	Insulated walls	Pitched, insulated loft	Insulated floor	Double glazed	B	11/08/11	NO	NO
CS16	Detached	2	314	3	2012	Insulated walls	Pitched, insulated loft	Insulated floor	High performance double glazed	A	16/12/14	NO	NO
CS17	Detached	2	179	3	1992	Insulated walls	Pitched, insulated roof	Probably no insulation	Double glazed	C	12/05/14	NO	Summer 2015: conservatory roof insulation

CS18	Detached	2	346	4	2012	Insulated walls	Pitched, insulated roof	Insulated floor	High performance double glazed	B	15/01/13	Significant drought presence due to building skin defect	NO
CS19	Detached	2	95	3	1820s +extension	Stone wall, no insulation+filled cavity	Pitched, insulated loft (300mm)	Insulated floor (25mm PUR)	Double glazed	C	03/12/15	Leak/damp probably associated with upstairs window	Late 2015: brick cavity wall filled in (kitchen area)
CS20	Semi	2	99	2	1956	Filled cavity (imperfect)	Pitched, insulate loft	Uninsulated	Double glazed	C	07/01/15	Rising damp on gable wall	NO
CS21	Mid terrace	1	102	3	1970s +extension	Filled cavity	Pitched, insulate loft	Probably no insulation	Double glazed	D	09/02/14	NO	NO

** Interventions refer to the monitoring period only.*

Table E 5. Natural and mechanical ventilation regime, as narrated by householders

ID	Smoker in house	Window opening			Mechanical ventilation with Heat Recovery
		Winter	Summer	Main reason(s)	
CS01	YES	**Limited** - Windows closed apart from backyard door if weather is nice	**YES** – windows open in summer, no particular ventilation routine	Temperature control; to let dog out; householder also stands at the backyard door when smoking	**NO**
CS02	NO	**Limited** – bedroom window open every day if weather is nice; other windows tend to be closed unless in shower or cooking	**YES** – most windows open when weather is nice	Temperature control; fresh air	**YES** – available but turned off as it blows cold air
CS03	YES	**NO**	**Limited** – lounge door open every day	All windows locked apart from lounge door	**YES –** turned on, fan on high
CS04	YES	**Limited** – windows closed but lounge door almost always slightly open	**YES** – windows tend to be kept open when weather is nice, closed at night	Temperature control; to let dog out; fresh air	**YES –** turned on 24hrs/day
CS05	NO	**Limited** – Lounge door and some windows open for a while if weather is nice	**YES** – windows more open in summer than in winter, no particular schedule, trickle vents open	Temperature control; fresh air	**YES** – available but mostly turned off as it blows cold air and is noisy (on in the morning only)
CS06	NO	**NO** – windows open only if it gets too warm on a sunny day	**YES** – Windows in most rooms wide open (openable parts)	Temperature control	**NO**
CS07	NO	**NO** – Occasionally when drying washing inside	**Limited** – kitchen, bedroom and bathroom windows may be open for a while when warm outside	Fresh air	**NO**
CS08	NO	**YES** – windows open a lot in the morning (and perhaps later on in the day) and closed around tea time (afternoon)	**YES** – windows open all day and closed at night	Fresh air	**NO**
CS09	NO	**NO** – Windows open very rarely	**YES** – windows open in kitchen and bedroom area	Fresh air	**NO**

CS10	NO	**NO –** windows closed	**NO –** windows closed, backyard door may be open	No need for fresh air, house is not air-tight and takes a long time to heat up – doors open for children to play out	**NO**
CS11	NO	**NO –** windows closed, occasionally open for a quick blow-through, trickle vents closed	**Limited –** windows open if too hot, trickle vents mostly closed	Temperature control; fresh air	**NO**
CS12	NO	**NO –** windows closed, trickle vents might be opened (lounge only) for a while as it starts feeling draughty	**YES –** windows usually open when in house, behaviour also depends on temperature	Fresh air	**NO**
CS13	NO	**Very limited –** windows open only if it feels very dry or stuffy (if not too cold outside)	**YES –** windows always open	Temperature control, fresh air	**NO,** occupant considers MVHR installation to resolve dry air issues arising from building air-tightness in conjunction with underfloor heating
CS14	NO	**NO –** windows closed, bathroom window open when in shower, trickle vents closed	**YES –** windows open all the time, trickle vents open	Temperature control	**NO**
CS15	NO	**NO –** Windows closed, trickle vents open in rooms used	**YES –** windows open when weather is good and HP is off	Temperature control, fresh air	**NO**
CS16	NO	**Limited –** windows open 2-3 times/week	**YES –** windows mostly open (in occupied rooms)	Temperature control, fresh air	**NO**
CS17	NO	**NO –** windows not open	**Limited –** Doors/windows open occasionally *[recorder failed/missing data]*	Doors open when siting outside/to go in and out *[recorder failed/missing data]*	**NO**
CS18	NO	**NO –** windows closed, trickle vents blocked (as they were mistakenly thought to have been causing draught)	**Limited –** windows open mainly in conservatory area, and in bedroom area only if it there is a really hot night	Temperature control	**NO**
CS19	NO	**Very limited –** windows open occasionally, i.e. once/week, trickle vents closed	**Limited –** windows more open in summer than winter (depending on weather), trickle vents mostly open	Fresh air	**NO**

CS20	NO	**NO –** windows mostly closed	**Very limited –** bedroom windows open very rarely, mostly if there is a warm day	Fresh air	**NO**
CS21	NO	**Limited –** some windows open every morning for 5-10'	**YES –** windows generally open	Temperature control; fresh air	**NO**

E3 Technical information on HPs

Table E 6. HP type, size and heat emitter characteristics

ID	HP type	Declared net capacity (kW)	MCS certificate date	Previous fuel	Emitter type	Radiators		
						All new	From previous system	
							All	Partly
CS01	ASHP	14	Pre-2012	N/A (newbuild)	Underfloor	N/A	N/A	N/A
CS02	ASHP	5.5-7	2013	Gas	Rads	✗	✗	All original apart from 1 new added (lounge)
CS03	GSHP	6*	2012	Gas	Rads	Unknown, system installed before householder moved in		
CS04	GSHP	6	2012	Gas	Rads	✗	✗	All original apart from 1 new added (lounge)
CS05	GSHP	6	2012	Gas	Rads	✗	✗	All original apart from 2 new added (lounge), 1 replaced (bath)
CS06	ASHP	5	2009	Storage heaters	Rads+hydronic fan convector	✓	✗	✗
CS07	ASHP	5	2012	Storage heaters	Rads+hydronic fan convector	✓	✗	✗
CS08	ASHP	5	2012	Storage heaters	Rads+hydronic fan convector	✓	✗	✗
CS09	ASHP	16	2012	Oil	Rads	✗	✗	Some original, some replaced (e.g. at least 3 in bedroom area) and 1 new added (kitchen)
CS10	ASHP	Two HPs: 14 and 8.5**	2012	Coal	Underfloor + Rads	✓	✗	✗
CS11	ASHP	14	2012	Oil	Rads	✗	✗	All original apart from 2 new added (kitchen and study)
CS12	GSHP	7	2013	N/A (newbuild)	Underfloor + Rads	N/A	N/A	N/A
CS13	GSHP	12	2013	Oil	Underfloor	N/A	N/A	N/A
CS14	GSHP	12	2012	N/A (newbuild)	Underfloor	N/A	N/A	N/A
CS15	GSHP	11	2014	N/A (newbuild)	Underfloor + Rads	N/A	N/A	N/A
CS16	GSHP	12	2012	N/A (newbuild)	Underfloor +Bath Rads	N/A	N/A	N/A
CS17	GSHP	12	2011	Oil	Rads	✗	✗	Some original (e.g. hall, living room and kitchen), some replaced (e.g. dining) & some moved place

CS18	GSHP	12	2013	N/A (newbuild)	Underfloor	N/A	N/A	N/A
CS19	GSHP	9	2012	Oil	Underfloor + Rads	✗	✓	✗
CS20	ASHP	11	2011	Storage heaters	Rads	✓	✗	✗
CS21	ASHP	7	2011	Oil	Rads	✗	✓	✗

**Wrong entry in the MCS certificate as information for solar panels have been entered instead of the HP details*

***Inaccurate entry in the MCS certificate, naming a single 14kW HP only but with a Metadata declared net capacity of 22.5kW*

Table E 7. Comparison between metering schematics and actual installation, as observed

ID	Original monitoring schematic	Revised monitoring schematic	Monitoring Schematic Description	Description (observed)	Is schematic listed correct?	Comment
CS01	2.4	2.4	ASHP providing SH and DHW, with separate electricity supply to immersion heater for DHW only	ASHP connected to integrated packaged cylinder in unheated uninsulated garage. 4 circ' pumps in garage plus 1 in house – total circ' load approximately 400 W. 2 manifolds to UFH. Pipe insulation generally poor plus no insulation to pumps or valves.	YES	All control settings available to occupant.
CS02	2.4	2.4	ASHP providing SH and DHW, with separate electricity supply to immersion heater for DHW only	ASHP connected through 'cold roof' space to cylinder in house with 50 W circ' pump. Pipes well insulated, no pump or valve insulation. Cylinder used for washing up only. Electric shower. Radiators. User control by room thermostat only. Radiator plus electric resistance fan heater in bathroom.	YES	Listed as wrong MCS number. No user control other than room thermostat
CS03	16.12	16.12	GSHP providing SH and DHW, with integral DHW storage and no separately-supplied boost heaters for either SH or DHW	GSHP with borehole connected through 'cold roof' to integrated HP and cylinder. Pipes, etc, unevenly insulated. Circ' pump speed 1 – 35 W. Cylinder used for washing up only. Electric shower. Radiators. User control by room thermostat only. Radiator plus electric resistance fan heater in bathroom.	YES	No user control other than room thermostat
CS04	16.12	16.12	GSHP providing SH and DHW, with integral DHW storage and no separately-supplied boost heaters for either SH or DHW	GSHP with borehole connected through 'cold roof' to integrated HP and cylinder. Pipes, etc, unevenly insulated. Circ' pump speed 2 – 45 W. Buffer vessel. Cylinder used for washing up only. Electric shower. Radiators. User control by room thermostat only. Radiator plus electric resistance fan heater in bathroom.	YES	No user control other than room thermostat
CS05	16.12	16.12	GSHP providing SH and DHW, with integral DHW storage and no separately-supplied boost heaters for either SH or DHW	GSHP with borehole connected through 'cold roof' to integrated HP and cylinder. Installation sink pipes, etc, unevenly insulated, ground loop pipes well insulated. Circ' pump speed 2 – 45 W. Buffer vessel. Cylinder used for washing up only. Electric shower. Radiators. User control by room thermostat only. Radiator plus electric resistance fan heater in bathroom.	YES	No user control other than room thermostat
CS06	2.4	2.4	ASHP providing SH and DHW, with separate electricity supply to boost heater for DHW only	ASHP insulated pipes on outside wall into attic. Packaged HP & cylinder with controls & 2 circ' pumps in 'cold roof'. Pipes insulated not pumps or valves. Radiators with hydronic fan convector in kitchen & bathroom. Electric fire in living room.	YES	No access to HP control. SH & DHW control by user programmer

CS07	2.4	2.4	ASHP providing SH and DHW, with separate electricity supply to boost heater for DHW only	ASHP insulated pipes on outside wall into attic. Packaged HP & cylinder with controls & 2 circ' pumps in 'cold roof'. Pipes insulated not pumps or valves. Radiators with hydronic fan convector in kitchen & bathroom. Electric fire in living room.	YES	No access to HP control. SH & DHW control by user programmer
CS08	2.4	2.4	ASHP providing SH and DHW, with separate electricity supply to immersion heater for DHW only	ASHP insulated pipes on outside wall into attic. Packaged HP & cylinder with controls & 2 circ' pumps in 'cold roof'. Pipes insulated not pumps or valves. Radiators with hydronic fan convector in kitchen & bathroom. Electric fire in living room.	YES	No access to HP control. SH & DHW control by user programmer
CS09	3.4	3.4	Split ASHP providing SH and DHW. internal unit fitted with booster and separately supplied immersion heater for DHW	Split system ASHP. Outdoor unit located far from house. cylinder inside house. Controller used by occupants with wireless room 'stat. Radiators. Wood burning stoves and electric underfloor heating (UFH) in bathroom. Range cooker in kitchen.	YES	No comment
CS10	Unknown	Unknown	-	There are TWO separate HPs supplying DHW, UFH to kitchen/lounge & radiators to the rest of the house. Both HPs remotely located from house. Cylinder, circ' pumps and valves in unheated utility room. 5 circ' pumps plus a secondary return pump - total load approx' 450 W. Plate heat exchangers between HPs & installation. Very poor quality insulation. 7 day programmer. Wood burning stoves in two rooms.	N/A	Closest schematic is 2.4. Note: Only ONE of the TWO HPs is heat metered
CS11	0.4	0.4	ASHP providing SH and DHW, with immersion heater for DHW	Cylinder & 3 circ' pumps in insulated 'warm roof' space with plate heat exchanger between HP and installation. Good pipe insulation not pumps or valves. control with programmer for occupant use.	NO	Wrong schematic. DHW immersion unmetered
CS12	16.12	16.12	GSHP providing SH and DHW, with integral DHW storage and no separately-supplied boost heaters for either SH or DHW	integrated GSHP and cylinder with buffer. 350-360m straight ground loop. UFH downstairs & radiators upstairs. 3 circ pumps.	YES	No comment
CS13	0.12	0.12	GSHP (2-pipe, single/common output) providing integral boost SH and DHW. Separate cylinder with immersion.	UFH driven by variable speed pump. DHW circuit with fixed speed pump. UFH throughout. Wood burning stove.	NO	No comment
CS14	9	8.12	GSHP (2-pipe, single/common output) providing integral boost to SH and DHW.	Double borehole feeding HP with cylinder & buffer in unheated garage. Insulated buried pipework to UFH in bungalow. Insulated pipework, valves & circ' pumps. 3 external circ' pumps visible. 6 Circ pumps to UFH zones . 9 circ' pumps total.	NO	No comment

CS15	0.12	0.12	GSHP (2-pipe, single/common output) providing integral boost SH and SHW.	HP in unheated garage with professional insulation to pipes and insulated valve boxes. Buffer and packaged cylinder in heated space. UFH downstairs radiators upstairs. 4 circ' pumps. 2 wood burning stoves, 1 in use. Electric UFH in bathroom	YES	No comment
CS16	16.12	16.12	GSHP providing SH and DHW, with integral DHW storage and no separately-supplied boost heaters for either SH or DHW	HP in house. Buffer with 4 UFH manifolds. Approximately 700 W circ' power plus secondary return circ' pump. Aga plus wood burning stove.	YES	No comment
CS17	8.12	8.12	GSHP providing SH and DHW, with no separately-supplied boost heaters or supplementary electrical heating	HP and integrated cylinder & buffer vessel in unheated garage. Pipes insulated not pumps or valves. Variable speed circ' pump (25-45 W) to radiators.	NO	No comment
CS18	0.12	0.12	GSHP (2-pipe, single/common output) providing integral boost to SH and DHW.	HP, buffer & cylinder in house. 2 UFH manifold circ' pumps on speed 3. Total circ' pump approximately 700 W.	NO	No comment
CS19	6.13	6.13	GSHP (2-pipe) providing SH and DHW, with booster heater for SH integrated with buffer vessel; with separately-supplied boost heaters for SH and DHW	HP, buffer with immersion, 1 ground loop and 2 main installation circ' pumps in unheated shed. Insulation of top quality with circ' pump and manifold boxes. 2 more circ' pumps indoors alongside cylinder. Total circ' pump load 600 W. UFH downstairs, radiators upstairs. Living room fire.	NO	No comment
CS20	Unknown	Unknown	-	ASHP connected to buffer and circ' pipes in unheated shed. DIY insulation to buffer. Very long run from HP into house. Radiators supported by wood burning stove in 2 living rooms. DHW provided by solar thermal and immersion heater (unmetered)	N/A	Correct schematic is 4.1. ASHP providing SH only with immersion in buffer vessel
CS21	4c	4.1	ASHP providing SH and DHW through a thermal store with immersion heater.	ASHP providing SH and DHW through a thermal store with immersion heater.	NO	None of the existing schematics matches this type of installation

Table E 8. Presence of boost (based on HP model specification), immersion (based on site observation), weather compensation and estimation of SH flow temperatures, SH/DHW proportions and the amount of heat provided by the DHW immersion.

ID	Boost	Separate DHW cylinder immersion	Buffer immersion	Thermal store immersion	Average flow temperature in SH mode (°C)*	Peak flow temperature in SH mode (°C)*	Weather compensation**	% SH to total heating ***	Proportion of DHW heating by the immersion****
CS01	NO	YES	NO or N/A	N/A	34.18	42.25	YES	72.94	7.21
CS02	NO	YES	NO or N/A	N/A	Unknown	Unknown	N/A	92.92	Unknown but non-zero
CS03	YES	NO	NO or N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS04	YES	NO	NO or N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS05	YES	NO	NO or N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS06	NO	YES	NO or N/A	N/A	37.37	40.34	YES	86.85	36.00
CS07	NO	YES	NO or N/A	N/A	Unknown	Unknown	YES	91.18	Unknown but non-zero
CS08	NO	YES	NO or N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS09	YES	YES	NO or N/A	N/A	Unknown	Unknown	N/A	93.63	Unknown but non-zero
CS10	NO	YES	Unknown	N/A	N/A	N/A	N/A	N/A	N/A
CS11	NO	YES	Unknown	N/A	36.15	41.57	N/A	79.84	0.00
CS12	YES	NO	NO or N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS13	YES	Unknown	Unknown	N/A	Unknown	Unknown	N/A	75.00	0.00
CS14	YES	NO or N/A	NO or N/A	N/A	35.27	44.40	YES	53.39	0.00
CS15	YES	NO	NO or N/A	N/A	Unknown	Unknown	N/A	Unknown	0.00
CS16	YES	NO	NO or N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS17	YES	NO or N/A	NO or N/A	N/A	Unknown	Unknown	YES	75.29	0.00
CS18	YES	YES	Unknown	N/A	31.67	43.34	N/A	78.58	0.00
CS19	NO	Unknown	YES	N/A	42.21	46.70	N/A	86.93	0.00
CS20	NO	N/A	YES	N/A	N/A	N/A	N/A	N/A	N/A
CS21	NO	N/A	N/A	YES	44.76	47.38	N/A	95.68	0.00

Note: The algorithms in the last five columns could only run for sites in Sample B2.

** The calculation relies on the mode algorithm so the cells of sites whose mode algorithm was deemed to be untrustworthy are marked as 'Unknown'. This is explained in the Performance Variations Report and the RHPP MCS Report.*

*** The calculation was only possible to be done for very few sites in Sample B2. The method for the identification of weather compensation is explained in the RHPP MCS Report (DECC, 2016c).*

**** The calculation relies on the same mode algorithm mentioned above, thus those sites with 'Unknown' in the 'Average flow temperature in SH mode' column cannot necessarily be trusted.*

***** The calculation relies on the same mode algorithm mentioned above. If entry is zero then it is correct (not to be confused with missing data or wrong entries).*

Table E 9. Median monthly on-to-on cycle durations in minutes for Case Studies in Sample B2.

ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CS01	6	6	6	6	8	480	480	480	512	14	8	6
CS02	258	246	341	16	18	Not enough cycles	Not enough cycles	64	Not enough cycles	131	190	184
CS03	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS04	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS06	93	77	52	44	10	18	14	16	28	36	48	46
CS07	62	66	74	77	112	242	1198	408	242	202	70	60
CS08	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS09	462	1440	1436	802	616	600	574	610	660	512	491	460
CS10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS11	10	10	10	10	10	445	540	540	562	10	10	10
CS12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS13	120	110	108	108	119	125	116	111	114	102	106	110
CS14	108	96	102	109	160	284	290	176	210	92	94	112
CS15	64	62	62	88	148	557	526	337	108	88	60	66
CS16	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS17	106	56	104	110	34	114	166	114	124	100	76	109
CS18	34	32	34	40	44	904	1413	818	50	36	34	32
CS19	42	44	44	75	78	206	530	211	212	82	46	44
CS20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS21	Not enough cycles	44	28	30	32	96	141	129	100	26	20	30

Note: Where a cell indicated 'not enough cycles, it means that cycling was not sufficient to determine a path. A cycle is defined from compressor start to compressor start.

E4 Control and usage of heating systems

Table E 10. SH sources, use & control during monitoring period, as narrated by householders

ID	Main SH system				Secondary SH
	HP type and emitters	Winter Control	Changes since installation & summer/holiday control	Comment	
CS01	ASHP Underfloor	Zone control: 7-8 zones, bedrooms not used (on frost protection) Thermostats: @19-20 °C Programmer: 2°C lower at night TRVs: N/A Category: night setback	Changes: NO Summer: SH off Holidays: N/A (if on holiday thermostat would be turned down a bit so that house does not get cold)	Lowers thermostat T at night-time to save energy and avoid HP from the HP coming on during the night	Wood burner (3kW) in lounge Reason: to top up heat; in case it is cold & HP won't warm up quickly, also feels cosy Use: ~ 40 times a year (mostly late afternoons & evenings)
CS02	ASHP Rads	Zone control: single zone Thermostat: @23°C (turned down only if too warm) Programmer: Unknown TRVs: not used Category: continuous	Changes: NO Summer: SH off Holidays: N/A	Thermostat in lounge Householder was told to never set thermostat lower than 15°C Kitchen rad turned off (otherwise gets warm)	Wall mounted electric resistance fan heater in bathroom Reason: fitted by RSL Use: not used
CS03	GSHP Rads	Zone control: Single zone Thermostat: @23°C (turned down to 15°C at night and only if too warm during the day) Programmer: Unknown TRVs: not used Category: night setback	Changes: NO Summer: - Holidays: N/A	Thermostat in lounge If HP is kept at 23°C day and night, then it becomes too hot	Wall mounted electric resistance fan heater in bathroom Reason: fitted by RSL Use: not used *Portable electric heater used once when householder was away for a couple of weeks (HP was off) as it takes so long to heat up a cold house

CS04	GSHP Rads	Zone control: Single zone Thermostat: turned up to 20°C for HP to kick in, then turned down to 18°C, switched off at night Programmer: HP switches on between 7-12pm and off at 11pm TRVs: not used Category: off at night	Changes: NO Summer: - Holidays: -	Thermostat in lounge Householder asked for the specific programmer settings	Wall mounted electric resistance fan heater in bathroom Reason: fitted by RSL Use: not used
CS05	GSHP Rads	Zone control: Single zone Thermostat: @18°C day and night Programmer: Unknown (HP probably on 24hr) TRVs: different settings in different rooms, fiddled with rarely Category: uncertain	Changes: NO Summer: - Holidays: -	Thermostat in lounge Householder was told to keep the thermostat temperature constant Kitchen rad (behind machinery) & storage room rads turned off	Electric wall heater in bathroom Reason: fitted by RSL Use: to warm up bathroom further whenever needed (was used frequently due to illness)
CS06	ASHP Rads Hydronic fan-assisted convectors	Zone control: Single zone Thermostat: set high, up to 30°C Programmer: HP on between 7:30am-11:30pm TRVs: - Category: off at night	Changes: NO Summer: SH off (May to Sep) Holidays: N/A	Thermostat in lounge Householder occasionally overrides system to turn on later (8:30-9am) Hydronic fan convectors in kitchen and bathroom	2-bar electric fire in lounge Reason: fitted by RSL Use: only in emergency, e.g. used when HP broke down
CS07	ASHP Rads Hydronic fan-assisted convectors	Zone control: Single zone Thermostat: @21°C, setback T@17°C Programmer: HP on 5am-9pm TRVs: not used Category: night setback	Changes: NO Summer: - Holidays: -	Thermostat in lounge Hydronic fan convectors in kitchen	None *some other form of heating is available but householders never use it (even when HP broke down) as it will cost a lot to run
CS08	ASHP Rads Hydronic fan-assisted convectors	Zone control: Single zone Thermostat: @21°C (occasionally put up to 23°C for a few hours only) Programmer: unknown TRVs: - Category: continuous	Changes: NO Summer: - Holidays: heating stays on but turned down a bit to 17°C	Thermostat in lounge Hydronic fan convectors in kitchen and bathroom not used	None *Electric fire is just decorative

CS09	ASHP Rads	Zone control: Single zone Thermostat: not used as was fixed in unheated entry space, HP controlled by changing flow T instead (normally set around 35°C but if cold could be set around 45°C) Programmer: HP on 7am to 10-11pm TRVs: occasionally used Category: off at night	Changes: tried out different flow T and eventually found out it's more efficient to run the HP at a lower but constant T Summer: on frost protection (May-Sep), switched on occasionally when there is a cold day/off at night Holidays: on frost protection (summer)	Householders fitted a portable thermostat in the post-monitoring period	Wood burner in lounge; electric underfloor heating/towel rad in ensuite bathroom Reason: fire to top up heat and for social purposes; electric bath heating fitted at a later stage than HP Use: fire used mostly socially and in exceptional cases (e.g. if it's cold early in the morning)
CS10	ASHP Rads Underfloor	Zone control: Multiple zones Thermostat: T settings vary Programmer: typical schedule: 21°C (morning boost, not in every zone), 18-19°C (daytime, setting might be intermittent), 15°C (night/setback T) TRVs: not used Category: night setback	Changes: Yes, uncertain what kind of changes took place Summer: - Holidays: -	Underfloor heating in dining and kitchen area only	Wood stove in dining room Reason: - Use: ~ 20 times a year
CS11	ASHP Rads	Zone control: Single zone Thermostat: T controlled by moving portable thermostat around the house Programmer: 6 periods set throughout the day, T ranges between 18-20°C TRVs: different settings in different rooms, fiddled with rarely Category: continuous	Changes: NO Summer: settings remain the same throughout the year; HP on 24/7 Holidays: HP never turns off, thermostat is just turned down a bit so that it does not take a long time to bring T up	Householders say with the HP you need to have a 'long term thinking' Thermostat lives in 3 places: Hall (standard T location), lounge (warmer T) and porch (cooler T)	Portable electric resistance fan heater with timer/thermostat (normally in sunlounge) Reason: in case a bit more warmth is needed Use: used very rarely, exceptional circumstances only, comes on automatically if T<15°C

CS12	GSHP Underfloor Rads	Zone control: Multiple zones Thermostat: @17-18°C, very rarely overridden; sunroom kept at a lower T (13-14°C) Programmer: probably not TRVs: - Category: continuous	Changes: NO Summer: settings remain the same throughout the year; HP on 24/7 Holidays: -	Underfloor heating downstairs only	Wood burner in lounge Reason: Good to have a backup system if electricity goes down Use: as backup system only
CS13	GSHP Underfloor	Zone control: Multiple zones with centralised point controlling all zones Thermostat: @18-20°C, varies per zone (upper floors set at a lower T) Programmer: T setting may vary slightly during the day, e.g. boost of 20°C in some zones TRVs: N/A Category: continuous	Changes: NO Summer: settings remain the same throughout the year; HP on 24/7 Holidays: on frost protection (7°C)	On a hot day, householder might turn HP T down or off but generally hardly ever touches it	10kW (kitchen area) & 5kW (lounge area) wood stoves Reason: backup system in case of power cut, to top up heat if needed, also looks nice Use: 2-3 times a year
CS14	GSHP Underfloor	Zone control: Multiple zones Thermostat: @18-20°C, set at different T per zone, rarely change Programmer: probably not TRVs: N/A Category: continuous	Changes: NO Summer: - Holidays: Off or on frost protection	With the HP it takes 24hrs to make a temperature change HP also heats separate guest house (thermostat @15°C)	Wood stove in lounge Reason: to top up heat, social purposes Use: very occasionally
CS15	GSHP Underfloor	Zone control: Multiple zones Thermostat: @21-22°C in frequently used rooms, 19°C in the in-use bedroom section and lower in the rest (16-18°C) Programmer: probably not TRVs: N/A Category: continuous	Changes: NO Summer: - Holidays: -	Householder has fitted dual zone room thermostat (sensor that monitors the floor as well as the room space) in lounge to ensure the floor does not turn off completely when log burner is on.	Log burners (lounge & dining) Reason: rapid room warm up if needed Use: never lit them so far

CS16	GSHP Underfloor + bath rads	Zone control: Multiple zones Thermostat: @20-21°C, setback T@16°C, remote digital thermostats in each zone Programmer: Comfort thermostat setting (20-21°C) comes on morning and afternoon TRVs: N/A Category: intermitternt	Changes: NO Summer: - Holidays: -	The heating patterns changed only after the end of the monitoring period: householders trying out different control methods to work out why HP is so expensive thus using it as a background heating system – most rooms currently on 16°C; ensuite and hallways @21°C (certain times of the day only)	2 wood burners (snug & lounge), range cooker in open plan kitchen, electric backup towel radiators in bathrooms Reason: electric backup of towel radiators used once a week (this year, after the end of monitoring) to boost T Use: this year wood burners are used more; oven also used as a heating source sometimes (on snooze)
CS17	GSHP Underfloor Rads	Zone control: Single zone Thermostat: T is set on thermostat and if not warm enough, householder increases flow T (using HP graphs) Programmer: comfort T@21.5°C, setback T@14.5°C (10pm-7am) TRVs: all upper floor radiators are turned down otherwise too warm upstairs Category: night setback	Changes: NO Summer: householder changes HP graphs in summer; HP on 24/7 Holidays: -	Thermostat in hall Weather compensation used	Wood burner (lounge) Reason: to top up T Use: used when householders feel cool (when windy outside etc.)
CS18	GSHP Underfloor	Zone control: 12 zones Thermostat: @17-18.5°C (remote digital thermostats), T changes very rarely Programmer: probably not TRVs: N/A Category: continuous	Changes: NO Summer: SH off Holidays: whole system is shut down	-	Wood stove (lounge), electric only towel rads in baths Reason: fire purely decorative; householder didn't know towel rads could be connected to HP Use: often, will get warm but they don't really need more warmth

CS19	GSHP Underfloor	Zone control: Single zone Thermostat: NO, controls HP by setting flow T; fiddle with controls on rare occasional only Programmer: N/A TRVs: different settings in different rooms, fiddled with rarely Category: continuous	Changes: NO Summer: settings remain the same throughout the year; HP on 24/7 Holidays: same as above	Before monitoring started householder tried to control HP as a boiler (intermittent heating); it turned out it is cheaper to run it continuously	Oil condensing boiler (hybrid system) Reason: previous system Use: only as backup
CS20	ASHP Radiators	Zone control: Single zone Thermostat: @19°C (estimated, actual T setting not shown), control panel in kitchen, setting changed very rarely, might turn it up a bit if too cold Programmer: comfort T set for 6-8am and 3-11pm TRVs: different settings in different rooms, fiddled with rarely Category: intermittent	Changes: NO Summer: - Holidays: holiday mode or thermostat turned down very low	Householders feel it is very complicated to change HP setting so they just turn T up and down	2 open fire wood burners (lounge and dining) Reason: to top up heat, living room one used for decorative purposes as well Use: living room fire used every day while dining fire used only a few time in the year
CS21	ASHP Radiators	Zone control: Single zone Thermostat: NO, householder adjusts flow T, very rarely turns it up or down Programmer: probably not TRVs: different settings in different rooms, used to regulate T Category: continuous	Changes: NO Summer: SH off Holidays: turns all TRVs down to frost protection	-	Wood burner (lounge) Reason: to top up heat Use: occasionally in evenings

Table E 11. DHW sources, use and control during monitoring period, as narrated by occupants

ID	DHW source	DHW Use			DHW schedule (HP on periods)
		Showers per week	Baths per week	Washing up frequency	
CS01	ASHP	14	Occasionally	Daily	6-8am, afternoon (2hrs), pasteurisation once a week
	(duration)	Normal*	-	10’	
	(comment)	Mornings	-	Running water	
CS02	ASHP, electric shower	2	N/A	Daily	Unknown
	(duration)	Short*	-	-	
	(comment)	Electric shower used	-	Bowl/sink used	
CS03	GSHP, electric shower	>= 5	N/A	Daily	Unknown
	(duration)	short/very short	-	10’	
	(comment)	Electric shower used	-	Bowl/sink used	
CS04	GSHP, electric shower	7	N/A	Daily	Unknown
	(duration)	Very short*	-	-	
	(comment)	Electric shower used	-	Bowl/sink used	
CS05	GSHP, electric shower	14	N/A	Occasionally	Unknown
	(duration)	Fairly short*	-	-	
	(comment)	Electric shower used	-	Dishwasher used mostly	
CS06	ASHP	3	N/A	Daily	Unknown
	(duration)	Short*	-	Long	
	(comment)	Washbasin used	-	Bowl/sink used	
CS07	ASHP, kettle	2	N/A	Daily	9-10am, 3-5pm (old schedule), 1-3am (new schedule, Feb 2013 onwards)
	(duration)	Normal*	-	-	
	(comment)	-	-	Kettle used for hot water	
CS08	ASHP	3-4	N/A	Daily	3-5am, 3-5pm
	(duration)	Very short*	-	-	
	(comment)	-	-	Bowl/sink used	
CS09	ASHP	14	N/A	Daily	7-8am (approx.), 5-6pmp (approx.), booster very rarely needed
	(duration)	Short*	-	-	
	(comment)	Mornings	-	Bowl/sink used dishwasher used sometimes	

CS10	ASHP	14	7	Occasionally	Unknown
	(duration)	Long*	Bath fills in 5'	-	
	(comment)	Mornings	Evenings	Dishwasher used mostly	
CS11	ASHP	5-6	None	Daily	Twice a day
	(duration)	Short*	-	Very little	
	(comment)	-	-	Dishwasher used mostly	
CS12	GSHP	2-3	None	Daily	Unknown
	(duration)	Very short*	-	A little bit	
	(comment)	-	-	Bowl/sink used	
CS13	GSHP	16-19	None	N/A	Unknown, pasteurisation once in a while
	(duration)	Fairly short*	-	-	
	(comment)	Mostly mornings	-	Dishwasher used	
CS14	GSHP	2-3	4-5	Daily	Unknown, 'Normal' setting used, 'Advanced' setting used only when visitors around (higher T)
	(duration)	Normal*	-	a little bit	
	(comment)	-	-	running water & sink used	
CS15	GSHP	15	5	Daily	Unknown
	(duration)	Normal* (assumed)	-	A little bit	
	(comment)	-	-	Dishwasher used mostly Bowl/sink used	
CS16	GSHP, electric shower	14	Occasionally	Occasionally	Unknown, (probably in the morning when HP is heard coming on)
	(duration)	Normal*	-	-	
	(comment)	Electric shower (50%), DHW from HP (50%)	-	dishwasher used mostly (90%) Bowl/sink used (10%)	
CS17	GSHP	10-12	Occasionally	Occasionally	Unknown
	(duration)	Short*	-	-	
	(comment)	-	-	dishwasher used mostly Bowl/sink used	
CS18	GSHP	21	7	Daily	Heated it up all the time, no particular heating times
	(duration)	Normal* (assumed)	-	A little bit	
	(comment)	-	-	dishwasher used mostly water saving tap used	

CS19	GSHP	7	Occasionally	None	Unknown
	(duration)	Short*	-	-	
	(comment)	-	-	Dishwasher used once a week	
CS20	Solar thermal, resistance heater	7	None	Daily	Not linked to HP
	(duration)	Normal* (assumed)	-	-	
	(comment)	-	-	Bowl/sink used	
CS21	ASHP	4	N/A	Daily	Heated up when tap is on
	(duration)	Short*	-	-	
	(comment)	-	-	Bowl/sink used	

**For the purposes of this study the duration of shower is defined as follows: very short (less than 5'), short (approximately 5'), fairly short (approximately 7'), normal (approximately 8-10') and long (approximately 15')*

E5 Overall energy cost

Table E 12. Energy use and bills with current and previous heating system

ID	Total energy cost per year (approximation)		Electricity tariff	Appliances using most electricity	RES systems or other source alleviating the HP running cost (e.g. benefits)
	With previous heating system	With current heating system			
CS01	N/A	£2,150 (£800 for HP only)	Standard	Lights (100% energy saving), 2 computers (on most of the time), fridge/freezer (+backup freezer), hob, tumble drier, washing machine, dishwasher	None (except for £300 one-off RHPP payment)
CS02	Unknown	>£400 (benefit not included)	Unknown	**Electric shower**, washing machine (twice/week), microwave (to warm up ready meals), TV (on most of the time), lights (100% energy saving)	£200 annual winter fuel benefit
CS03	N/A	>£500	Standard (probably)	**Electric shower**, washing machine (once a week), oven (used scarcely), lights (100% energy efficient)	None/unknown
CS04	£560-640+ (£320 for electricity) (£240-320 for gas)	>£520-560 (>£400 for electricity) (£120-160 for gas cooker)	Standard (probably)	**Electric shower**, washing machine (twice/week), tumble drier (once/week but line used if weather is good), electric mobility scooter, lights (100% energy efficient)	None (passive solar system, i.e. trombe wall, present but not used much)
CS05	£890 (gas & electricity)	~£820 (£745 for electricity - benefits may be included) (£71+standing charge for gas cooker)	Standard, 1-phase	**Electric shower**, tumble drier, dishwasher (new), washing machine (new), lights (100% energy efficient)	£140 warm home grant & unknown amount of pension credit
CS06	Unknown	Unknown (electric only)	Economy, 1-phase	Washing machine/tumble drier, fridge/freezer, microwave, lights (100% energy efficient)	None/unknown
CS07	Unknown	£575-782 (electric only)	Standard, 1-phase	Washing machine, kettle, computer, television, lights (mostly energy efficient), oven (rarely used)	None/unknown
CS08	£720 (electric only)	£540 (temporary bill increase to £900 due to immersion heater issue) (electric only)	Standard, 1-phase	Washing machine, oven, hob, microwave, lights (mostly energy efficient)	None/unknown

CS09	Unknown	£1730 (incl. heating for swimming pool from a separate HP)	Standard, 1-phase	Kettle, cooker, microwave, washing machine/tumble drier, additional fridge/freezer in garage, lights (100% energy efficient)	£720/year RHI grant, electricity produced by PVs & feed-in tariff for PVs
CS10	N/A	£1135	Standard, 1-phase	Washing machine/tumble drier, dishwasher, freezer, lights	RHI grant
CS11	Unknown	£1200	Standard, 1-phase	Washing machine, dishwasher, cooker, tumble drier (not used a lot), lights (mostly energy efficient)	RHI grant
CS12	N/A	£850-1150 +gas payment for hob	Standard, 1-phase	Electric oven, freezer, fridge, washing machine, lights (partly energy efficient), TV/radio	RHI grant
CS13	Unknown	£2000	Standard, 1-phase	Washing machine/tumble drier, 2 dishwashers, ironing, zip tap (used a lot), lights (100% energy efficient)	RHI grant, electricity produced by PVs & electricity exported to grid
CS14	N/A	£1560	Standard, 1-phase	Washing machine/tumble drier, cooker, dishwasher (used all the time), lights (100% energy efficient)	RHI grant, feed-in tariff for PVs, electricity produced by PVs & electricity exported to grid
CS15	N/A	£1100	Standard, 1-phase	Lights (100% energy efficient), cooking (every day), washing machine/tumble drier, dishwasher (householder said they "tend to waste electric")	RHI grant, electricity produced by PVs
CS16	N/A	>£1900 (electricity consumed in summer is approx. 1/3 that of winter)	Standard, 3-phase (belongs to farming group)	**Electric shower,** oven, washing machine (4-5 times/week), tumble drier (winter time), dishwasher, lights	RHI grant, electricity produced by PVs, benefits of belonging to farming group
CS17	N/A	£1000-1200	Standard, 1-phase	Electric cooker, dishwasher (6 times/week), washing machine, lights (mostly energy efficient)	RHI grant, £1400/year electricity produced by PVs
CS18	N/A	£1000-1200	Standard, 1-phase	Washing machine/tumble drier, dishwasher (used at least once/day), lights (mostly energy efficient	RHI grant, electricity produced by PVs (installed Nov 2015)
CS19	£650-700 (cost for oil per year)	£900 (£450 for HP only)	Economy 7, 1-phase	Washing machine, kettle, dehumidifier, lights (mostly energy efficient	RHI grant, electricity produce by PVs
CS20	Unknown	£570 +gas payment for oven (electricity consumed in summer is approx. 1/3 that of winter)	Standard, 1-phase	Immersion heater for DHW (used 3hrs/day), washing machine (twice/week), lights (100% energy efficient	RHI grant, electricity produced by PVs, hot water provided by solar thermal
CS21	Unknown	£825-1000	Standard, 1-phase	Fridge/freezer, washing machine, TV, lights (mostly energy efficient), oven (rarely used)	RHI grant, £700 PV payments (annual), electricity produced by PVs, solar thermal is present but disconnected

E6 Occupant perception of comfort and satisfaction

Table E 13. Comparison between current and previous system

ID	Heating system: Previous	Heating system: Current	Satisfaction with current system	Comparison with previous heating system (either in current or previous house)	Householder recommendation
CS01	N/A	ASHP	**Very satisfied** – householder thinks efficiency depends on user knowledge	**Overall prefers HP** – easier to control oil (previous house system) but no hassle of filling up the tank or worrying about oil price with HP	Worth installing a **HP** in a well-insulated property only
CS02	Gas	ASHP	**Very satisfied** – feels comfortable & running cost is good	**Overall prefers HP** – happy with gas but pays a smaller amount of money now with HP	Definitely go for a **HP**
CS03	Gas	GSHP	**Very satisfied** – keeps house warm; expensive in terms of running cost but it's worth the money to spend (Note: capital cost paid by RSL)	**Overall prefers HP** – gas boiler worked ok but HP is much easier to control, although householder thinks that gas boiler worked out a bit cheaper (electricity is expensive)	Go for a **HP** – clean & efficient system
CS04	Gas	GSHP	**Very satisfied (when it works)** – disappointed when HP broke down, other than that works well & occupant does not have to worry about it	**Overall prefers gas** – boiler never broke down (even though it was an old one); control is ok with both	Hard to say – would suggest the **HP** if there was no chance of it breaking down
CS05	Gas	GSHP	**Satisfied** – other than not getting enough heat in bathroom (inadequate radiator), it is excellent	**Prefers HP –** Keeps house constantly warm; less noisy than gas boiler; hope HP turns cheaper; easy to control with thermostat (tends to ignore the rest as is complicated)	Go for a **HP** (especially in a new house with underfloor heating etc.) – economical, environmentally friendly;
CS06	Electricity	ASHP	**Very satisfied** – other than not getting enough heat in bathroom & kitchen (Hydronic fan convectors), it is excellent	**Overall prefers HP** – Nice comfortable heat comparing to storage heaters	Tried getting central **gas** – householder was told that gas is a lot warmer (i.e. need more heat in kitchen & bathroom) & more reliable (i.e. does not break down)

CS07	Electricity	ASHP	**Very dissatisfied** – Too expensive, not enough SH & DHW	**Prefer storage heaters** – cheaper; knew how to control them; more efficient than HP;	**Gas** is the best option – costs less; more physical heat; instant DHW
CS08	Electricity	ASHP	**Very satisfied** – 100%	**Prefers HP** – works out cheaper than storage heaters	Definitely go for a **HP** – although relative visiting house thinks it may a better fit in a bigger family house
CS09	Oil	ASHP	**Satisfied** – would even be happy if HP and gas cost the same as they get constant heat with HP	**Prefer HP** – Oil easier and more responsive but house felt cold (no stable or whole-house heat); no top-up hassle with HP	Go for a **HP**
CS10	Coal	ASHP	**Very satisfied** - efficient	**Prefer HP** – would also be happy with gas but HP system definitely suits the family (although house insulation still needs to be improved)	Definitely go for a **HP**
CS11	Oil	ASHP	**Satisfied** – But still haven't tested it in a very cold winter	**Prefer HP** – although haven't noticed a difference in running cost; no top-up hassle with HP; also feels more comfortable	Go for a **HP** – if circumstances are right; certainly go for it if there is no gas and property is big
CS12	N/A	GSHP	**Satisfied** – apart from little problems	**Prefer HP** – comparing with solid fuel burners & storage heaters (previous house); HP provides constant heat	Go for a **HP**
CS13	Oil	GSHP	**Very satisfied** – minimum cost and carbon footprint	**Prefer HP** - assumes HP turns out much cheaper than any other system	Go for a **HP** – it is a fantastic thing to do if you have the capital cost upfront
CS14	N/A	GSHP	**Neutral** – would have expected more savings	**Prefer HP** – Comparing with oil (previous house); no top-up hassle; environmentally friendly; less maintenance; cost effective in the long run but probably only marginally better/cheaper thank oil boiler	Go for a **HP** – but make sure you choose a good system and installer
CS15	N/A	GSHP	**Very satisfied**	**Prefer HP** – Comparing with oil (previous house); reasonable running cost; sufficient SH and DHW	Definitely go for a **HP**
CS16	N/A	GSHP	**Cannot express satisfaction** – want to find out what is going wrong first as HP keeps house warm but is very expensive (not efficient)	**Overall prefer oil** – easier to control; happy with heating provided; HP has high capital + running costs & is a complicated system to run yourself	Cannot advise a specific system – would suggest finding out more about running cost of electricity and asking other HP owners; pellet boilers might be good option

CS17	Oil	GSHP	**Very satisfied** – just one room not heated enough due to wind exposure	**Overall prefer HP** – comparing to gas (previous house); HP provides whole house heat but gas is easier to control, to make a quick change in sudden cold weather and to identify/fix problem if it breaks down	Go for a **HP** – a GSHP maybe better suited in a humid climate rather than an ASHP
CS18	N/A	GSHP	**Satisfied** – Environmentally friendly; quiet; zone control is handy	**Overall prefer HP** – comparing to gas (previous house) easier to control zones; fit and forget; less responsive but simpler	Go for a **HP** – performance gap is narrowing between GSHPs and ASHPs so better go for the latter to avoid digging up the field
CS19	Oil	GSHP	**Very satisfied** –	**Prefer HP** – Provides constant warmth; works well as long as you don't run it intermittently; fit and forget; easier to controls than oil boiler once you set it up	Definitely go for a **HP**
CS20	Electricity	ASHP	**Very satisfied** –	**Prefer HP** – Same running cost but more heat; temperature easier to control than with storage heaters	Better talk to an expert, e.g. some people think GSHPs are better than ASHPs but in this case it was not worth doing economically & did not have enough space to install
CS21	Oil	ASHP	**Very satisfied** –	**Definitely prefer HP** – constant warmth; easier to control; more cost effective; there were gaps in SH and DHW with oil boiler	Definitely go for a **HP** – It's hassle free

Table E 14. Occupant perception around comfort

ID	Perceived radiator warmth Comments on other emitter types	Perceived level of ambient warmth	Preferred level of ambient warmth	Warming up measures
CS01	**Rads**: N/A **UFH:** floor feels warm	Comfortable	A bit warmer than it is but householders compromise	Never change HP settings, put on a jumper/duvet or light log burner
CS02	**Rads**: Nice, just right, as they should	Comfortable	Comfortable	Turn up thermostat
CS03	**Rads**: Nice & warm, as they should	Warm	Warm	None/not needed
CS04	**Rads**: Slightly warm, you can put hand on	Warm	Warm	None/not needed
CS05	**Rads**: Warm, as expected	Warm (normally), comparing to external temperature	Fairly warm	Turn up thermostat (usually not needed)
CS06	**Rads**: Barely warm, warm enough **Hydronic fan convectors:** they do not give out enough heat	Quite warm	Quite warm	None/not needed
CS07	**Rads**: Feels like no heat comes out of them **Hydronic fan convector:** they not provide enough heat	Freezing, feels cool, not the heat expected	Warm	Put on more clothes
CS08	**Rads**: You get used to the idea that they don't get that hot **Hydronic fan convectors:** not used, feel draughty	Comfortable	Comfortable	None/not needed
CS09	**Rads**: Not noticeable when rads go warm as it is warm in general	Comfortable (usually)	Comfortable	Put clothes on, blanket
CS10	**Rads**: Warm **UFH:** floor feels lovely when you step on	Comfortable (apart from top floor, for this reason 2 rads will be added)	Comfortable	Light fire
CS11	**Rads**: Unknown	Comfortable	Warmer in the evening, cooler at night (bedrooms)	Turn up HP by 1°C, put on clothes, portable electric resistance fan heater used in exceptional circumstances
CS12	**Rads**: Unknown **UFH:** No comment	Comfortable	Unknown	Unknown
CS13	**Rads**: N/A **UFH:** No comment	Comfortable	Male occupant likes it cooler (especially in bedroom at night), females in family like it as it is	None/not needed
CS14	**Rads**: N/A **UFH:** No comment	Nice	Comfortable	None/not needed
CS15	**Rads**: Unknown **UFH:** No comment	Comfortable	Comfortable	None/not needed

CS16	**Bath towel rads only** **UFH:** No comment	Comfortable (normally)	Comfortable	Light wood burner in snug and leave doors open for warm air to circulate in house
CS17	**Rads**: as expected, occupants aware of low heat rads	Comfortable	Comfortable	Female occupant capable of adjusting flow T in winter and summer to get the comfort they want
CS18	**Rads**: N/A **UFH:** No comment	Comfortable (due to house built incorrectly, prevailing wind might cause the odd room to feel cold)	Comfortable	None/not needed
CS19	**Rads**: can feel warm during cold nights but generally you do not notice them **UFH:** No comment	Comfortable	Comfortable	Non/not needed
CS20	**Rads**: never get very warm, feel warmer when cold outside	Never feels too warm or too cold	Male occupant does not like it too warm	Light wood burner
CS21	**Rads**: Fine	Comfortable, never too cool	Comfortable	Turn flow temperature up only if it is very cold (very rarely). Light wood burner in living room

Table E 15. Occupant experiences of the HP system

ID	Training	Satisfaction with training	Ease of use	Issues since installation	Support & resolution
CS01	Brief **demonstration** on the basics of how to use a HP	Very dissatisfied – householder wanted info on how to optimise running conditions, i.e. a simple guide to ASHPs and how to operate them	Very easy – once you understand what you're doing	Installation fault (manifold floor valves were back to front) – front room wouldn't heat up when HP was first installed	Installers fixed it but householder was the one that spotted the source of the problem (due to his background)
CS02	**NO**, householder was told to use just the thermostat	Satisfied – would not have wanted more information	Easy	NO	N/A
CS03	Manufacturer representative **demonstration**; occupant was told to leave it on all the time @23°C and control through thermostat	Satisfied	Very easy	NO	N/A
CS04	Full technical group briefing (**presentation**), **books**, **manuals**; occupant was told not to touch HP, just control trough thermostat	Very satisfied – Read manual but didn't understand much	Easy	Cracked antifreeze tube in cupboard outside - NO HEATING during winter	Installers fixed it – It took 2 months
CS05	Full technical group briefing (**presentation**), occupant was told to keep temperature constant	Neutral – Too much technical detail and no practical info; even leaflets were very technical	Easy – re thermostat control but rest is complicated	NO	N/A
CS06	RSL officer **demonstration**; occupant was told to use thermostat	Very satisfied – At first was a bit complicated but now occupant knows what to do	Easy – But occupant does not know what to do if anything goes wrong	(a) Faulty HP generator (exploded) - NO HEATING during winter (b) blockage in tank & lounge rad (c) hydronic fan convector in bathroom went off (d) damp patch from external unit – can be slippery	(a) Installers replaced external HP unit, (b) installers restored flow, (c) friend adjusted settings (d) unresolved

CS07	Technician gave **demonstration** on how to use programmer; it was suggested that stat is kept at 21°C; **booklet**	Dissatisfied – Instructions given were difficult to understand; neither installer nor occupants could get the HP work properly	No answer – Occupants feel they know how to use the system but installation/settings being correct is critical	(a) faulty inlet air fan for ASHP – there were many problems before HP burnt itself out - NO HEATING during winter (b) HP does not provide enough heat - never heated up the dwelling properly	(a) installers replaced fan, (b) installers couldn't resolve issue
CS08	Attended **technical meeting, leaflets** and **cards**	Satisfied – They are sufficient but meeting was too technical	Easy – Occupant's daughter thinks system is too complicated for elderly people	(a) faulty motherboard – - NO HEATING during winter (b) dripping issue (c) increased bills – booster heater was either left on by mistake by the renovation team or system reset itself during power on/offs	(a) Technicians replaced the whole unit – took 6-8 weeks to resolve (b) Drip-tray installed - drain pipe was present but not connected (c) Booster switched off - nobody could understand there is no fault in the system apart from a particular technician
CS09	Installer **demonstration,** occupants' son has also provided them with handwritten instructions	Satisfied – Training & assistance is accessible but instructions are too technical, a couple of post installation visits would be useful	Easy – Male occupant can change flow temperature but controls are very complicated	NO	N/A
CS10	Installer **demonstration**	Satisfied – Could not have been better	Easy – After male occupant set everything up	NO	N/A
CS11	Installer **demonstration**	Very satisfied	Easy – No need to touch controls, just use thermostat	HP turned off – due to power cut	Occupants turned HP off and on again - after reading instructions
CS12	Electrician **demonstration**, little **booklets** and **cards**	Satisfied	Easy – Occupants hardly ever touch HP (main part)	(a) pump problem, (b) faulty sensor – heating was not kicking in due to miscommunication between sensor & controller (c) increased bills - booster heater left on by mistake by plumbers	(a) installers changed pump (b) electrician & plumber fixed problem (c) occupant resolved this with the help of her father – they read instructions

CS13	Just **manuals**, manufacturer **helpdesk** available	Dissatisfied – more info & instructions desired, e.g. a central resource of knowledge with examples of how typical installations work, reference sites etc.	Very easy – No need to touch it	Air in ground loops – bad installation	Plumber & engineer in collaboration with occupant resolved issues, i.e. removed air from ground loops and put in relief valves
CS14	Engineer **demonstration**	Dissatisfied – Would have liked more instructions, i.e. how to fine tune HP & improve it	Easy – Due to male occupant's technical background but other people might not find it as easy	Antifreeze leak – Major problems after installation, level of topping up bottle kept dropping due to leak in boreholes	Installers dug up, found leak in both boreholes and fixed it
CS15	Installer **presentation**, **leaflets**	Very satisfied	Easy	NO	N/A
CS16	Installer **demonstration**, **leaflets**	Satisfied – because instructions are not used; occupants just wanted to be able to put the heating on themselves	Easy	Excessive electricity consumption	Issue is still being investigated
CS17	Installer **demonstration**	Satisfied – Would have liked installer to come back after a few months	Very easy	Big surge in voltage – HP broke down and resistance heater had kicked in but occupants only realised due to increased bills - NO HEATING during winter	Installer did some diagnostics in collaboration with manufacturer – took 3 weeks to fix problem
CS18	Installer **demonstration**, **leaflets**	Satisfied – Installer showed more things than occupant uses, e.g. heat curves, HP works so occupant does not need to use instructions	Easy	Reoccurring 'motor-P' error – probably related to power supply, occupant realised as whenever this happens there is no DHW	Occupant turns HP off/on and issue gets resolved
CS19	**Book**, installer suggested HP runs better when running all the time	Satisfied – Control panel is self-evident, book quite reasonable	Easy – Just sits there and does the job	NO	N/A

CS20	**Book**, installer **demonstration**	Satisfied – Installer could not have done a better job but book is complex & control panel is not very intuitive (2-3 buttons only)	Easy – Because they don't really control HP (otherwise would be difficult), they just put temperature up and down	NO	N/A
CS21	**Paperwork** provided, installer **demonstration**	Very satisfied - occupant phones them up if needed	Easy	Connection problem – ASHP inlet air fan wouldn't go round soon after installation	Installers fixed it

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