Volume 2: Appendices

Understanding the drivers affecting the in-situ performance of domestic heat pumps in the UK

Eleni Oikonomou

UCL Energy Institute

The Bartlett School of Environment, Energy and Resources

University College London

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A1 MCS standards for heat pump installation certification

MCS provides several standards, including:

- MIS 3005 – the Microgeneration Installation Standard sets the *"requirements for MCS contractors undertaking the supply, design, installation, set to work, commissioning and handover of microgeneration heat pump systems"* (MCS, 2017).
- MCS 021 – the 'MCS Heat Emitter Guide for Domestic Heat Pumps' is a Microgeneration Product Standard aiming to enhance the understanding of the relationship between a building's heat loss, heat-emitter characteristics and flow temperature, and their impact on HP performance (MCS, 2019b).
- MCS 001 – the MCS Contractor Standard covers both the requirements that should be met by contractors (part 1) and the certification process they should follow to ensure their compliance with MCS requirements (part 2) (MCS, 2020a, 2020b).
- MCS 025 – the Microgeneration Installation Standard sets out the competence criteria required for installer companies to comply with the requirements of the MCS scheme (MCS, 2019c).

MCS also provides a set of guides and tools that, alongside the standards, aim to support the installation process and ensure well-performing HPs under the scheme. These include a best-practice guide, a DHW cylinder selection guide, an installer handover checklist and several calculators/calculation methods for the estimation of heat losses, SH/DHW and overall system performance, as well as a method for carrying out the MCS design calculations (MCS, 2020c). It is a requirement that the SCOP is calculated through the dedicated MCS SCOP calculator which offers a product- and flow temperature- specific efficiency estimation, enabling comparison between different HP models. Based on the calculation of SCOP, the installer subsequently produces an annual estimate (SPF value) that is included in the MCS database and utilised in the RHI payment calculation, providing this SPF is at least 2.5 (Ofgem 2016).

According to MCS 3005 v5.0 (MCS, 2017), the HP sizing is set to meet at least 100% of the design SH load at the prescribed indoor and outdoor temperatures. However, supplementary heating is set to be utilised for the coldest 1% hours of a year, otherwise an increase in the HP's heating capacity is needed. Where additional heating systems are present, these are expected to be fully integrated and controlled as a single system. In this case, the additional heating systems should be set to meet the aforementioned heat load in part and thus the HP is sized for the remaining part. The DHW design is based on the anticipated DHW consumption (following discussion with users), taking into consideration the number and types of access points, the intended DHW storage temperature and the cylinder's recovery rate. HPs working with DHW cylinders are rated at 55 °C. The system's overall electricity calculation includes the energy consumed by any supplementary heating for DHW, as well as collectors and emitter circulation pumps, when more than two are utilised or when emitter circulation pumps operate longer than the HP's operating hours.

MCS 021 v2.2 (MCS, 2019b) states that the designer should first calculate each room's specific heat loss and then consult the Guidance Table that enables the identification of those emitter specifications that will meet each room's design heat loss. This is achieved through the cross-tabulation of room specific heat loss, emitter types and emitter flow temperature. This process provides the maximum pipe spacing for UFH and the radiator oversize factor to be used for the determination of the required rated output. Design room temperature and water flow rate also influence emitter output, as do parameters relating to the individual characteristics of the selected emitter type, such as air flow rate and floor construction/covering in the case of fan convectors and UFH, respectively (MCS and RECC, 2018).

MCS also provides guidance on the, *e.g.,* ensuring appropriate drainage and sufficient air circulation around the external unit. An acoustic survey is required to ensure ASHP are neither cause noise nuisance to neighbouring properties nor are placed close to bedrooms or on vibration-transmitting floors. All SH- and DHW- providing installations are also subject to local building regulations and standards (*e.g.,* Building Regulations and Domestic Building Services).

A2 MCS certification for installers and alternative training paths

The HP installer certification under the MCS scheme involves four main steps:

a. Quality workmanship is assured through the assessment of contractor companies by an independent Certification Body against MCS 001 and MIS 3005, including the inspection of a nominated installation site.
b. Customer care is ensured through participation in the Trading Standards Institute-approved Consumer Code that sets the customer service standards.
c. Demonstration of competency is required for all those involved in every aspect of the HP installation process. MCS sets the Competency Criteria (MCS, 2019a) required for scheme compliance and lists the relevant installer standards, including MCS 025. Competence can be proved either via in-date qualifications, attendance on an MCS-approved qualification course and/or demonstrable experience (aka the 'Experienced Workers Route').
d. Continuous to continuous improvement is demonstrated via a Quality Management System as per MCS 001 and Consumer Code requirements.

However, the HPA (HPA, 2020) acknowledges weaknesses in the current training schemes, with them being significantly more complex and expensive than the equivalent schemes for traditional heating systems. It highlights the need for a wider and more robust installer base to bridge the current skills gap and support the Government's plans for an ambitious HP uptake. With this in mind, HPA collaborated with key industry stakeholders to develop a simplified pathway, starting with 'The Low Temperature Heating Course', a generic two-day course covering the essential skills required for any heat source technology. A one-day follow-up training course could then focus on specialised technologies, such as HP. The suggestion of a 'Low Carbon Skills Card' linked to the courses undertaken, could serve as a proof of the installer's training and accreditation to enhance consumer confidence. This process is seen as being part of a wider accreditation scheme involving refresher courses to ensure the installers' knowledge is kept up to date.

A3 Additional RHI scheme options

Assignment of Rights (AoR) - an option linked to the RHI that allows a third party to fund the purchase and/or installation of the HP and then receive RHI payments. Under the AoR, a registered investor funds the upfront costs and becomes the recipient of RHI payments. It was introduced in 2017, with a view to prevent third-party unauthorised funding.

Kensa's Shared Group Array Funding - The use of private funds that assist the installation of HP in newbuilds, at least in part, is an interesting addition to the list of schemes available to the domestic sector. Kensa's funding (The Kensa Group Limited, 2018) is linked to the Non Domestic RHI scheme (Ofgem, 2021) and the 2018 change to the RHI rules, making external funding possible and allowing the shared ownership and operation of GSHP infrastructure. This scheme targets housing providers rather than individual owners to co-fund the installation of GSHP serving multiple properties through linked ground loops that are fully funded through the RHI.

Appendix B: Communication to case study households

B1 Cover letter to private householder

B2 Cover letter to social landlord

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B5 Consent form

B6 Topic guide

B1 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]

B2 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]

B3 Invitation letter to participant

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

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

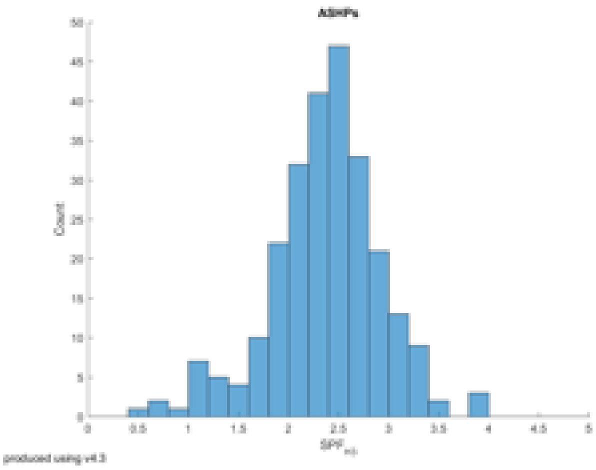
[NAME]
[ADDRESS]

[DATE]

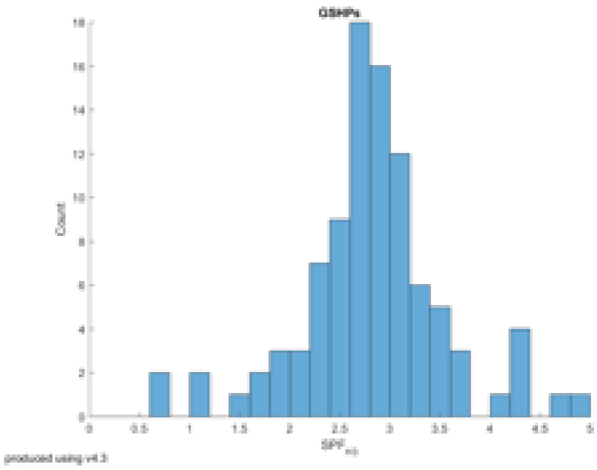
Dear Householder,

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

B4 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)

You will be given a copy of this information sheet.

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	[redacted]

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.

B5 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:

B6 Topic guide

1 Briefing section

Explaining why researchers are here and what they are going to do. Participants to be provided with the trial information sheet and option to sign consent for participation.

- 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
USER(S) BACKGROUND	…
TIME LIVING IN PROPERTY	…
CHANGES IN NUMBER OF PEOPLE LIVING HERE DURING MONITORING?	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' 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?
- 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	ASHP / GSHP
HP MODEL	…
HP POWER	…
CIRC' PUMP TYPE	…
CIRC' PUMP SETTING	…
HEAT EMITTER TYPE	Gas / Electricity / other
PREVIOUS FUEL	Radiators / underfloor / fan-assisted radiators Were these installed when the system was installed? Yes / No / Unknown

- 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 C: Case study variables

C1 Seasonal Performance Factor estimates

C2 Social information and decision making

C3 Dwelling and ventilation information

C4 Technical information

C5 Control and usage of heating systems

C6 Overall energy cost

C7 Occupant perception on comfort and satisfaction

C1 Seasonal Performance Factor estimates

As explained in subsection 3.1.1 of the main document, the case studies were selected based on sample S1, which was the only subset available at the time of the case study recruitment and selection. Sample S1 was subsequently superseded by sample S2 and sample S3 (see subsection 3.3.2 of the main document). The case study field work was already in progress when the more robust S2 and S3 subsets were defined and as some of the case studies fell short of their subset selection criteria, their SPF was not calculated. For the sites excluded from sample B2, a final SPF estimate was inferred through the examination of data monitoring periods when the level of missing data was thought to have a minimal impact on SPF_{H4}. Table 1 lists the SPFs assigned to each case study at different boundaries, based on the calculation period compatible with the criteria specific to each dataset. Utilising different inclusion criteria and data periods for the calculation of SPFs resulted in significantly different final SPF estimates at boundary level H4 in only three cases, *i.e.,* moving CS07, CS09 and CS15 from the worst-performing sites to the middle range of those that volunteered, as shown in Figure 4-1 of the main document. Monthly mean COP, electricity and heat data for all case studies are graphically represented in Appendix D of the RHPP Case Study Report (Lowe *et al.*, 2017).

Table 1: SPF calculated at different boundary levels and as part of different RHPP datasets.

Dataset	Sample S1			Sample S2	Sample S3	Final SPF estimates	
ID	SPF_{H2}	SPF_{H3}	SPF_{H4}	SPF_{H4}	SPF_{H4}	SPF_{H4}	SPF calculation period
CS01	2.4	2.4	2.3	2.3	2.3	2.3	12/2013 – 12/2014
CS02	3.0	2.6	2.3	2.3	2.3	2.3	03/2014 – 03/2015
CS03	2.5	2.5	2.4	N/A	N/A	2.4	11/2013 – 11/2014
CS04	3.1	3.1	3.0	N/A	N/A	3.0	11/2013 – 11/2014
CS05	2.6	2.6	2.6	N/A	N/A	2.6	11/2013 – 11/2014
CS06	3.2	2.9	2.8	2.8	2.8	2.8	04/2013 – 04/2014
CS07	1.6	1.5	1.5	2.7	2.7	2.7	02/2014 – 02/2015
CS08	2.6	2.6	2.4	N/A	N/A	2.4	11/2013 – 11/2014
CS09	1.0	1.0	1.0	2.7	2.7	2.7	03/2012 – 03/2013
CS10	3.3	3.3	3.2	N/A	N/A	3.2	11/2013 – 11/2014
CS11	3.2	3.2	3.0	2.9	2.9	2.9	02/2014 – 02/2015
CS12	0.7	0.7	0.8	N/A	N/A	0.8	11/2013 – 11/2014
CS13	4.7	4.7	4.2	4.1	4.1	4.1	01/2014 – 01/2015
CS14	3.9	3.9	3.5	3.6	3.6	3.6	11/2013 – 11/2014
CS15	0.8	0.8	0.8	0.6	N/A	3.0	03/2014 – 03/2015
CS16	1.7	1.7	1.7	N/A	N/A	1.7	11/2013 – 11/2014
CS17	3.5	3.5	3.1	3.1	3.1	3.1	01/2014 – 01/2015
CS18	4.6	4.6	4.3	4.4	4.4	4.4	08/2013 – 08/2014
CS19	4.5	4.5	4.1	4.0	4.0	4.0	03/2014 – 03/2015
CS20	4.3	4.3	3.5	N/A	N/A	3.5	11/2013 – 11/2014
CS21	1.9	1.9	1.8	1.3	N/A	1.3	12/2012 – 12/2013

C2 Social information and decision making

Table 2: Ownership type and household occupancy.

ID	Ownership	Household size	Move-in / HP installation year	Time spent at home	Annual away-from-home periods
CS01	Private	2 to 3	2012 / 2011-12	Most days	None or limited
CS02	Social	1	2012 / 2013	Most days	None or limited
CS03	Social	1	2013 / 2012	Most days	None or limited**
CS04	Social	1	2009 / 2012	Most days	2 Weeks max
CS05	Social	2	2011 / 2012	Most days	None or limited
CS06	Social	1	2007 / 2009	Most days	None or limited
CS07	Social	2	2010 / 2012	Most days	None or limited
CS08	Social	1	2011 / 2012	Most days	4-6 Weeks
CS09	Private	2	1997 / 2012	Most days	2-4 Weeks
CS10	Private	2 + 2*	2011 / 2012	Most days	None or limited***
CS11	Private	2	1991 / 2012	Most days	6-8 Weeks
CS12	Private	1	2009 / 2008-09	Most days	None or limited
CS13	Private	2 + 2*	2006 / 2013	Most days	4 Weeks
CS14	Private	2	2012 / 2012	Most days	8 weeks
CS15	Private	2	2011 / 2011	Most days	None or limited
CS16	Private	2 to 4	2012 / 2012	Most days	None or limited
CS17	Private	2	2011 / 2011	Most days	3 weeks max
CS18	Private	2 + 2*	2013 / 2013	Most evenings	None or limited
CS19	Private	1 to 2	1997 / 2012	Most days	5-6 Weeks
CS20	Private	2	2005 / 2011	Most days	2-3 Weeks
CS21	Private	1	2002 / 2011	Most days	None or limited

* Household members below 18 years of age ** Except for 8 weeks in 2015 ***Except for 3 weeks in 2015

Table 3: Interviewees and occupation characteristics.

ID	Pseudonym(s)	Gender	Occupation type	Date of interview
CS01	Amanda / Andrew	F / M	Administrative / Physical sciences* (both working from home)	18/11/2015
CS02	Beatrice	F	Skilled trade (retired)	20/11/2015
CS03	Clive	M	Metal forming, welding and related trade (retired)*	25/11/2015
CS04	Dawn	F	Elementary process plan (retired)	25/11/2015
CS05	Elva	F	Health and social services (carer, off work)	25/11/2015
CS06	Francis	M	Elementary storage (off work)	09/02/2015
CS07	Gabi / Greg	F / M	Unknown (retired) / Engineering (retired)*	09/12/2015
CS08	Helen / Hilda (visitor)	F / F	Unknown (retired) / Food preparation and hospitality	09/12/2015
CS09	Irena / Ian	F / M	Teaching and education (both retired)	16/12/2015
CS10	Jennifer / James	F / M	Natural sciences (off work) / Engineering (partly working from home)*	16/12/2015
CS11	Kate / Kevin	F / M	Health professional (retired) / Business finance (retired)	18/12/2015
CS12	Lynn / Leonard (visitor)	F / M	Elementary services (off work) / Unknown (retired)	13/01/2016
CS13	Marvin	M	Information technology and management (partly working from home)*	13/1/2016
CS14	Nicole / Nathan	F / M	Stay-at-home spouse / Energy and management (not working, by choice)*	14/1/2016
CS15	Olivia / Oliver	F / M	Information, technology and telecommunications / Construction and building (not working, by choice)	14/1/2016
CS16	Patricia	F	Agriculture (working from home)	20/01/2016
CS17	Quianna / Quentin	F / M	Physical sciences (retired)* / Electrical engineering (retired)*	22/01/2016
CS18	Rafael	M	Hospitality	20/01/2016
CS19	Samuel	M	Physical sciences / Engineering (retired)*	27/01/2016
CS20	Teresa / Teo	F / M	Teaching / Teaching	27/01/2016
CS21	Ursula	F	Administrative (retired)	29/01/2016

* Occupants with some level of technical knowledge.

Table 4: HP type, previous fuel and decision making.

ID	Previous fuel	Pre-existing HP	Occupant receives RHI payment	HP installation motivation for owner occupiers or communication with RSL
CS01	N/A	Yes	No	N/A
CS02	Gas	No	No	RSL asked tenant, tenant happy to have HP
CS03	N/A	Yes	No	N/A
CS04	Gas	No	No	RSL gave no option, tenant did not mind
CS05	Gas	No	No	RSL gave no option, tenant did not object
CS06	Electricity	No	No	RSL gave no option, tenant wanted gas
CS07	Electricity	No	No	RSL gave no option, tenant wanted gas
CS08	Electricity	No	No	RSL gave no option, tenant wanted gas
CS09	Oil	No	Yes	Lower running cost, fits with PV, RHI scheme, constant heat provided
CS10	Coal	No	Yes	Lower overall cost, environmentally friendly, constant heat provided
CS11	Oil	No	Yes	Recommended by trusted installer, no mains gas available, regulations prohibiting oil tank refit
CS12	N/A	No	Yes	Green info day, no mains gas available, visited another house with HP
CS13	Oil	No	Yes	Minimal running cost/energy footprint, environmentally friendly
CS14	N/A	No	Yes	Environmentally friendly, cost efficiency, RHI scheme, long standing, minimal maintenance, no mains gas available
CS15	N/A	No	Yes	Interested in HP for own business purposes, tried pit to understand technology better, no mains gas
CS16	N/A	No	Yes	Recommended by planning people, installer and friends, land available, efficient technology
CS17	Oil	No	Yes	Desire to invest on renewable heating
CS18	N/A	No	Yes	RHI scheme, economically and environmental sound choice
CS19	Oil	No	Yes	Interested in RES, cost effective solution (considering RHI scheme and PV payback)
CS20	Electricity	No	Yes	Recommended by experts, fits well with PV
CS21	Oil	No	Yes	Recommended by experts, RHI scheme, regulations prohibiting oil tank refit

C3 Dwelling and ventilation information

Table 5: Property type, rating and interventions post the HP installation.

ID	Age	Property type / number of floors	EPC date and band	Interventions since HP installation
CS01	2011-12	Detached / 2	26/09/12 C	No
CS02	1954-64	Mid-terraced / 1	05/02/15 D	No
CS03	1954-64	End-terraced / 1	01/04/15 D	No
CS04	1954-64	End-terraced / 1	01/04/15 D	No
CS05	1954-64	Mid-terraced / 1	10/02/15 D	No
CS06	1930s-50s	Semi-detached / 1	18/03/15 D	CWI (autumn 2015)
CS07	1930s-50s	Mid-terraced / 1	09/02/15 E	CWI and loft insulation (winter 2013)
CS08	1930s-50s	Mid-terraced / 1	17/03/15 D	CWI, bath/kitchen renovation (2012-13)
CS09	1973	Detached / 1	25/03/15 D	Conversion of a previously single room to ensuite and study (2012-13)
CS10	Pre-1999	Detached / 3	14/09/24 F	Roof insulation in utility and kitchen only, UFH insulation (2013)
CS11	1958	Detached / 2	21/10/14 D	No
CS12	2008-09	Detached / 2	19/03/15 D	No
CS13	1780s	Detached / 3	30/06/12 B	No
CS14	2012	Detached / 1	29/05/12 B	No
CS15	2011	Detached / 2	11/08/11 B	No
CS16	2012	Detached / 2	16/12/14 A	No
CS17	1992	Detached / 2	12/05/14 C	Conservatory roof insulation* (summer 2015)
CS18	2012	Detached / 2	15/01/13 B	No
CS19	1920s	Detached / 2	03/12/15 C	CWI in kitchen (late 2015)
CS20	1956	Semi-detached / 2	07/01/15 C	No
CS21	1970s	Mid-terraced / 1	09/02/14 D	No

* Outside the heated envelope.

Table 6: Constructional and building thermal characteristics.

ID	Wall type	Roof type	Floor type	Glazing type
CS01	Insulated brick and block	Pitched, insulated loft (350mm)	Carpeted, insulation unknown	Double
CS02	Filled cavity & EWI	Pitched, insulated loft	Uninsulated (likely)	Double
CS03	Filled cavity & EWI	Pitched, insulated loft	Uninsulated (likely)	Double
CS04	Filled cavity & EWI	Pitched, insulated loft	Uninsulated (likely)	Double
CS05	Filled cavity & EWI	Pitched, insulated loft	Uninsulated (likely)	Double
CS06	Filled cavity	Pitched, insulated loft	Uninsulated (likely)	Double
CS07	Filled cavity	Pitched, insulated loft (>200 mm)	Uninsulated (likely)	Double
CS08	Filled cavity	Pitched, insulated loft	Uninsulated (likely)	Double
CS09	Partially filled cavity	Pitched, variable loft insulation, 200-370 mm	Uninsulated	Triple, argon filled
CS10	Stone wall, uninsulated	Pitched, partial roof insulation (100 mm)	UFH areas insulated only	Double, thinner in GF kitchen/toilet
CS11	Filled cavity	Pitched, insulated loft (150mm)	Sunlounge floor insulated only	Double
CS12	Insulated brick wall	Pitched, insulated loft	Insulated ground floor	Double, high performance
CS13	Highly insulated brick wall	Pitched, roof insulation at rafters	Insulated ground floor and in-between floors	Double, high performance
CS14	Insulated brick cavity	Pitched, insulated loft	Insulated floor	Triple, argon filled
CS15	Insulated wall	Pitched, insulated loft	Insulated floor	Double
CS16	Insulated wall	Pitched, insulated loft	Insulated floor	Triple
CS17	Insulated wall	Pitched, insulated loft	Uninsulated (likely)	Double
CS18	Insulated wall	Pitched, insulated roof	Insulate floor	Double, high performance
CS19	Uninsulated stone wall	Pitched, insulated loft (300 mm)	Insulated floor (25 mm PUR)	Double
CS20	Imperfectly filled cavity	Pitched, insulated loft	Uninsulated	Double
CS21	Filled cavity	Pitched, insulated loft at joists (400 mm)	Uninsulated (likely)	Double

Table 7: Window opening patterns.

ID	Winter ventilation	Summer ventilation
CS01	Limited – Windows closed apart from backyard door in nice weather	Yes – No particular routine
CS02	Limited – Bedroom window open daily in nice weather, other windows closed unless cooling or in shower	Yes – Most windows open in nice weather
CS03	No	Limited – Lounge door open every day, all windows locked
CS04	Limited – Windows closed but lounge door nearly always slightly open	Yes – Windows open in nice weather, closed at night
CS05	Limited – Lounge door and windows open for a while in nice weather	Yes – No particular routine
CS06	Limited – Windows open only if too warm on a sunny day	Yes – Most windows wide open
CS07	Limited – Occasionally when drying washing inside	Limited – Kitchen/bedroom/bathroom windows open for a while when warm outside
CS08	Yes – Windows open a lot in the morning and likely later in the day, closed around teatime (afternoon)	Yes – Windows open all day and closed at night
CS09	No – Windows open very rarely	Yes – Windows open in kitchen and bedroom area
CS10	No – Windows closed	No – Windows closed, backyard door may be open
CS11	No – Windows close, occasionally open for a quick blow-through, trickle vents closed	Limited – Windows open if too hot, trickle vents mostly closed
CS12	Limited – 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
CS13	Limited – Windows open only if it feels very dry or study (in not too cold outside)	Yes – Windows always open
CS14	No – Bathroom window open when in shower, trickle vents closed	Yes – Windows open all the time, trickle vents open
CS15	No – Trickle vents open in rooms used	Yes – Windows open in warm weather when HP off
CS16	Limited – windows open 2-3 times a week	Yes – Windows mostly open in occupied rooms
CS17	No	Limited – Doors/windows open occasionally
CS18	No – Trickle vents blocked (they were mistakenly thought to cause draught)	Limited – Windows open in conservatory and bedrooms (only if there is a really hot night)
CS19	Limited – Windows open occasionally, i.e., once a week, trickle vents closed	Limited – weather dependent, trickle vents open
CS20	No – windows mostly closed	Extremely limited – bedroom windows open only if there is a warm day
CS21	Limited – several windows open every morning for 5-10'	Yes – windows tend to stay open

Table 8: Mechanical ventilation with heat recovery and natural/mechanical ventilation triggers.

ID	MVHR	Ventilation triggers
CS01	No	Smoking, pets, temperature control
CS02	Yes – turned off as it blows chilly air	Fresh air, temperature control
CS03	Yes – turned on, fan on high, every day, daytime only	Smoking
CS04	Yes – turned on 24/7	Smoking, pets, fresh air, temperature control
CS05	Yes – mostly turned off as it blows chilly air and is noisy	Fresh air, temperature control
CS06	No	Temperature control
CS07	No	Fresh air
CS08	No	Fresh air
CS09	No	Fresh air
CS10	No	Children playing out
CS11	No	Fresh air, temperature control
CS12	No	Fresh air
CS13	No – householder considers MVHR installation to counteract dry air	Fresh air, temperature control
CS14	No	Temperature control
CS15	No	Fresh air, temperature control
CS16	No	Fresh air, temperature control
CS17	No	Sitting outside
CS18	No	Temperature control
CS19	No	Fresh air
CS20	No	Fresh air
CS21	No	Fresh air, temperature control

C4 Technical information

Table 9: Monitoring dates and installation characteristics.

ID	HP type	Monitored period	MCS certificate issue date	Declared Net Capacity (kW)	Retrofit installation	Previous system radiators retained
CS01	ASHP	9/2013 – 3/2015	2011-12	14	No	N/A
CS02	ASHP	1/2013 – 3/2015	2013	5.5 - 7	Yes	All except for one (lounge)
CS03	GSHP	3/2013 – 3/2015	2012	6	Unknown	N/A
CS04	GSHP	3/2013 – 3/2015	2012	6	Yes	All except for one (lounge)
CS05	GSHP	3/2013 – 3/2015	2012	6	Yes	All except for two (lounge, bath)
CS06	ASHP	3/2012 – 3/2015	2009	5	No	N/A
CS07	ASHP	3/2012 – 3/2015	2012	5	No	N/A
CS08	ASHP	3/2012 – 3/2015	2012	5	No	N/A
CS09	ASHP	3/2012 – 9/2014	2012	16	No	In part, e.g., living and dining area
CS10	ASHP	3/2012 – 9/2014	2012	14 and 8.5	No	N/A
CS11	ASHP	9/2013 – 3/2015	2012	14	Yes	All expect for two (kitchen and study)
CS12	GSHP	9/2013 – 3/2015	2008-09	7	N/A	N/A
CS13	GSHP	5/2013 – 3/2015	2013	12	N/A	N/A
CS14	GSHP	3/2012 – 3/2015	2012	12	N/A	N/A
CS15	GSHP	3/2012 – 3/2015	2011	11	N/A	N/A
CS16	GSHP	6/2013 – 3/2015	2012	12	N/A	N/A
CS17	GSHP	9/2013 – 3/2015	2011	12	Yes	In part, e.g., in hall, living room and kitchen
CS18	GSHP	5/2013 – 3/2015	2013	12	N/A	N/A
CS19	GSHP	9/2012 – 3/2-15	2012	9	Yes	All
CS20	ASHP	3/2012 – 3/2015	2011	11	No	N/A
CS21	ASHP	1/2013 – 3/2015	2011	7	Yes	All

Table 10: Information on the presence of HP services and components, based on model specification and site observations.

ID	Service provision	Buffer vessel	Thermal store	In-line resistance heater	Immersion heater
CS01	SH and DHW	No	No	No	DHW
CS02	SH and DHW	No	No	No	DHW
CS03	SH and DHW	Yes	No	Yes	None
CS04	SH and DHW	Yes	No	Yes	None
CS05	SH and DHW	Yes	No	Yes	None
CS06	SH and DHW	No	No	No	DHW
CS07	SH and DHW	No	No	No	DHW
CS08	SH and DHW	No	No	No	DHW
CS09	SH and DHW	No	No	Yes	DHW
CS10	SH and DHW	No	No	No	DHW
CS11	SH and DHW	No	No	No	DHW
CS12	SH and DHW	Yes	No	Yes	None
CS13	SH and DHW	No	No	Yes	None
CS14	SH and DHW	Yes	No	Yes	None
CS15	SH and DHW	Yes	No	Yes	None
CS16	SH and DHW	Yes	No	Yes	None
CS17	SH and DHW	Yes	No	Yes	None
CS18	SH and DHW	Yes	No	Yes	DHW
CS19	SH and DHW	Yes	No	No	Buffer
CS20	SH only	Yes	No	No	Buffer
CS21	SH and DHW	No	Yes	No	Thermal store

Table 11: SH flow temperature calculation, DHW proportion and weather compensation estimation based on the algorithms developed by the RHPP team that could run for sites in the Sample B2 only.

ID	Mean Tsf in SH mode (°C)	Max Tsf in SH mode (°C)	Weather compensation**	DHW to total heating ration
CS01	34.18	42.25	Yes	27%
CS02	Unknown*	Unknown*	N/A	6%
CS03	N/A	N/A	N/A	N/A
CS04	N/A	N/A	N/A	N/A
CS05	N/A	N/A	N/A	N/A
CS06	37.37	40.34	Yes	13%
CS07	Unknown*	Unknown*	Yes	9%
CS08	N/A	N/A	N/A	N/A
CS09	Unknown*	Unknown*	N/A	6%
CS10	N/A	N/A	N/A	N/A
CS11	36.15	41.57	N/A	20%
CS12	N/A	N/A	N/A	N/A
CS13	Unknown*	Unknown*	N/A	25%
CS14	35.27	44.4	Yes	47%
CS15	Unknown*	Unknown*	N/A	Unknown*
CS16	N/A	N/A	N/A	N/A
CS17	Unknown*	Unknown*	Yes	25%
CS18	31.67	43.34	N/A	21%
CS19	42.21	46.7	N/A	13%
CS20	N/A	N/A	N/A	N/A
CS21	44.76	47.38	N/A	4%

* ‘Unknown’ denotes sites whose mode algorithm was deemed to be untrustworthy. This is explained in the Performance Variations Report (Love *et al.*, 2017) and the RHPP MCS Report (Gleeson *et al.*, 2017).
** The weather compensation calculation was possible for very few sites in Sample B2. The identification method utilised is described in the RHPP MCS report (Gleeson et al., 2017)

Table 12: 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	6	480	480	480	512	14	8	6
CS02	258	246	341	16	18	NEC	NEC	64	NEC	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	497	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	NEC	44	28	39	32	86	141	129	100	26	20	30

* NEC stands for ‘Not Enough Cycles’, indicating cycling was not sufficient to determine a path.

C5 Control and usage of heating systems

Table 13: Heat pump space heating controls, as derived from user narrative.

ID	Heating zones	Thermostat type / comfort temp. (°C)	Programmer settings	Flow temp. control	TRV use	Category
CS01	Multiple (7-8)	Digital, fixed / 19-20	2 °C lower at night	No	N/A	Daytime-only (with setback)
CS02	1	Analogue / 23	Unknown	No	Not used	Continuous
CS03	1	Analogue / 23	Unknown	No	Not used	Daytime-only (with setback)
CS04	1	Analogue / 18	On between 7:00 – 24:00 off at 23:00	No	Not used	Daytime- only (off at night)
CS05	1	Analogue / 18	Unknown, on 24/7 (likely)	No	Settings vary per room	Continuous
CS06	1	Digital, fixed / ≤30	On between 7:30 - 23:30	No	Unknown	Daytime-only (off at night)
CS07	1	Digital, fixed / 21	Comfort T: 5:00 - 21:00	No	Not used	Daytime-only (with setback)
CS08	1	Digital, fixed / 21	Unknown	No	Unknown	Continuous
CS09	1	N/A	On between 7:00 – 23:00	Yes	Settings vary per room	Daytime-only (off at night)
CS10	Multiple	Digital, fixed / 18-21	Varied	No	Not used	Daytime only (with setback)
CS11	1	Portable* / 18-20	Six periods throughout the day	No	Settings vary per room	Daytime only (with setback)
CS12	Multiple	Digital, fixed / 17-18	Probably not	No	Unknown	Continuous
CS13	Multiple	Digital, fixed / 18-20	Varied	No	N/A	Continuous
CS14	Multiple	Analogue / 18-20	Probably not	No	N/A	Continuous
CS15	Multiple	Analogue & digital / 21-22	Probably not	No	Settings vary per room	Continuous
CS16	Multiple	Portable / 16-21	On: morning & afternoon	No	N/A	Intermittent
CS17	1	Analogue / 21.5	Comfort T: 7:00-22:00	Yes	Turned down on upper floor	Daytime-only (with setback)
CS18	Multiple (12)	Portable / 17-18.5	Probably not	No	N/A	Continuous
CS19	1	N/A	N/A	Yes	Settings vary per room	Continuous
CS20	1	Digital, fixed / 19**	Comfort T: 6:00-8:00 & 15:00-23:00	No	Settings vary per room	Intermittent
CS21	1	N/A	Probably not	Yes	Settings vary per room	Continuous

* Flow temperature control was used as the main control method until a single zone portable room thermostat was installed the day before the site visit investigation. ** Estimated temperature setting as actual temperature not shown on control panel.

Table 14: Additional heat pump space heating control information, as derived from user narrative.

ID	Summertime / holiday settings	Additional SH control-related information
CS01	Off / N/A	Bedrooms not-in-use set on frost protection; night setback used to save energy and avoid night-time HP noise.
CS02	Off / N/A	Kitchen radiator turned off, otherwise kitchen gets warm.
CS03	Unknown / N/A	Night setback used as if HP kept at 23 °C day and night, then it becomes too hot.
CS04	Unknown / Unknown	Thermostat turned up to 20 °C for HP to kick in and then down to 18 °C.
CS05	Unknown / Unknown	User rarely fiddles with TRV; both kitchen radiator (located behind machinery) and storage room radiator are turned off.
CS06	Off / N/A	Thermostat usually set a high temperature; user rarely overrides systems to turn on later.
CS07	As usual / Unknown	Night setback T=17 °C.
CS08	Unknown / Thermostat turned down to 17 °C	Thermostat occasionally set to 23 °C, for a few hours only; kitchen and bathroom hydronic fan convectors not used.
CS09	On frost protection but may be switched on occasionally if cold / On frost protection	Thermostat not used as fixed in unheated entry space; flow temperature usually set at 35 °C and up to 45 °C if cold; a portable thermostat was fitted in the post-monitoring period.
CS10	Unknown / Unknown	Programmer typical schedule: 21 °C (morning boost, not in every zone), 18-19 °C (daytime, setting might be intermittent), 15 °C (night setback)
CS11	As usual / Thermostat turned down a bit	Users rarely fiddle with TRV and do not change thermostat setting; instead, portable thermostat is moved to three different locations: hall (standard location), lounge (warmer environment) and porch (cooler environment).
CS12	As usual / Unknown	Sunroom kept at a lower T=13-14 °C.
CS13	As usual / On frost protection	Centralised control point for all zones, upper floor thermostats set at a lower temperatures.
CS14	As usual / On frost protection	Thermostat settings rarely change it takes 24hrs to make a temperature change; standalone guest room heated at 15 °C.
CS15	As usual / Unknown	Lower thermostat T=16-18 °C in rarely used rooms and 19 °C in in-use bedrooms; dual zone room thermostat fitted in lounge to ensure floor does not turn off completely when log burner is on.
CS16	As usual / Unknown	Setback T=16 °C, portable digital thermostats; after the end of the monitoring period, users tried out different control methods, including using it as a background heating system only, to work out why HP is so expensive.
CS17	User changes HP graphs / Unknown	Night setback T-14.5 (10pm-7am), T set on thermostat and if not warm enough user increases Tflow (using HP graphs); weather compensation in use.
CS18	As usual / Off	Portable digital thermostats, whose settings change very rarely.
CS19	As usual / As usual	User rarely fiddles with flow temperature controls; prior to the monitoring period, user tried to control HP as a boiler (intermittent heating), but it turned out it is cheaper to run it continuously.
CS20	As usual / On holiday mode or frost protection	Actual thermostat setting not shown in control panel; settings rarely change, might turn up a bit if too cold.
CS21	Off / TRV on frost protection	Flow temperature rarely adjusted.

Table 15: Heat pump domestic hot water controls and water usage, as derived from user narrative.

ID	Heat pump DHW schedule	DHW usage		
		Showers per week, duration	Baths per week	Washing up frequency, duration, method
CS01	Morning and afternoon (2hrs each)	14, normal	Occasional	Daily, 10', under running water
CS02	Unknown	2, short	N/A	Daily, bowl/sink
CS03	Unknown	≤5, short	N/A	Daily, 10', bowl/sink
CS04	Unknown	7, very short	N/A	Daily, bowl/sink
CS05	Unknown	14, short	N/A	Occasionally, dishwasher mostly
CS06	Unknown	3, short	N/A	Daily, bowl/sink
CS07	9:00-10:00 and 15:00-17:00 until Feb 2013, then13:00-15:00	2, normal	N/A	Daily
CS08	3:00-5:00 and 15:00-17:00	3-4, short	N/A	Daily, bowl/sink
CS09	7:00-8:00 and 17:00-18:00	14, short	N/A	Daily, bowl/sink, dishwasher
CS10	Unknown	14, long	7	Occasionally, dishwasher mostly
CS11	Twice a day	5-6, short	0	Daily, dishwasher
CS12	Unknown	2-3, short	0	Daily, bowl/sink used
CS13	Unknown	16-19, short	0	Dishwasher only
CS14	Unknown	2-3, normal	4-5	Daily, under running water
CS15	Unknown	15, normal	5	Daily, bowl/sink, dishwasher
CS16	Unknown	14, normal	Occasionally	Occasionally, bowl/sink, dishwasher mostly
CS17	Unknown	10-12, short	Occasionally	Occasionally, bowl/sink, dishwasher mostly
CS18	All the time, no particular heating times	21, normal	7	Daily, water saving tap, dishwasher mostly
CS19	Unknown	7, short	Occasionally	Dishwasher only
CS20	N/A	7, normal	0	Daily, bowl/sink
CS21	Instantaneous	4, short	N/A	Daily, bowl/sink

Table 16: Supplementary heating methods

ID	Auxiliary space heating		Auxiliary domestic hot water heating
	Type	Use and/or reasoning for installation	
CS01	Wood burner (3KW) in lounge	~40 times a year; topping up heat when HP won't warm up quickly; also feels cozy	None
CS02	Wall mounted electric resistance fan heater in bathroom	Not used; fitted by RSL	Electric shower
CS03	Wall mounted electric resistance fan heater in bathroom*	Not used; fitted by RSL	Electric shower
CS04	Wall mounted electric resistance fan heater in bathroom	Not used; fitted by RSL	Electric shower
CS05	Wall mounted electric resistance fan heater in bathroom	Tops up heat whenever needed; fitted by RSL	Electric shower
CS06	Two-bar electric fire in lounge	Only in emergency; fitted by RSL	
CS07	None**	N/A	Kettle
CS08	None***	N/A	None
CS09	Wood burner in lounge; electric underfloor heating and towel radiator in ensuite bathroom	Fire used mostly socially and in exceptional cases to top up heat; resistance heating fitted at a later stage than the HP due to the subsequent room conversion	None
CS10	Wood stove in dining room	~20 Times a year	None
CS11	Portable resistance fan heater with timer/thermostat in sunlounge	Used rarely, in exceptional circumstances only; comes on automatically if T<15 °C	None
CS12	Wood burner in lounge	Backup heating system	None
CS13	Wood stoves in kitchen (10kW) and lounge (5kW)	2-3 times a year; backup heating systems; topping up heat (occasionally); looks nice	None
CS14	Wood stove in lounge	Topping up heat (occasionally); and for social purposes	None
CS15	Log burners in lounge and dining	Never lit so far; backup systems for rapid room warm up if needed	None
CS16	Wood burners in snug and lounge, range cooker in open plan kitchen and electric backup towel radiators in bathrooms	All used often in the year following the monitoring period in search of HP alternatives to reduce running costs	Electric shower
CS17	Wood burner in lounge	Topping up heat when occupants feel cool	None
CS18	Wood stove in lounge; electric only towel rads in baths	Used often; wood stove purely decorative; user unaware towel rads work with HP.	None
CS19	Oil condensing boiler (previous system turned into a hybrid system)	Only as a backup	None
CS20	Open fires in lounge and dining	Topping up heat; decorative purposes; lounge fire used every day while dining fire a few times a year	Solar thermal, resistance heater
CS21	Wood burner in lounge	Topping up heat occasionally	None

* A portable electric heater was used once when user returned from a couple of weeks away and HP was off, as it takes a long time to heat up a cold house. ** User stated some other form of supplementary heating was available but they never used it (even when HP broke-down) due to cost considerations. ***Electric fire present, just decorative.

C6 Electricity bills

Table 17: Energy use and bills with current and previous heating system, as quoted by users.

ID	Estimation of total energy cost per year (£)		Energy intensive appliances	RES or other cost alleviating mechanisms (annual quote)
	With previous heating system	With current heating system		
CS01	N/A	2,150 (800 for HP)	Lights, computers, fridge/freezer, hob, tumble drier, washer/drier, dishwasher	None, except for £300 one-of RHPP payment
CS02	Unknown	440	Electric shower, drier, microwave, TV, lights	£200 winter benefit
CS03	N/A	>500	Electric shower, washer, oven, lights	None
CS04	£560 – 640 (gas & electric)	>400 + gas cooker cost	Electric shower, washer/drier, electric mobility scooter, lights	None***
CS05	£890 (gas & electric)	745 + gas cooker cost	Electric shower, washer/drier, dishwasher, lights	£120 Warm home grant, pension credit
CS06	Unknown	Unknown	Washer/drier, fridge/freezer, microwave, lights	None
CS07	Unknown	≥700	Washer, kettle, computer, TV, lights, oven	None
CS08	720	540*	Washer, oven, hob, microwave, lights	None
CS09	Unknown	1730	Kettle, cooker, microwave, washer/drier, fridge/freezer, lights	£720 RHI grant, PV FIT & electricity production
CS10	N/A	1135	Washer/drier, dishwasher, freezer, lights	RHI grant
CS11	Unknown	1200	Washer/drier, dishwasher, cooker, lights	RHI grant
CS12	N/A	850 – 1150 + gas hob cost	Electric oven, fridge/freezer, washer, lights, TV	RHI grant
CS13	Unknown	2000	Washer/drier, dishwasher, iron, zip tap, lights	RHI grant, PV electricity production & grid export
CS14	N/A	1560	Washer/drier, cooker, dishwasher, lights	RHI grant and PV FIT & electricity production
CS15	N/A	1100	Lights, cooking, washer/drier, dishwasher	RHI grant, PV electricity production
CS16	N/A	1900**	Electric shower, oven, washer/drier, dishwasher, lights	RHI grant, PV electricity production, farming group
CS17	N/A	1000 - 1200	Electric cooker, dishwasher, washer, lights	RHI grant, PV electricity production (£1400)
CS18	N/A	1000 - 1200	Washer/drier, dishwasher, lights	RHI grant, PV electricity production (£1400)
CS19	659 – 700 (oil only)	900 (450 for HP)	Washer, kettle, dehumidifier, lights	RHI grant, PV electricity production
CS20	Unknown	570 + gas payment for	DHW immersion heater, washer, lights	RHI grant, PV electricity production, solar thermal
CS21	Unknown	825 - 1000	Fridge/freezer, washer, TV, oven	RHI grant, PV FIT (£700) & electricity production****

* Temporary bill increase to £900 due to DHW immersion use. ** Summer electricity consumption reported to be one third that of winter. *** Trombe wall present but not utilised. **** Solar thermal panels disconnected.

C7 Occupant perception on comfort and satisfaction

Table 18: Comparison between current and previous heating system.

ID	Satisfaction with heat pump	Comparison with previous heating system experience
CS01	**Very satisfied** *	**Prefers HP** – easier to control oil but no hassle filling up the tank or worrying about oil price with HP.
CS02	**Very satisfied** – good running cost; feels comfortable.	**Prefers HP**– happy with gas but HP cheaper to run.
CS03	**Very satisfied** – clean/efficient; high running cost but keeps house warm.	**Prefers HP** – gas boiler worked out ok, perhaps a little cheaper but HP much easier to control.
CS04	**Very satisfied (when it works)** – fit & forget; generally works well.	**Prefers gas** – control is ok with both, but boiler never broke down (even though it was an old one).
CS05	**Satisfied** – keeps house constantly warm; other than inadequate bathroom radiator, it is excellent.	**Prefers HP** – economical/environmentally friendly; less noisy than gas boiler; easy to control thermostat, tends to ignore the rest that is complicated.
CS06	**Very satisfied** – excellent but not getting enough heat in kitchen/bath.	**Prefers HP** – nice, comfortable heat comparing to storage heaters, but gas is a lot warmer and reliable.
CS07	**Very dissatisfied** - too expensive, insufficient SH/DHW.	**Prefers storage heaters** – cheaper, more efficient, knew how to control them; gas is best as costs less and provides more physical heat and instant DHW.
CS08	**Very satisfied**	**Prefers HP** – cheaper than storage heaters.
CS09	**Satisfied** – constant heat; happy if HP and gas cost the same.	**Prefers HP** – no top-up hassle; oil easier/more responsive but house felt cold (i.e., no continuous/whole house heat).
CS10	**Very satisfied** – efficient system.	**Prefers HP** – would also be happy with gas but HP definitely suits the family in comparison to coal.
CS11	**Satisfied** – but still hasn't tested it in a very cold winter.	**Prefers HP** – no difference in running cost comparing to oil but no top-up hassle with HP and feels more efficient.
CS12	**Satisfied** – apart from little problems.	**Prefers HP** – comparing to solid fuel burners and storage heaters, HP provides constant heat.
CS13	**Very satisfied** – minimum cost and carbon footprint.	**Prefers HP** – setting aside capital cost, user assumes HP turns out much cheaper than any other system.
CS14	**Neutral** – would have expected more savings.	**Prefers HP** – no top-up hassle; environmentally friendly; less maintenance; cost effective in the long run but probably only marginally better/cheaper to oil.
CS15	**Very satisfied**	**Prefers HP** – Reasonable running cost and sufficient SH/DHW in comparison to oil.
CS16	**Cannot express satisfaction** – currently investigating high HP cost.	**Prefers oil** – easier to control, happy with heating provided; HP has high capital/running costs and is complicated.
CS17	**Very satisfied** – just one room not heated enough due to wind exposure.	**Prefers HP** – comparing to gas, HP provides whole house heat, but gas is easier to control, make a quick change in sudden cold weather and to identify and fix a breakdown.
CS18	**Satisfied** - environmentally friendly and quiet.	**Prefers HP** – comparing to gas, it is easier to control zones, fit and forget system; less responsive but simpler.
CS19	**Very satisfied** – provides constant warmth; fit and forget system.	**Prefers HP** – easier to control than oil boiler once set it up; works well as long as you don't run it intermittently.
CS20	**Very satisfied**	**Prefers HP** – same running cost as storage heaters but more heat; temperature easier to control.
CS21	**Very satisfied** - hassle-free and constant warmth provided.	**Prefers HP** – easier to control and more cost-effective than oil boiler; SH/DHW gaps with oil boiler.

* Owner thinks HP are worth installing in well-insulated properties only & efficiency depends on user knowledge.

Table 19: Occupant perception of comfort with heat pump.

ID	Radiator type and perceived warmth	Perceived level of ambient warmth	Perceived level of ambient warmth	Warming up measures
CS01	UFH – floor feels warm	Comfortable	A bit warmer that it is but users compromise	Never change HP settings; adding clothing layers or lighting log burner
CS02	Rads – just right	Comfortable	Comfortable	Turning up thermostat
CS03	Rads – just right	Warm	Warm	None / Not needed
CS04	Rads – slightly warm on touch	Warm	Warm	None / Not needed
CS05	Rads – warm, as expected	Warm	Fairly warm	Turning up thermostat (usually not needed)
CS06	Rads – barely warm / HFC – not enough heat	Quite warm	Quite warm	None / Not needed
CS07	Rads – feels like no heat comes out / HFC – not enough heat	Freezing, cool	Warm	Adding clothing layers
CS08	Rads – you get used to them not getting that hot / HFC - draughty	Comfortable	Comfortable	None / Not needed
CS09	Rads – not noticeable when they go warm as it is generally warm	Comfortable	Comfortable	Adding clothing layers
CS10	Rads – warm / UFH – lovely to step on	Comfortable, except for top floor	Comfortable	Lighting fire
CS11	No comment	Comfortable	Warmer in the evening, cooler at night (bedrooms)	Turning up heat by 1 °C, putting on clothes, rarely using portable resistance fan heater
CS12	No comment	Comfortable	Unknown	Unknown
CS13	No comment	Comfortable	Cooler (male user), comfortable (female)	None / Not needed
CS14	No comment	Nice	Comfortable	None / Not needed
CS15	No comment	Comfortable	Comfortable	None / Not needed
CS16	No comment	Comfortable	Comfortable	Lighting wood burner, leaving doors open for warm air to circulate
CS17	Rads – as expected	Comfortable	Comfortable	Adjusting flow T curves to get the required comfort
CS18	No comment	Comfortable*	Comfortable	None / Not needed
CS19	Rads – not noticeable when they get warm**	Comfortable	Comfortable	None / Not needed
CS20	Rads – never get too warm**	Comfortable	Comfortable	Lighting wood burner
CS21	Rads – fine	Comfortable	Comfortable	Lighting wood burner, increasing flow T (rarely)

* Due to building defects, prevailing wind might cause the odd room to feel cold.
** Rads feel warmer when cold outside.

Table 20: Occupant training and reported ease of use

ID	Training & satisfaction	Satisfaction with training	Ease of use
CS01	Brief demonstration on the basics.	**Very dissatisfied** – running conditions optimisation info required (simple guide).	**Very easy** - once you understand what you are doing.
CS02	Householder was just told to use the thermostat.	**Satisfied** – would not have wanted to know more.	**Easy**
CS03	Manufacturer demonstration, suggesting thermostat control/ continuous operation at 23°C.	**Satisfied**	**Very easy**
CS04	Books/manuals, full technical group briefing/ presentation suggesting thermostatic control only.	**Very satisfied** – read manual but didn't understand much.	**Easy**
CS05	Full technical group briefing/presentation, user told to keep temperature constant.	**Very satisfied** – complicated except for thermostatic control.	**Easy** – complex, except for thermostat control.
CS06	RSL demonstration, user told to use thermostat.	**Very satisfied** – looked complicated at first.	**Easy** – but unsure what to do if anything goes wrong.
CS07	Technician demonstration on how to use programmer, booklet; it was suggested to keep thermostat at 21°C.	**Dissatisfied** – instructions difficult to understand; neither technicians nor users could get it work properly.	**No answer** – users feel they know what to do but the installation/settings are incorrect.
CS08	Technical meeting, leaflets, cards	**Satisfied** – sufficient but meeting too technical.	**Easy**
CS09	Installer demonstration, occupants' son has also provided them with handwritten instructions.	**Satisfied** – training/ assistance accessible but instructions too technical, post-installation visits would have been useful.	**Easy** – male partner can change flow temperature, but controls are very complicated.
CS10	Installer demonstration.	**Satisfied** – could not have been better.	**Easy** – after male partner set everything up.
CS11	Installer demonstration.	**Very satisfied**	**Easy** – no need to touch
CS12	Electrician demonstration, little	**Satisfied**	**Easy** – hardly ever touch HP.
CS13	Manuals, manufacturer helpdesk available.	**Dissatisfied** – more info/ instructions required, *e.g.*, central knowledge resource on typical installations, reference sites etc.	**Very easy** – no need to touch it.
CS14	Engineer demonstration.	**Dissatisfied** – more instructions required, *e.g.*, how to fine tune/improve.	**Easy** – due to user's technical background but others might not find it easy.
CS15	Installer presentation, leaflets.	**Very satisfied**	**Easy**
CS16	Installer demonstration, leaflets.	**Satisfied** – instructions not used, users just need to know how to put	**Easy**
CS17	Installer demonstration.	**Satisfied** – would have liked installer to come back after a few months.	**Very easy**
CS18	Leaflets, Installer demonstration, where more things were shown than user utilises, *e.g.*, heat curves.	**Satisfied** – HP work so instructions not needed.	**Easy**
CS19	Book, installer suggested continuous operation.	**Satisfied** – self-evident control panel, book quite reasonable.	**Easy** – just sits there and does the job.
CS20	Installer demonstration, book.	**Satisfied** – book is complex and control panel not intuitive (2-3 button only).	**Easy** – temperature adjustment only otherwise it would be difficult.
CS21	Installer demonstration, paperwork	**Very satisfied** – users calls installer if needed.	**Easy**

* User's daughter finds it too complicated for seniors.

Table 21: Technical issues and resolution, as derived from user narrative.

ID	Issues since installation	Support and resolution
CS01	**Manifold floor valves back to front** - this installation fault resulted in one room wouldn't heat up when HP was first installed.	Installers fixed it but householder was the one that spotted the problem, due to his technical background.
CS02	No	N/A
CS03	No	N/A
CS04	**Cracked antifreeze tube** - resulted in wintertime heating interruption.	Installers fixed it but it took two months.
CS05	No	N/A
CS06	(a) **Faulty HP** – winter-time heat interruption; (b) **tank/rad blockage** – no heat coming through; (c) **fan convector off** – bathroom HFC; (d) **external unit damp patch** – slippery;	(a) Installers replaced HP unit; (b) installers restored flow; (c) friend adjusted settings; (d) unresolved
CS07	(a) **Faulty inlet air fan** – one of the many problems experienced before HP "burnt itself out"; (b) **increased bills** – insufficient heat at a high cost.	(a) Installers replaced fan; (b) unresolved
CS08	(a) **Faulty motherboard** – no heating during winter; (b) **increased bills** – booster heater either turned on by mistake during renovation or system reset itself during power on/off; (c) **dripping issue.**	(a) Technicians replaced the whole unit within 6-8 weeks; (b) resistance heater switched off, but nobody could understand there was no fault in the system except for one technician; (c) drip-tray installed; drainpipe was present but not installed.
CS09	No	N/A
CS10	No	N/A
CS11	**HP turned off** – due to power cut;	Users turning HP off and on again after reading instructions.
CS12	(a) **Faulty sensor** – heating not kicking in due to miscommunication between sensor and controller; (b) **increased bills** – resistance heater left on by plumber's mistake; (c) **pump problem**	(a) Electrician and plumber fixed problem (b) user resolved this with the help of a relative after reading instructions; (c) installers replaced pump.
CS13	**Air in ground loops** – improper installation	Plumber and engineer, in collaboration with user, resolved issues, i.e., remove air from ground loops and installed relief valves.
CS14	**Antifreeze leak** – major problem after installation as antifreeze level kept dropping due to borehole leak.	Installers dug up and fixed leak in both boreholes.
CS15	No	N/A
CS16	**Excessive electricity consumption**	Unresolved, issue was being investigated.
CS17	**Big surge in voltage** – HP broke down and resistance heater kicked in, but users only realised due to increased bills.	Installer diagnostics in collaboration with manufacturer but problem took 3 weeks to resolve leaving occupants without heating during winter.
CS18	**HP turning off** - recurring 'motor-P' error, probably related to power supply interruption; user only realised due to the lack of DHW.	Occupant turns HP on/off to resolve issue.
CS19	No	N/A
CS20	No	N/A
CS21	**Connection problem** - leading to ASHP inlet air fan not going round soon after installation.	Installers fixed it.

Appendix D: Monitoring schematics

D1 Assigned schematics and installation description

D2 Metering schematics 0.12, 2.4, 3.4, 4.1 and 16.12

D1 Assigned schematics and installation description

Table 22: Final schematic assignment and installation description.

ID	Schematic	Installation description (as observed)
CS01	2.4	ASHP connected to integrated packaged cylinder in uninsulated garage; 4 circulation pumps in garage plus one in house (total circulation pump load ~400W).
CS02	2.4	ASHP connected through 'cold roof' to cylinder in house with 50W circulation pump; pipes well insulated, no pump or valve insulation.
CS03	16.12	GSHP with borehole connected through 'cold roof' to integrated HP and cylinder; pipes *etc*. unevenly insulated; buffer vessel; circulation pump speed 1 (35W).
CS04	16.12	GSHP with borehole connected through 'cold roof' to integrated HP and cylinder; pipes *etc*. unevenly insulated; buffer vessel; circulation pump speed 2 (45W).
CS05	16.12	GSHP with borehole connected through 'cold roof' to integrated HP and cylinder; pipes *etc*. unevenly insulated; buffer vessel; circulation pump speed 2 (45W); ground loop pipes well insulated.
CS06	2.4	ASHP insulated pipes on outside wall into attic; packaged HP, cylinder with controls, 2 circulation pumps in 'cold roof'; insulated pipes but not pumps or valves.
CS07	2.4	ASHP insulated pipes on outside wall into attic; packaged HP, cylinder with controls, 2 circulation pumps in 'cold roof'; insulated pipes but not pumps or valves.
CS08	2.4	ASHP insulated pipes on outside wall into attic; packaged HP, cylinder with controls, 2 circulation pumps in 'cold roof'; insulated pipes but not pumps or valves.
CS09	3.4	Split system ASHP; outdoor unit located away from house; cylinder inside house.
CS10	N/A*	2 separate ASHP supplying DHW, UFH to kitchen/lounge and rads to the rest of the house; both HP located remotely from house; cylinder, circulation pumps and valves in heated utility room; 5 circulation pumps; secondary return pump (total circulation pump load ~450W); plate heat exchangers between HP and installation; very good quality insulation.
CS11	N/A	Cylinder and 3 circulation pumps in partly insulated garage with plate heat exchanger between ASHP and installation. Good pipe insulation but not pumps or valves; DHW immersion unmetered.
CS12	16.12	Integrated GSHP and cylinder with buffer; 350-360m straight ground loop; three circulation pumps; UFH downstairs and rads upstairs.
CS13	N/A	GSHP with UFH driven by variable speed pump; DHW circuit with fixed speed pump; UFH throughout.
CS14	N/A	Double borehole feeding HP with cylinder and buffer in unheated garage; insulated buried pipework to UFH in separate bungalow; insulated pipework, valves and circulation pumps; 3 external circulation pumps visible and 6 circulation pumps to UFH zones.
CS15	0.12	GSHP in unheated garage with professional insulation to pipes and insulated valve boxes; buffer and packaged cylinder in heated space; UFH downstairs and rads upstairs; 4 circulation pumps.
CS16	16.12	GSHP in heated perimeter of house; buffer with 4 UFH manifolds; ~700W circulation power plus secondary return circulation pump.
CS17	N/A	GSHP and integrated cylinder; buffer vessel in unheated garage; pipes insulated but not pumps or valves; variable speed circulation pump (25-45W) to radiators.
CS18	N/A	GSHP, buffer and cylinder in heated perimeter of house, 2 UFH manifold circulation pumps on speed 3 (total circulation pump load 700W).
CS19	N/A	GSHP buffer with immersion; 1 ground loop and 2 main installation circulation pumps in unheated shed; insulation of top quality with circulation pump and manifold boxes; 2 more circulation pumps indoors alongside cylinder (total circulation pump load 600W); UFH downstairs, radiators upstairs.
CS20	4.1	ASHP connected to buffer and circulation pumps in unheated shed. DIY insulation to buffer; very long run from HP into house; radiators supported by wood burning stove in two living rooms; DHW provided by solar thermal and unmetered immersion heater.
CS21	N/A	ASHP providing SH and DHW through a thermal store with immersion heater.

* Closest schematic 2.4.

D2 Metering schematics 0.12, 2.4, 3.4, 4.1 and 16.12

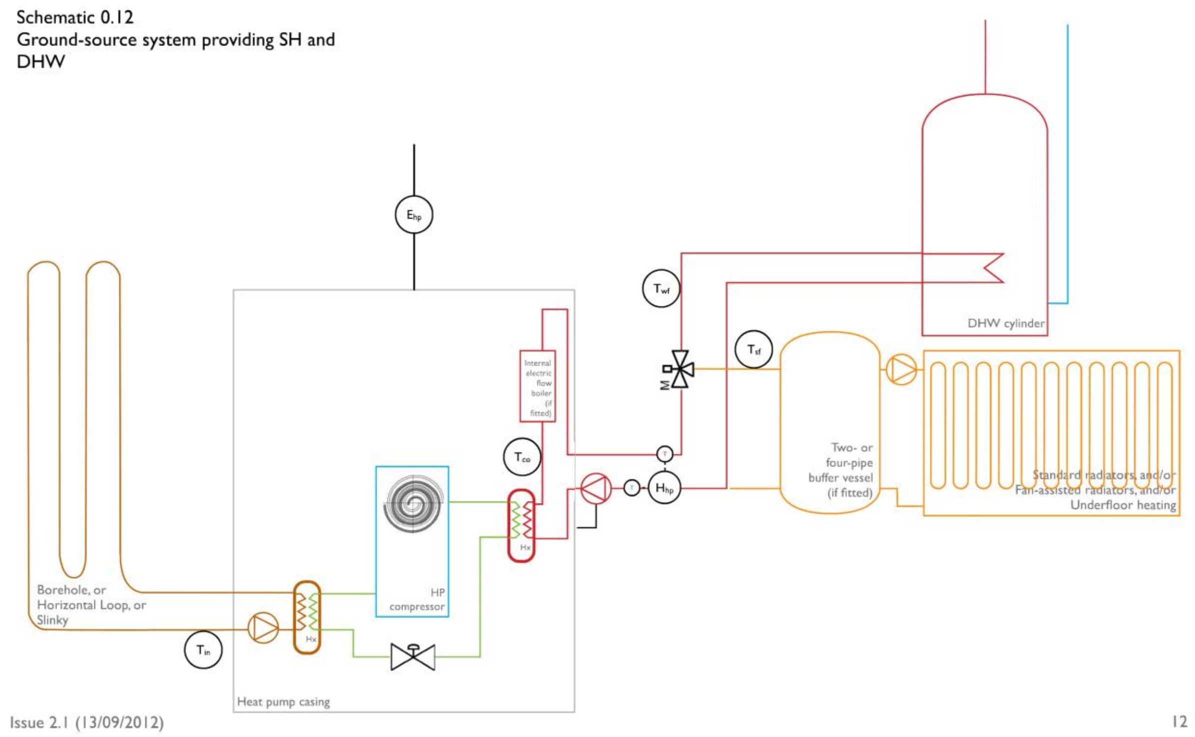


Figure 1: 2-pipe HP with no immersion heater.

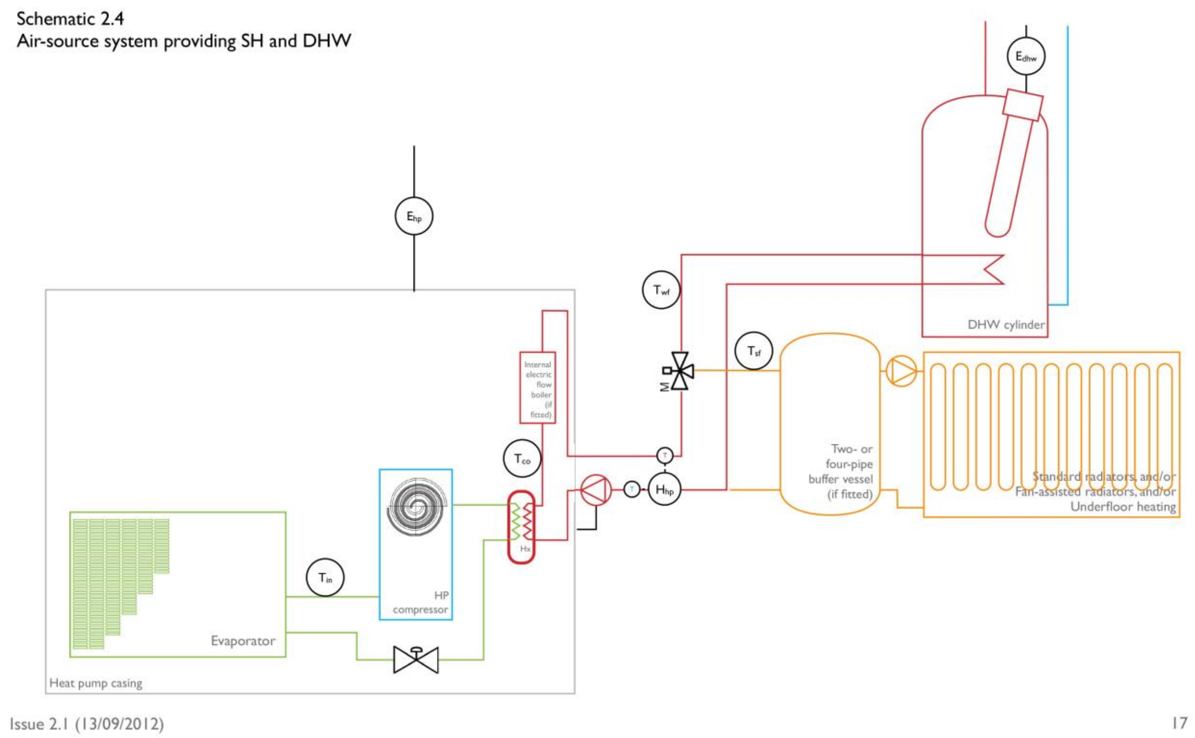


Figure 2: 2-pipe HP with immersion heater for DHW.

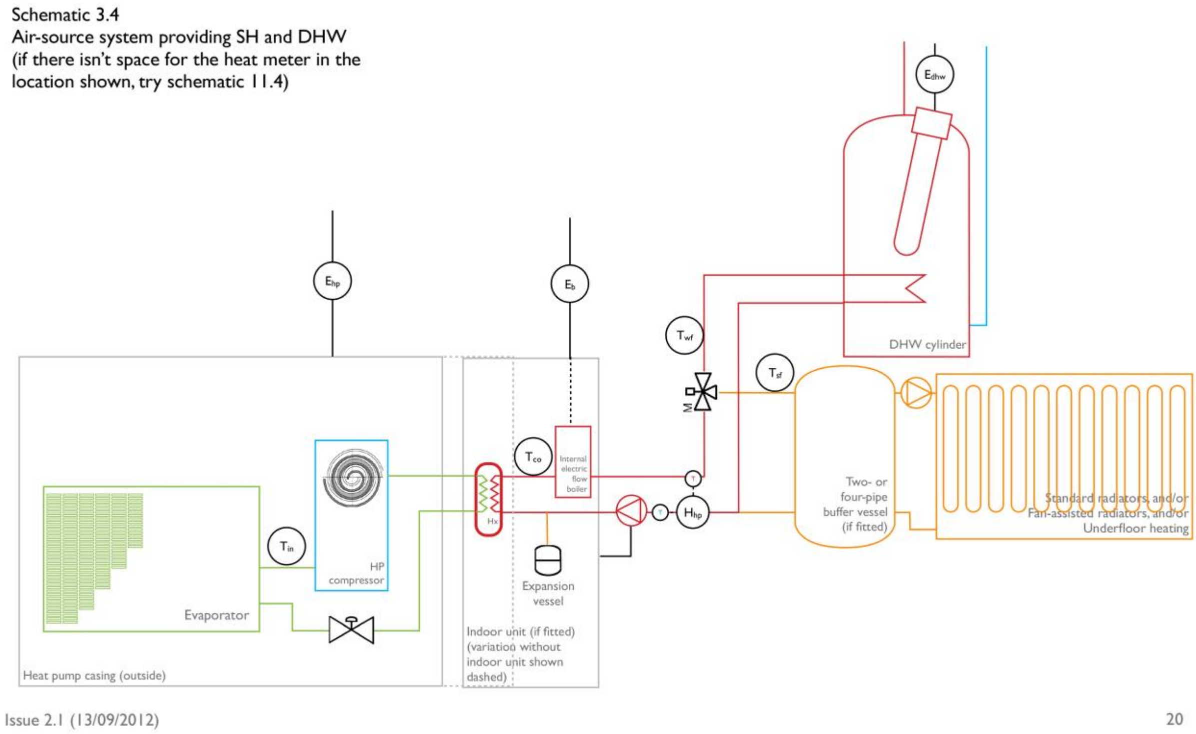


Figure 3: 2-pipe ASHP with immersion heater for DHW.

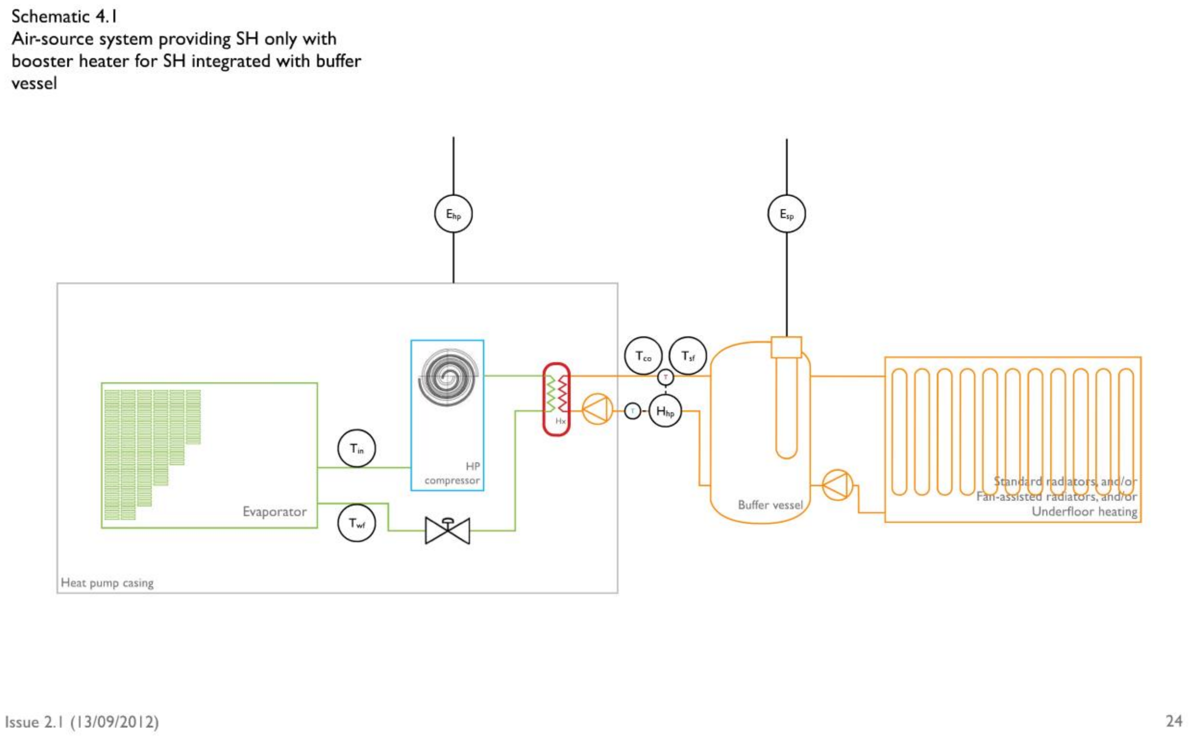


Figure 4: 2-pipe ASHP with immersion heater for SH only.

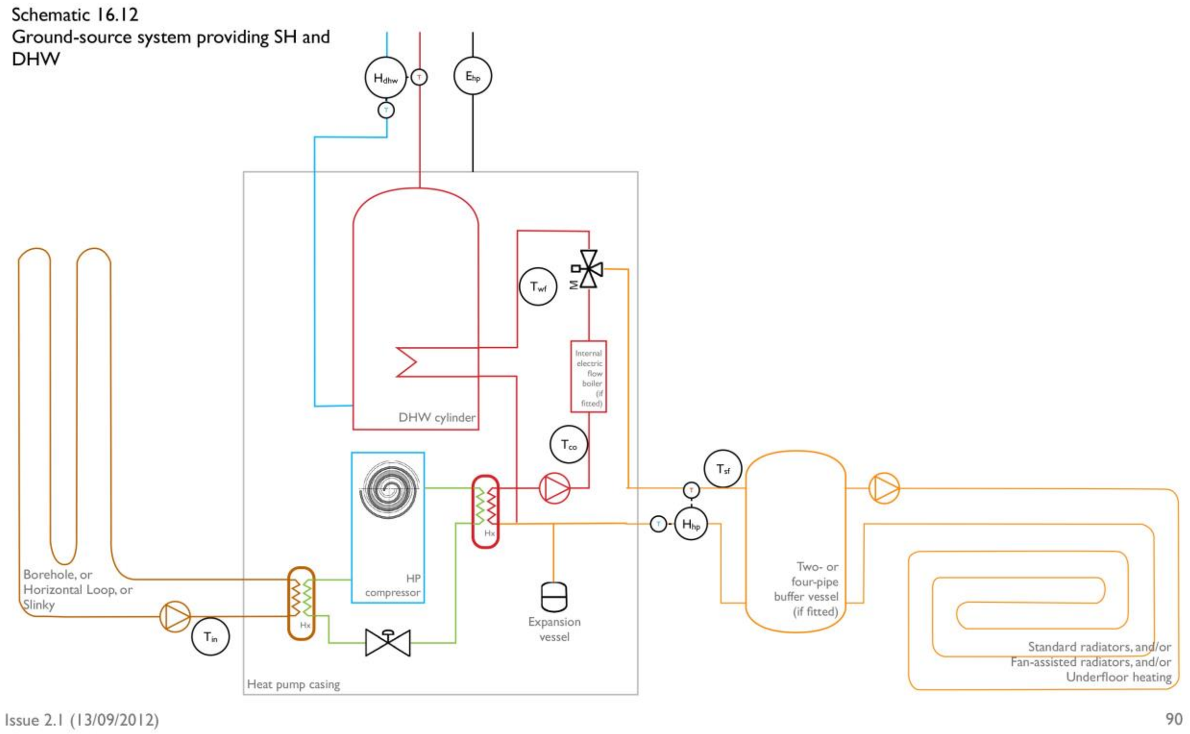


Figure 5: GSHP with integral DHW storage and no immersion heaters for either SH or DHW

Appendix E: Case study drawings and tailored schematics

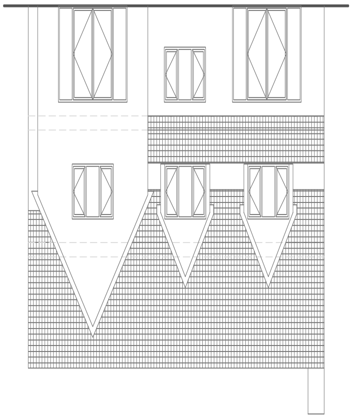
E1 Floor plans, facades and section

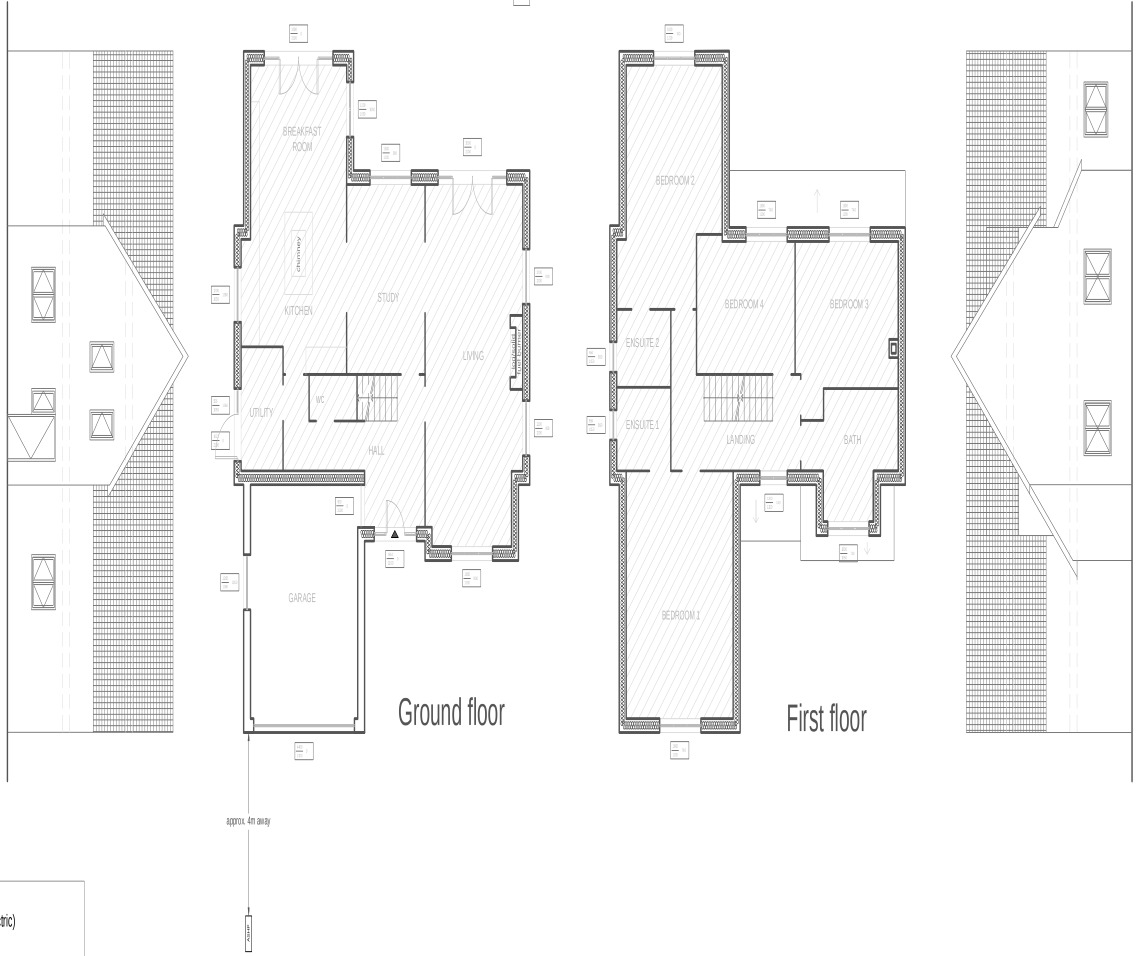
E2 Tailored schematics

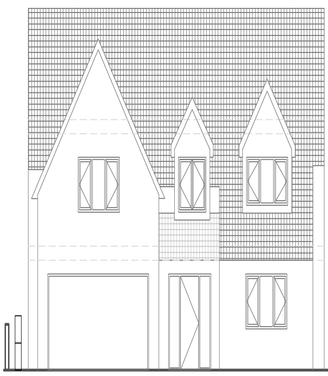
E1 Floor plans, facades and section

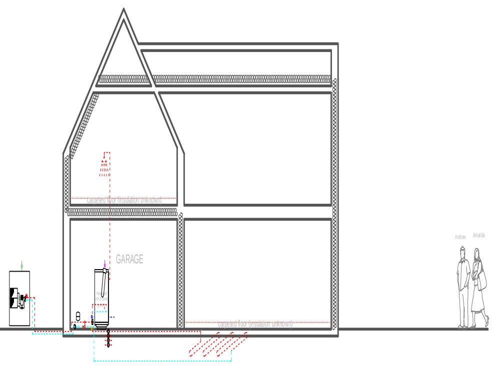
The drawings of this section derived from the architectural drawings provided by householders (where available) and the measurements, sketches and photographs obtained during the site visit investigations. They also contain information on the HP system installation (location of internal and external units, heat emitter type and location *etc.*), the building fabric insulation placement (based on the occupants' narrative, researchers' observations, technical documentation and energy performance certificates) and any other control systems available (*e.g.,* MVHR and dehumidifiers).

CS01 Drawing not to scale





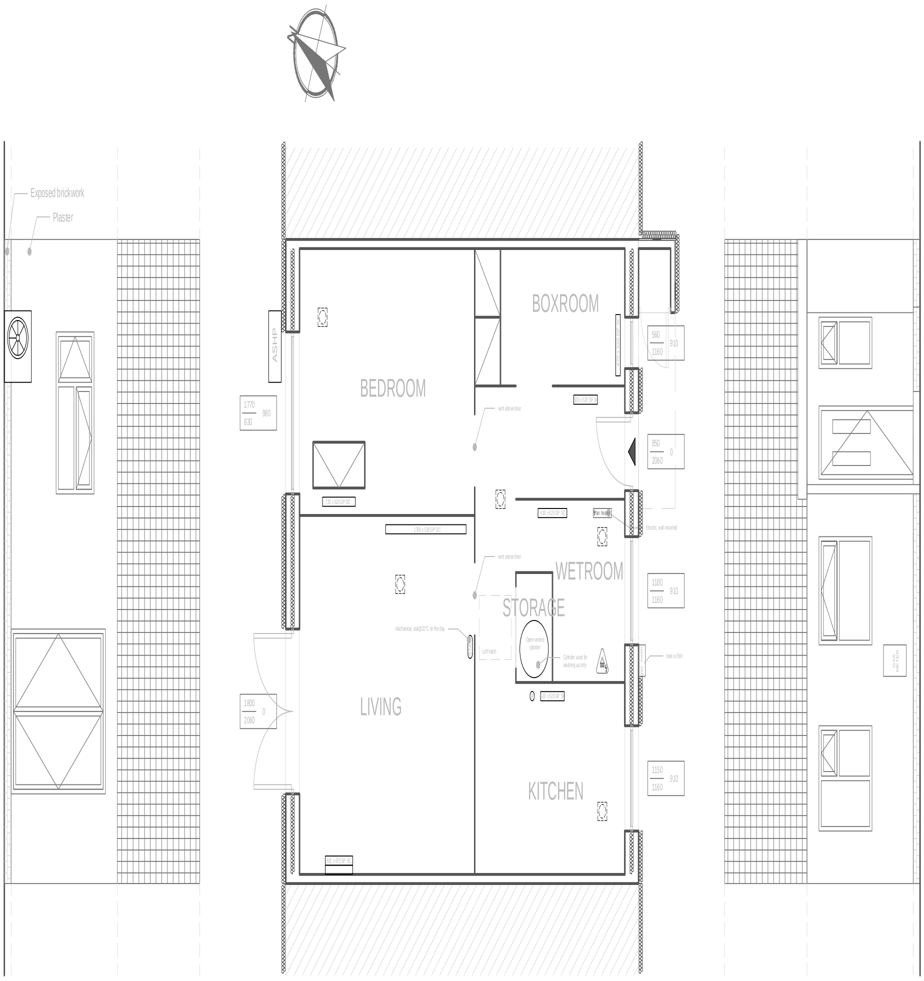




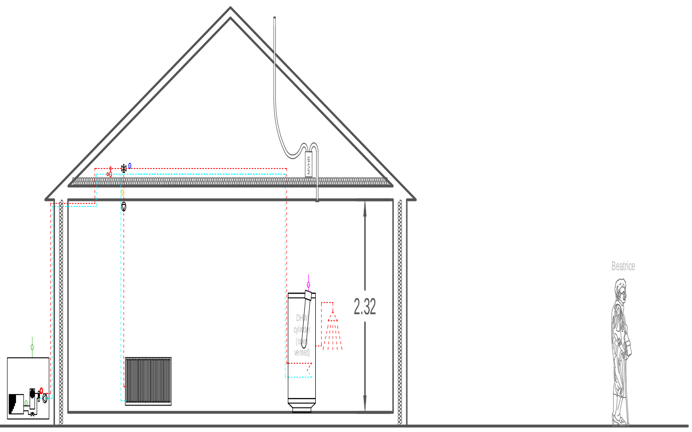
Key

- Dehumidifier (non electric)
- Dehumidifier (electric)
- Electric shower
- Electric fan heater
- Additional HP controls
- Thermostat
- Mechanical ventilation inlet or outlet
- Towel radiator (hybrid)
- Towel radiator (electric)
- Towel radiator (from mains)
- Insulation
- Radiator
- Convector
- Hydronic fan convector
- Bathroom underfloor heating (electric)
- Bathroom underfloor heating (from mains)
- Underfloor heating coverage

CS02 Drawing not to scale



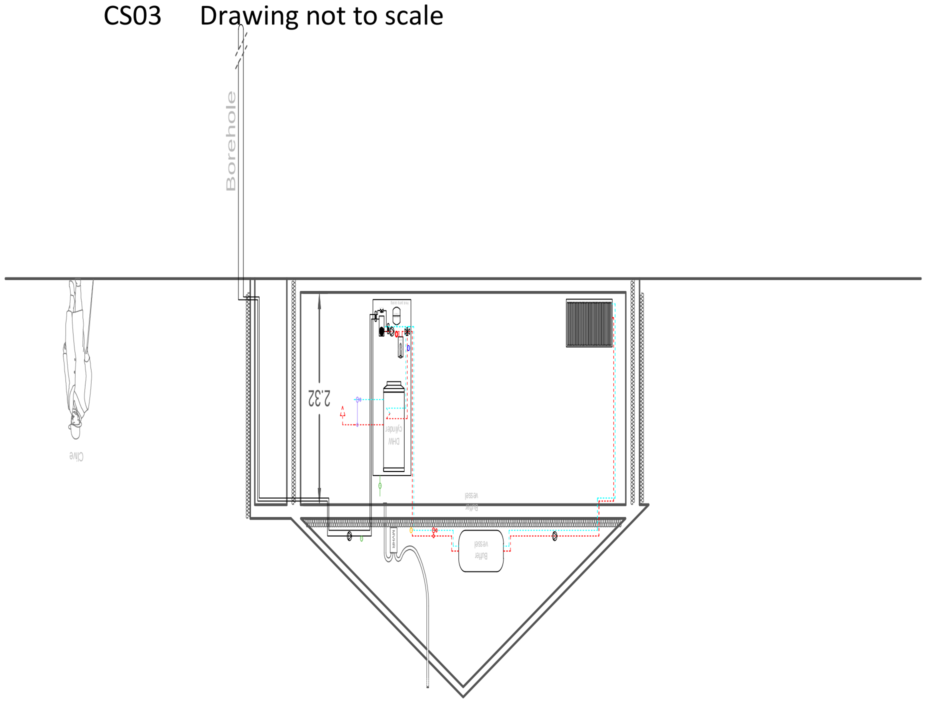
Ground floor

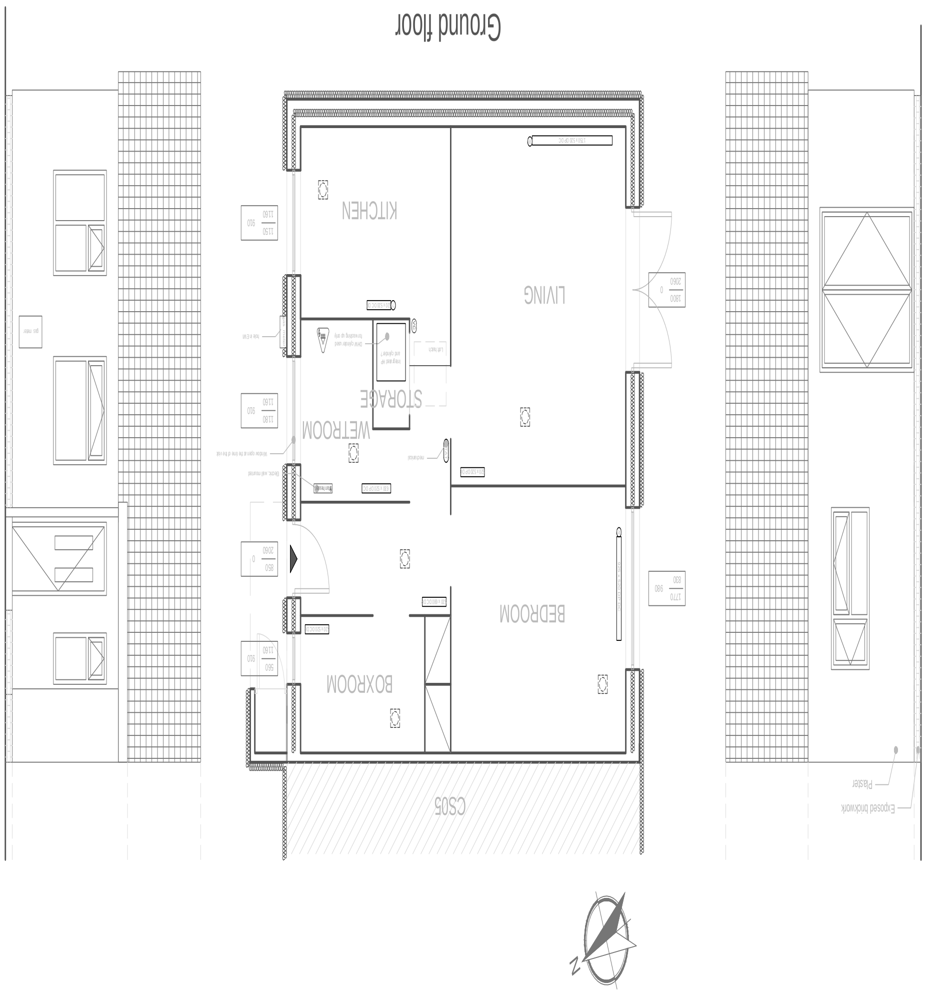


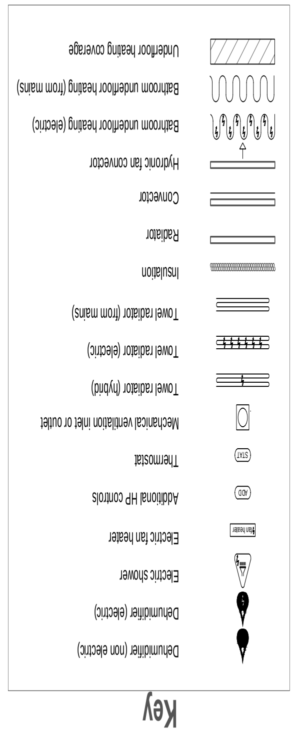
Key

- Dehumidifier (non electric)
- Dehumidifier (electric)
- Electric shower
- Electric fan heater
- Additional HP controls
- Thermostat
- Mechanical ventilation inlet or outlet
- Towel radiator (hybrid)
- Towel radiator (electric)
- Towel radiator (from mains)
- Insulation
- Radiator
- Convector
- Hydronic fan convector
- Bathroom underfloor heating (electric)
- Bathroom underfloor heating (from mains)
- Underfloor heating coverage

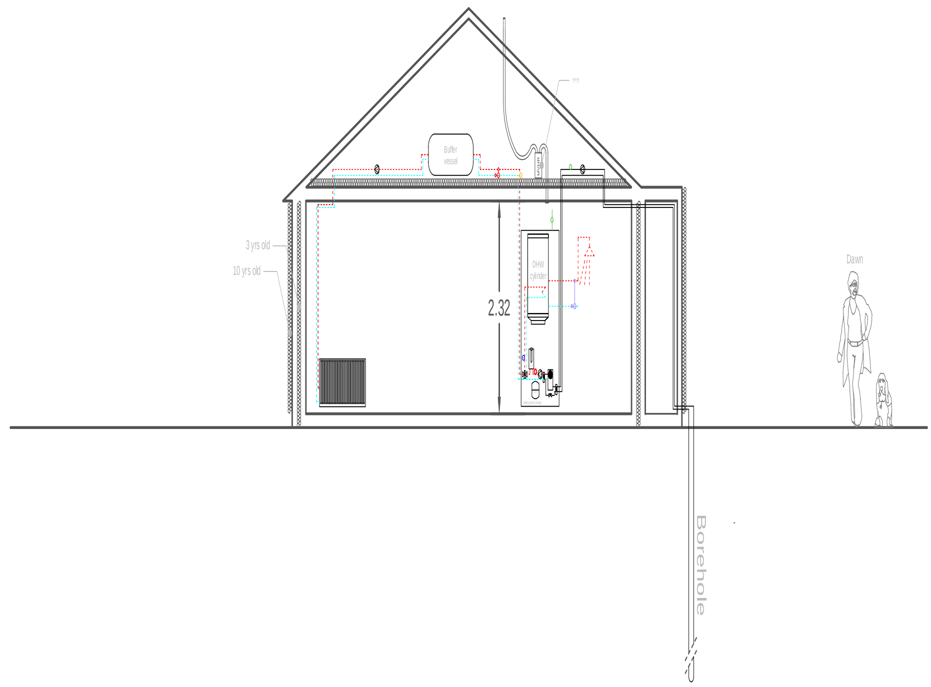
CS03 Drawing not to scale







Ground floor

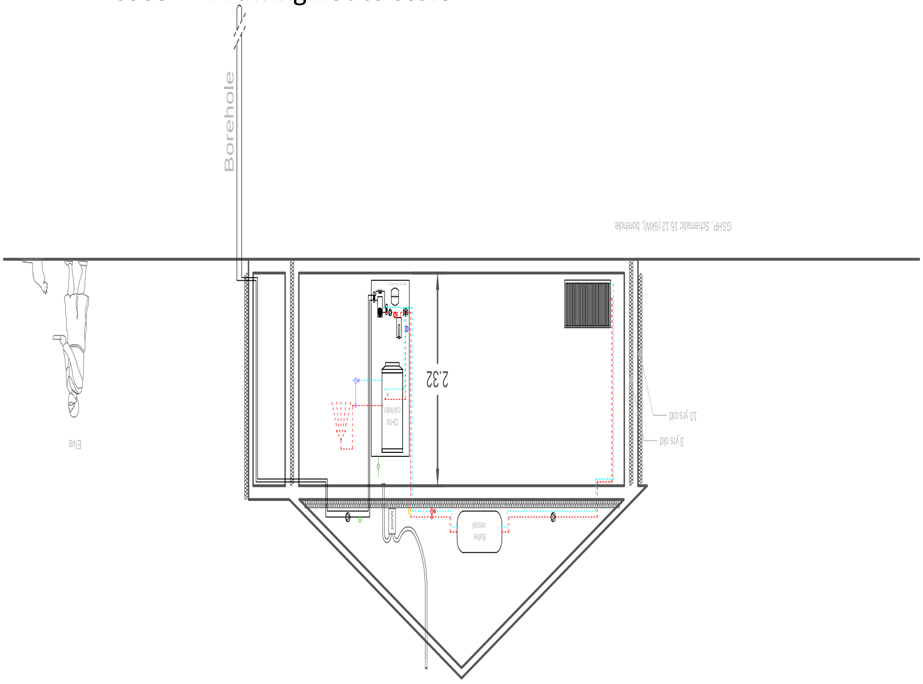


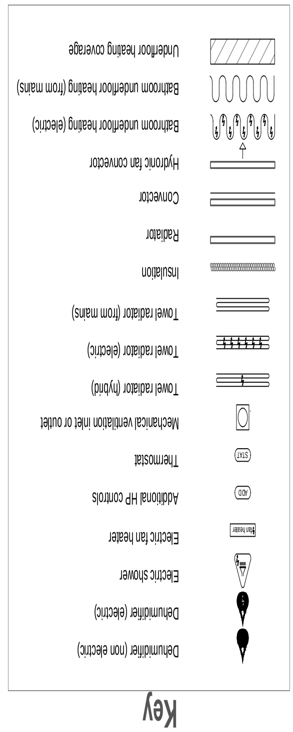
Key

- Dehumidifier (non electric)
- Dehumidifier (electric)
- Electric shower
- Electric fan heater
- Additional HP controls
- Thermostat
- Mechanical ventilation inlet or outlet
- Towel radiator (hybrid)
- Towel radiator (electric)
- Towel radiator (from mains)
- Insulation
- Radiator
- Convector
- Hydronic fan convector
- Bathroom underfloor heating (electric)
- Bathroom underfloor heating (from mains)
- Underfloor heating coverage

CS04 Drawing not to scale

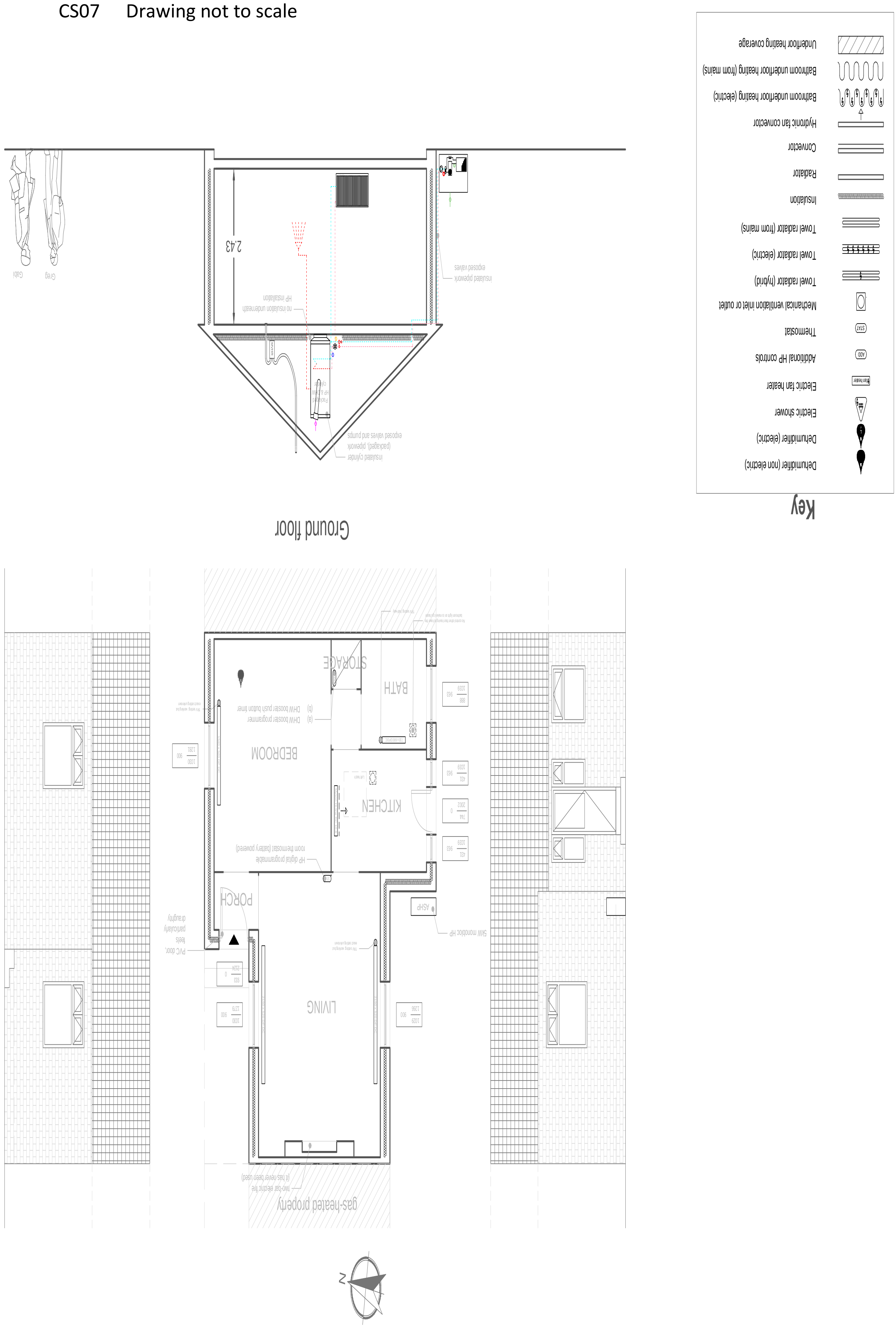
CS05 Drawing not to scale



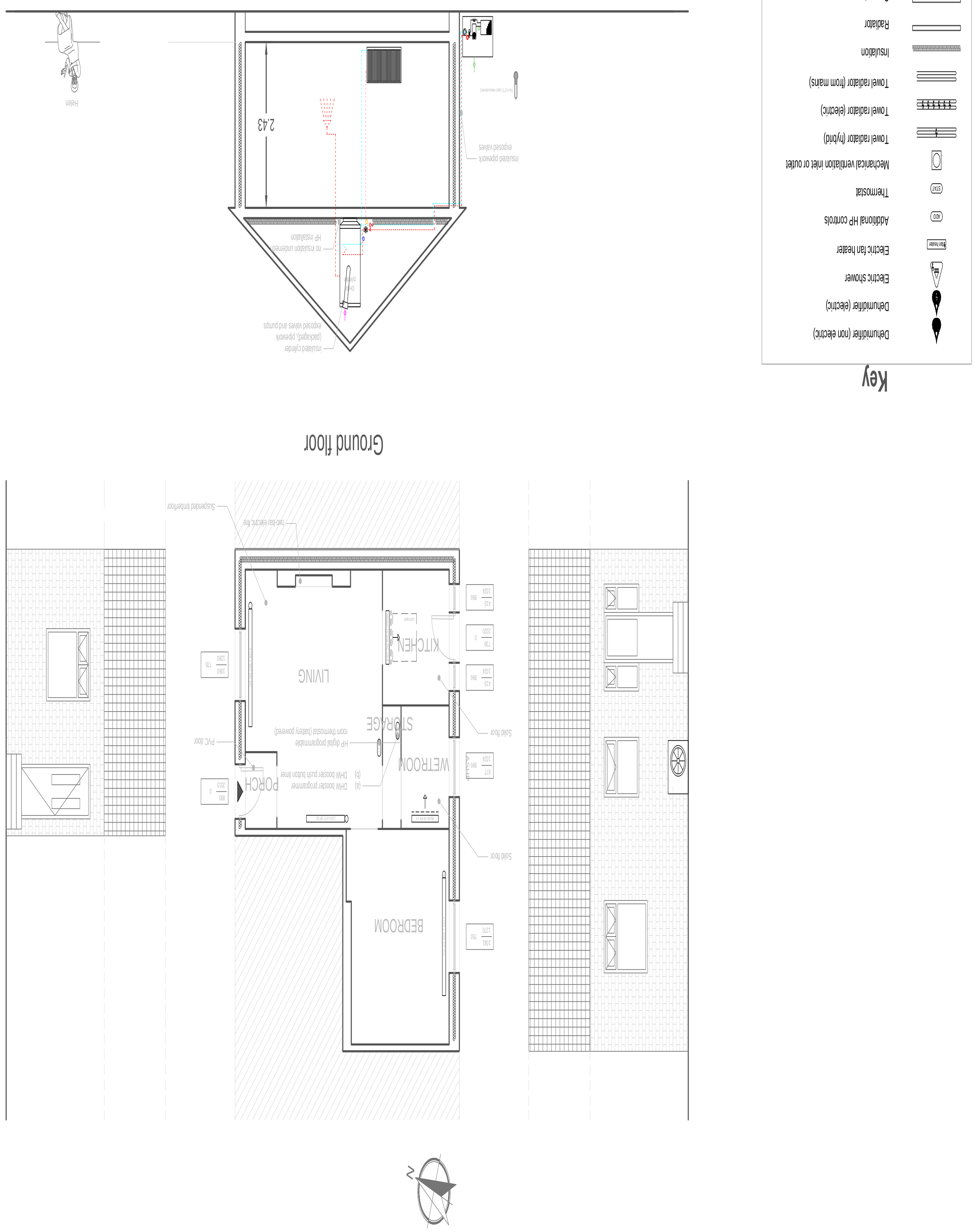


CS06 Drawing not to scale

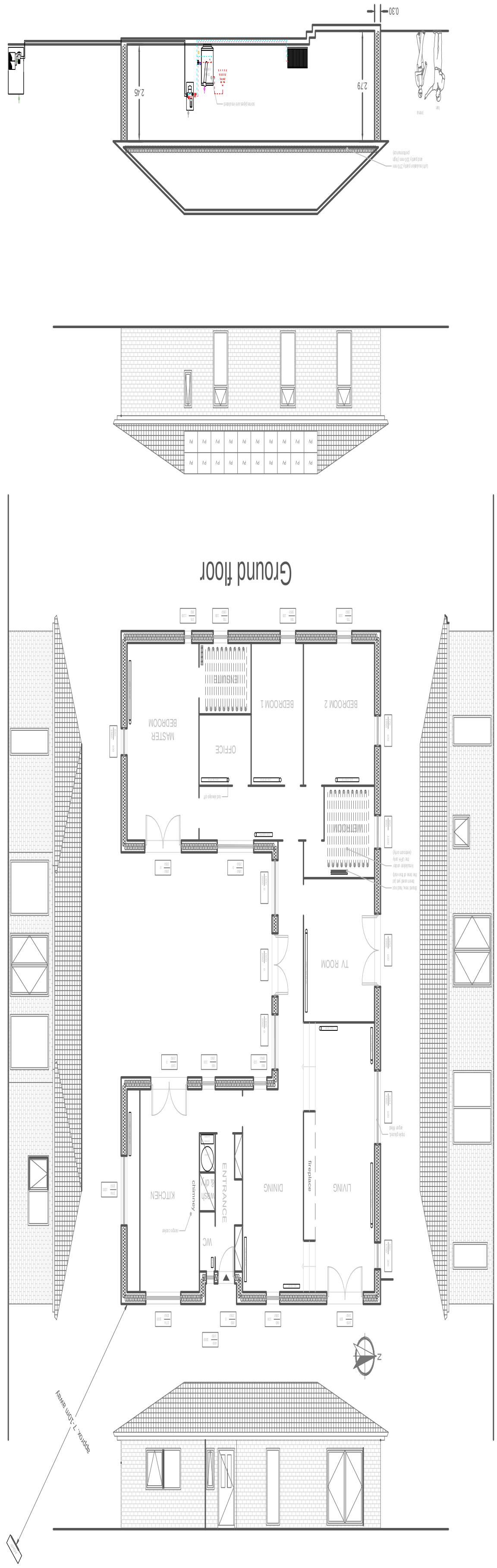
CS07 Drawing not to scale

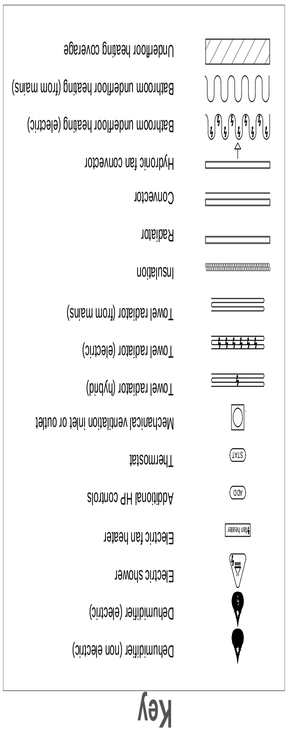


CS08 Drawing not to scale

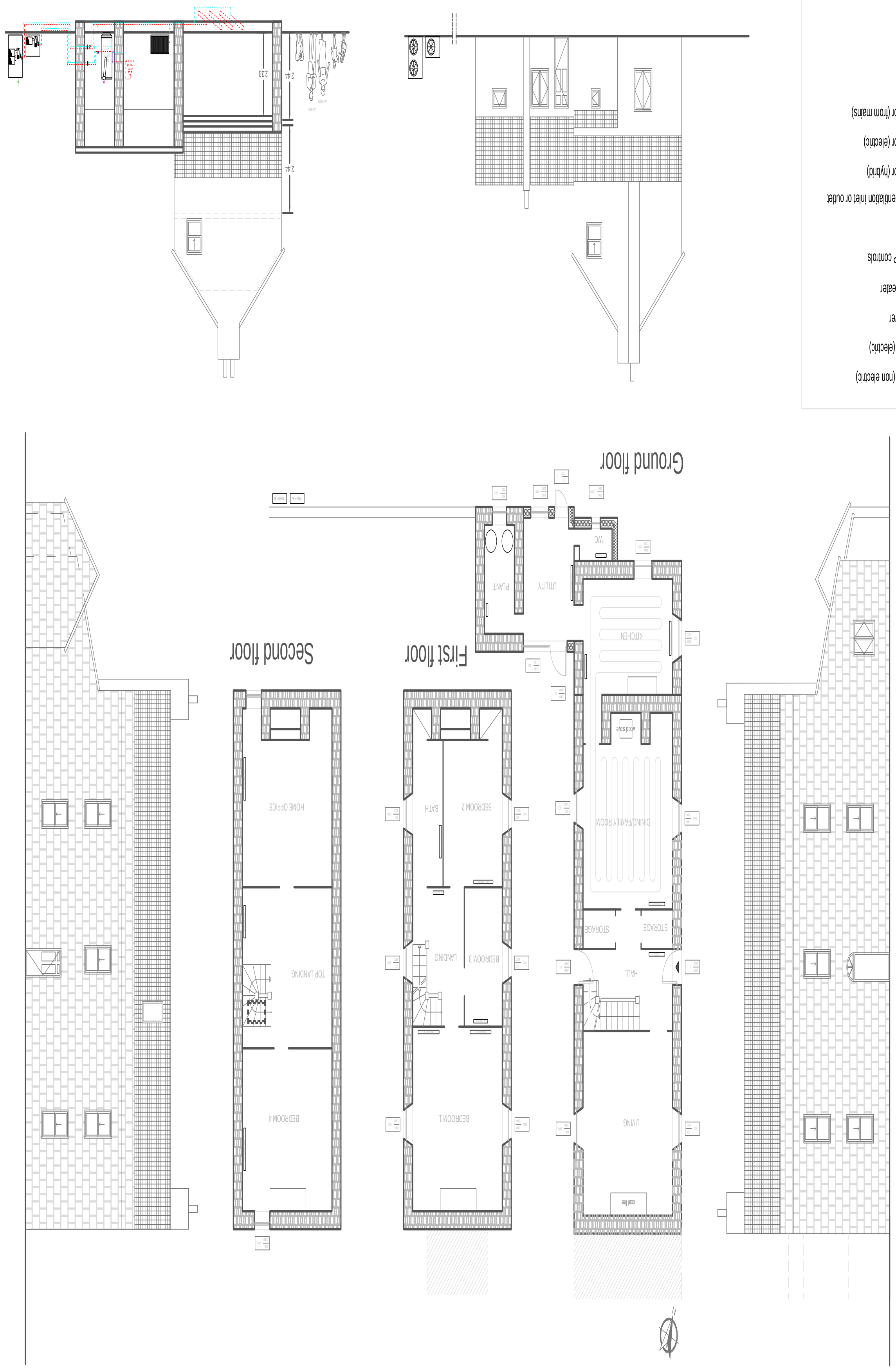


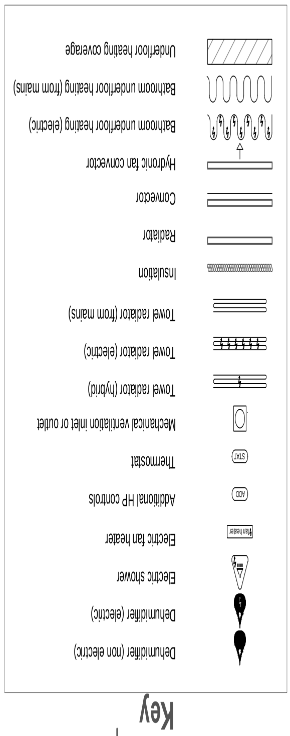
CS09 Drawing not to scale





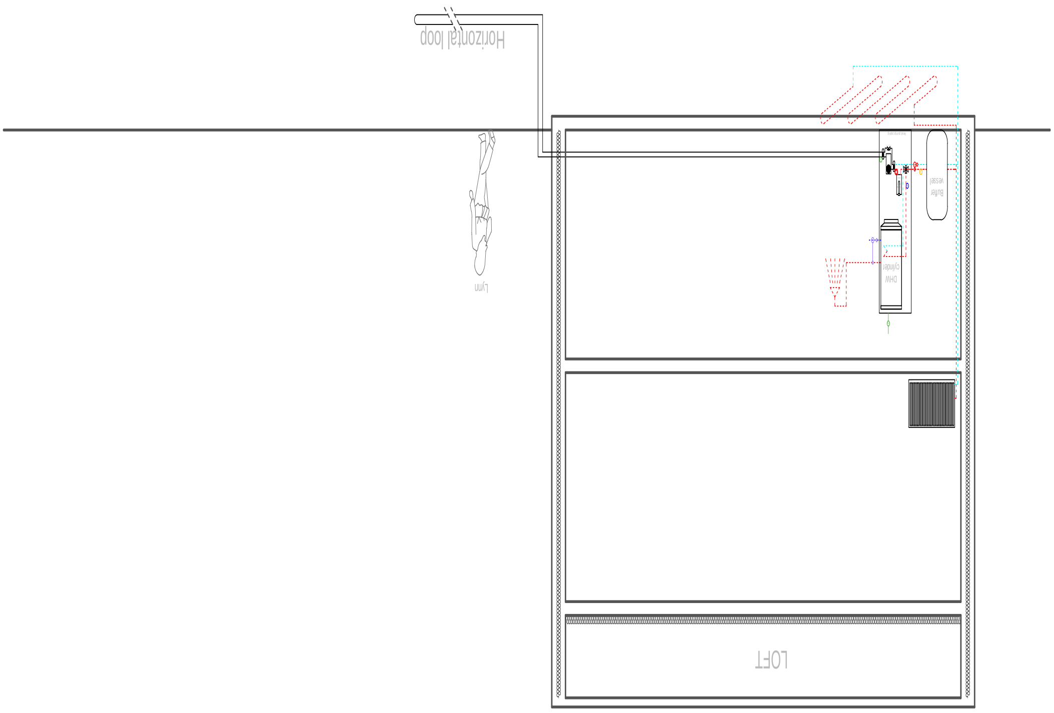
CS10 Drawing not to scale

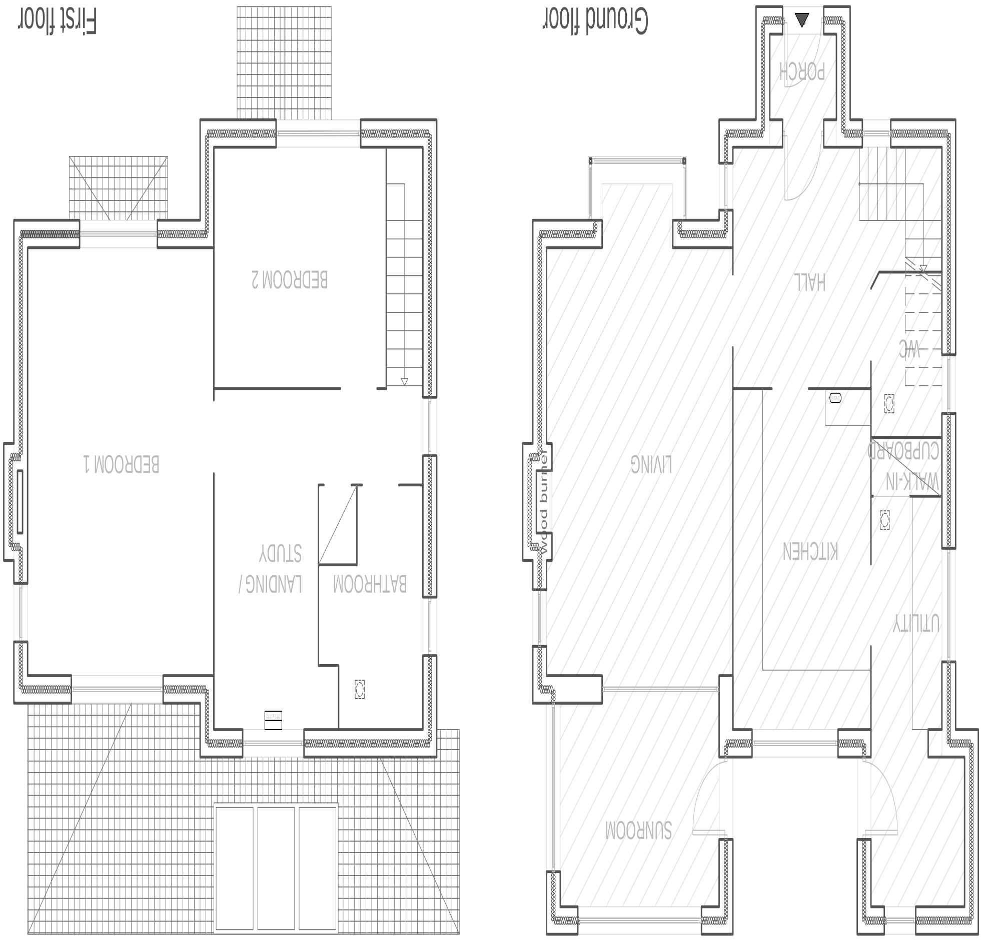




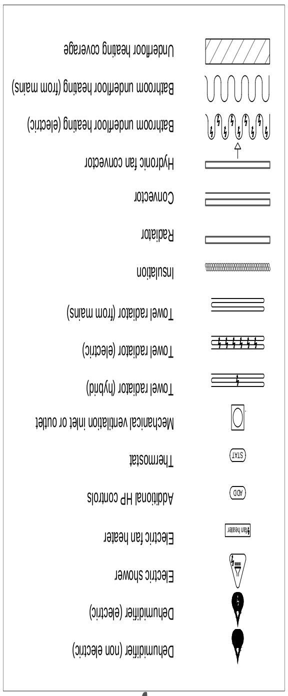
CS11 Drawing not to scale

CS12 Drawing not to scale

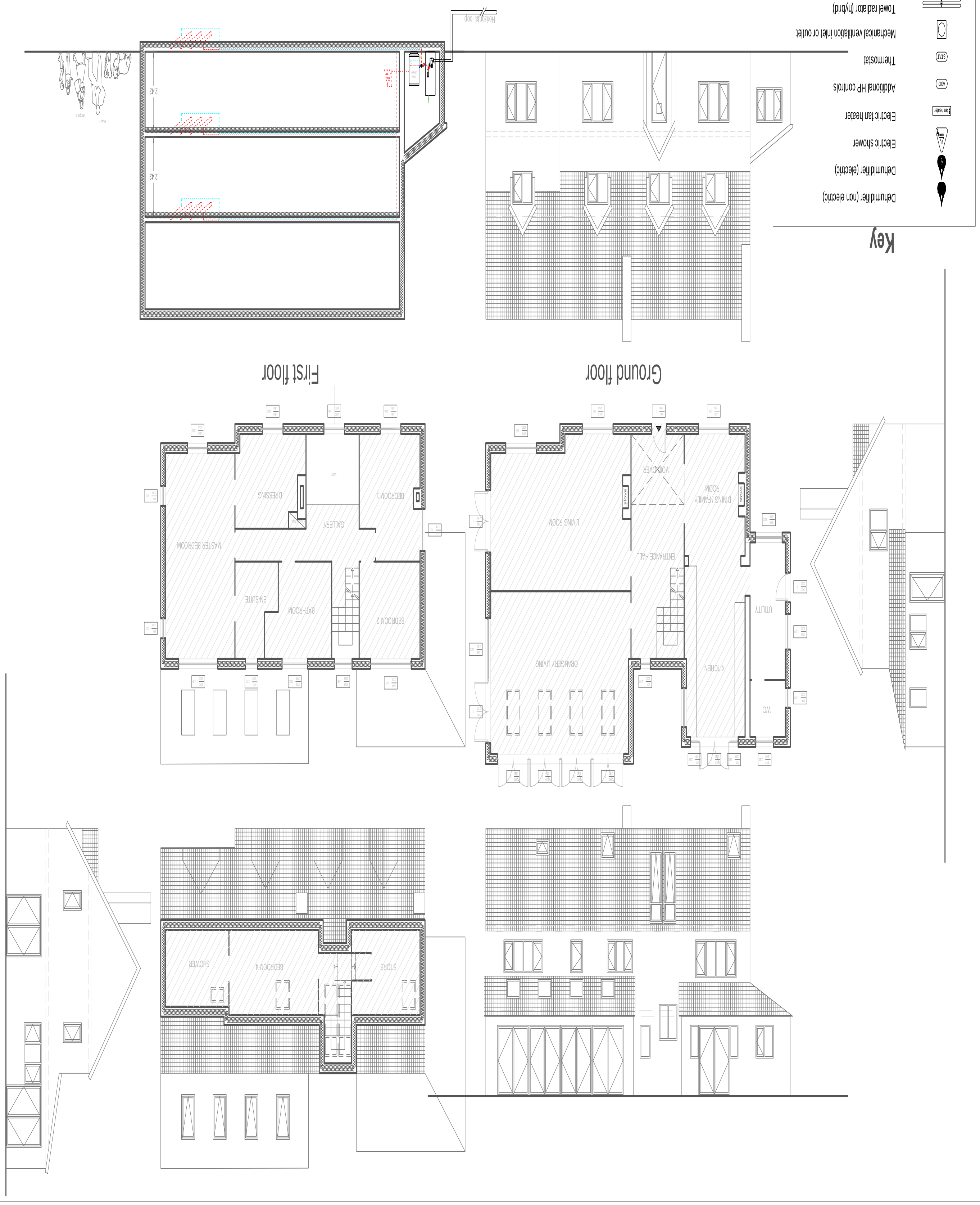




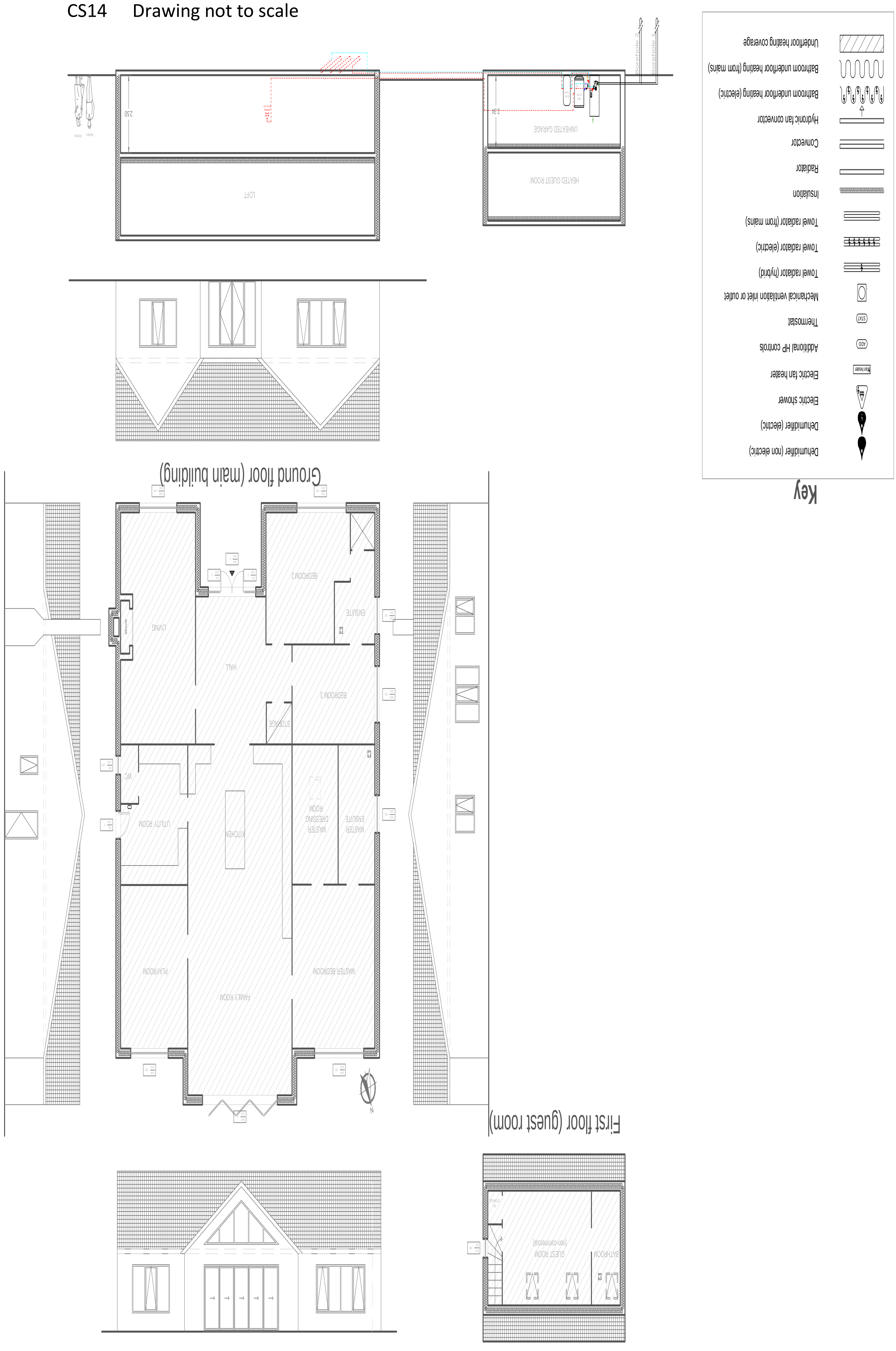
Key



CS13 Drawing not to scale

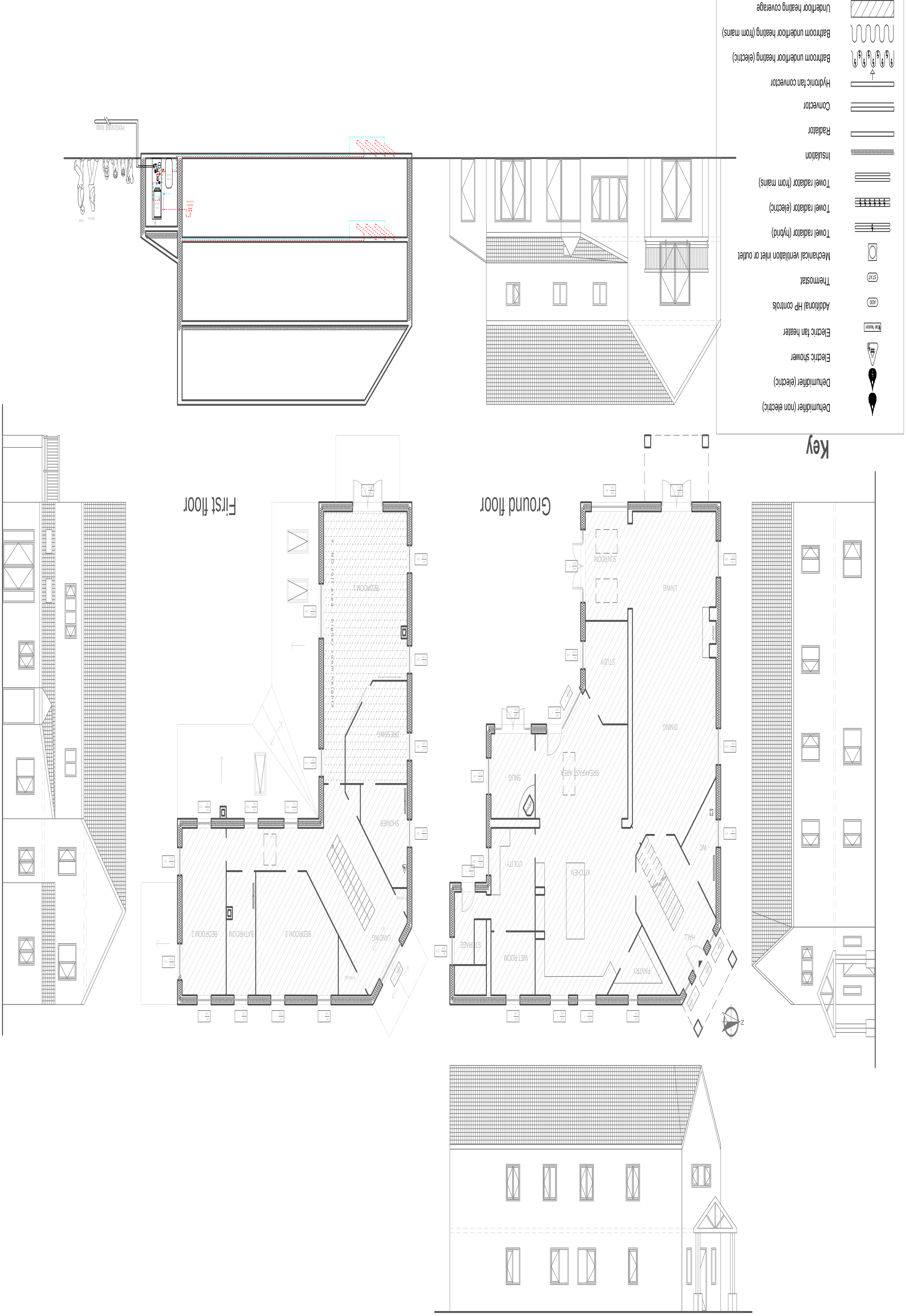


CS14 Drawing not to scale

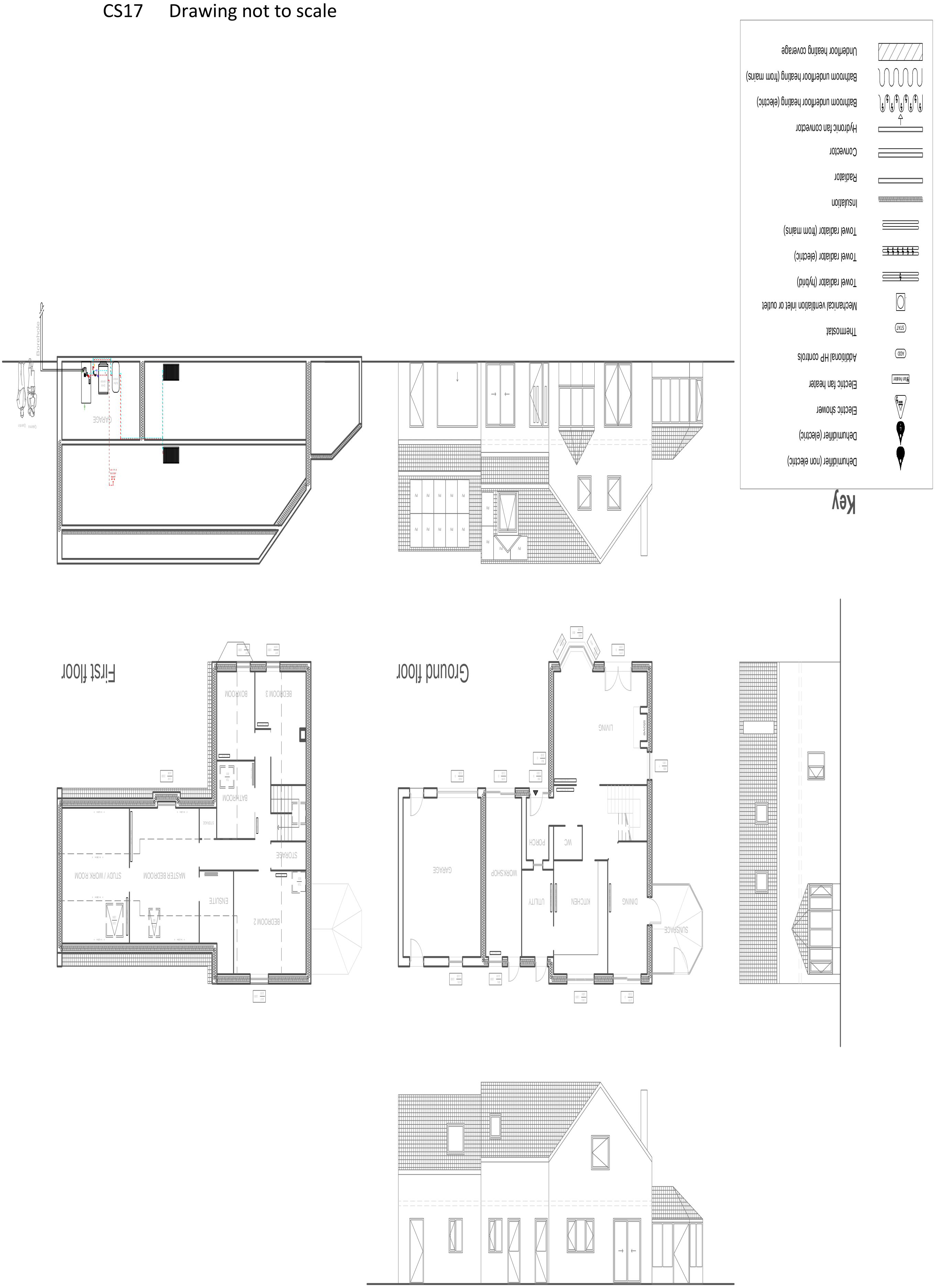


CS15 Drawing not to scale

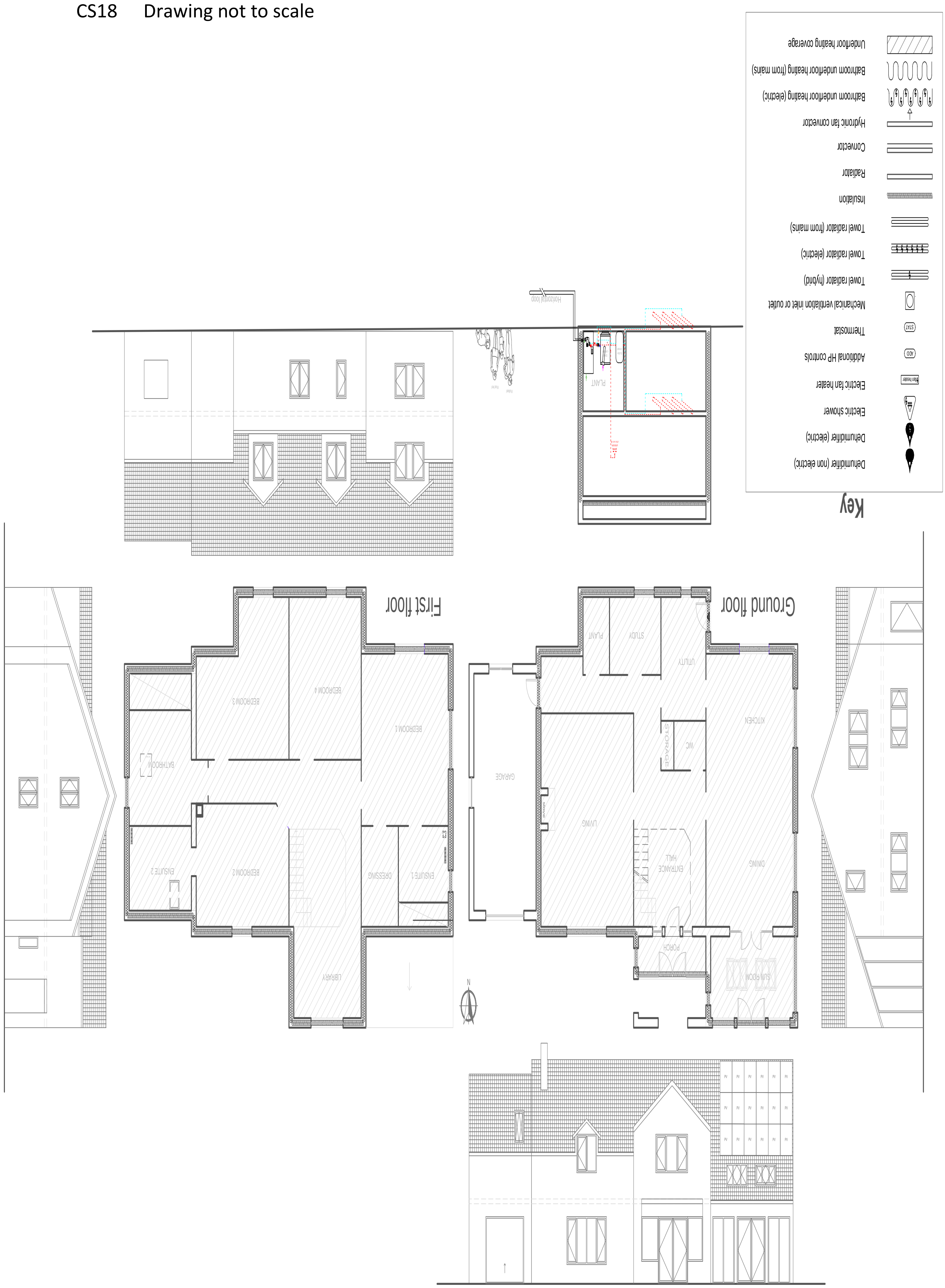
CS16 Drawing not to scale



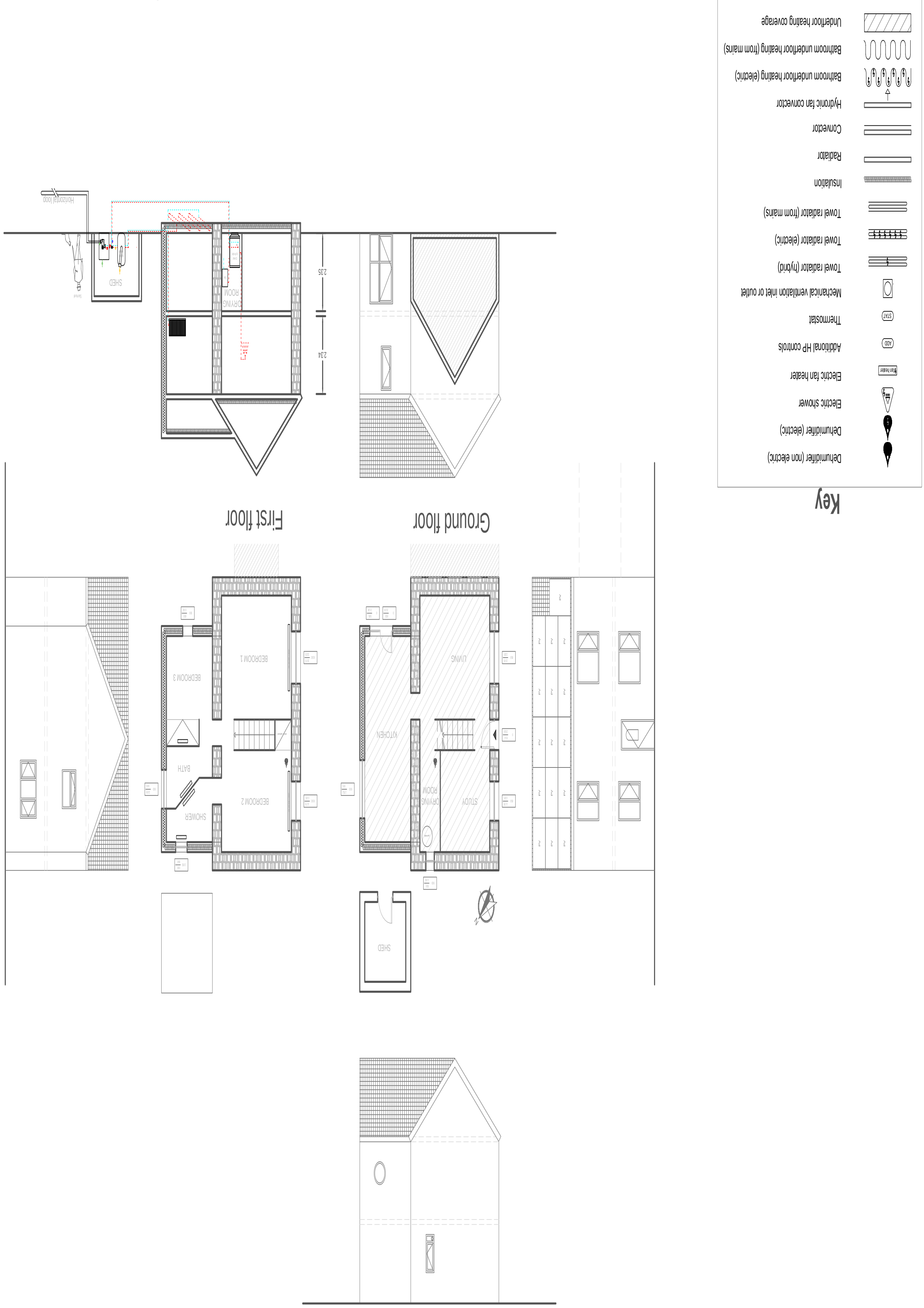
CS17 Drawing not to scale



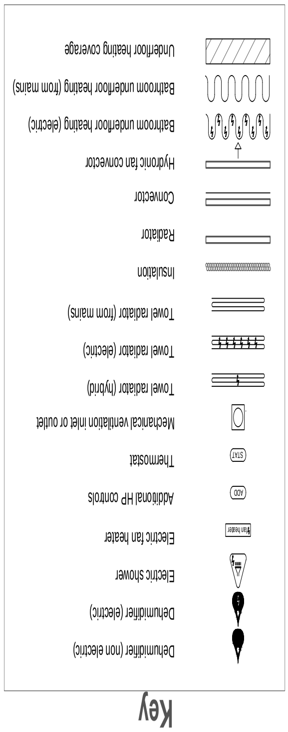
CS18 Drawing not to scale

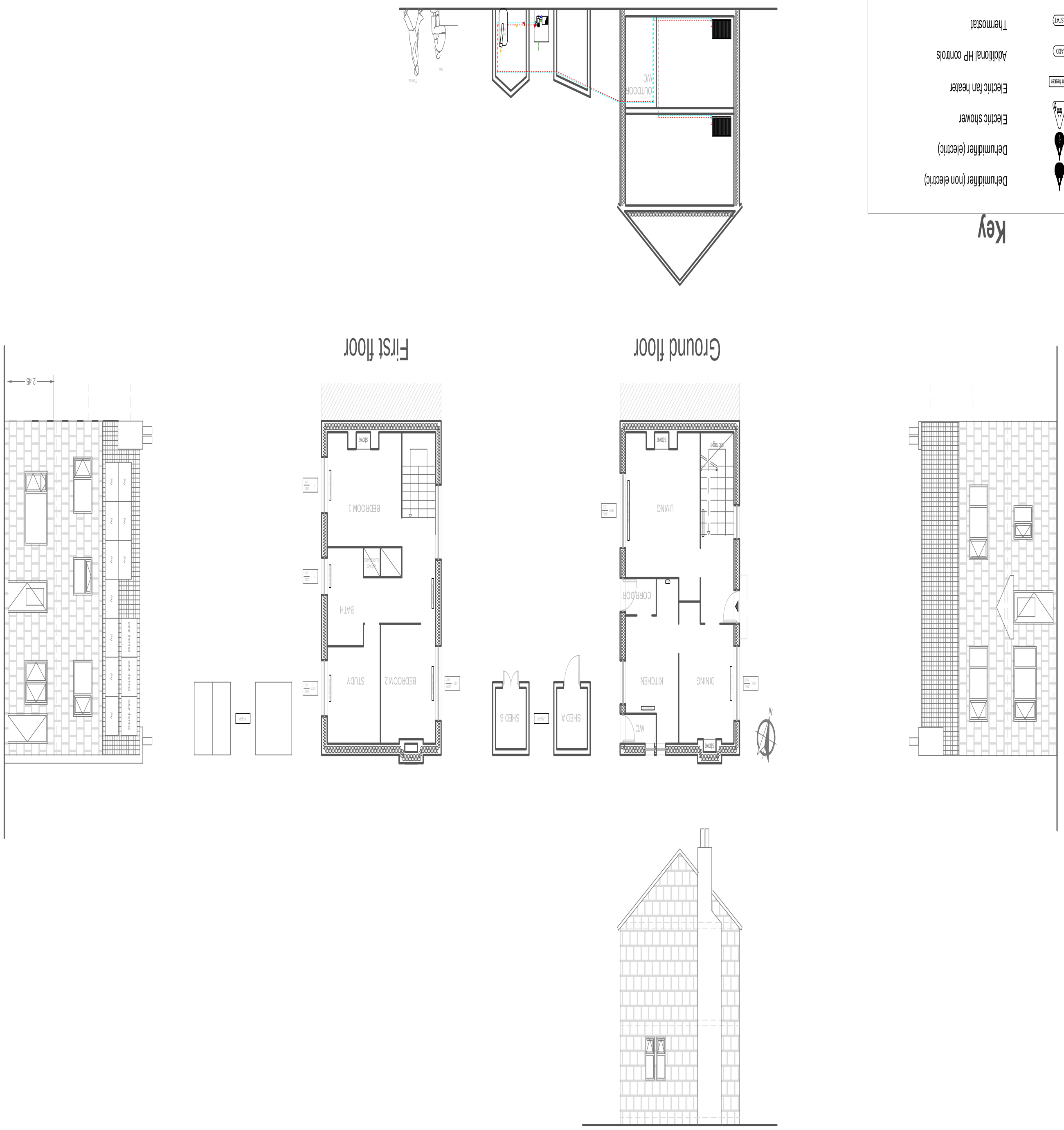


CS19 Drawing not to scale

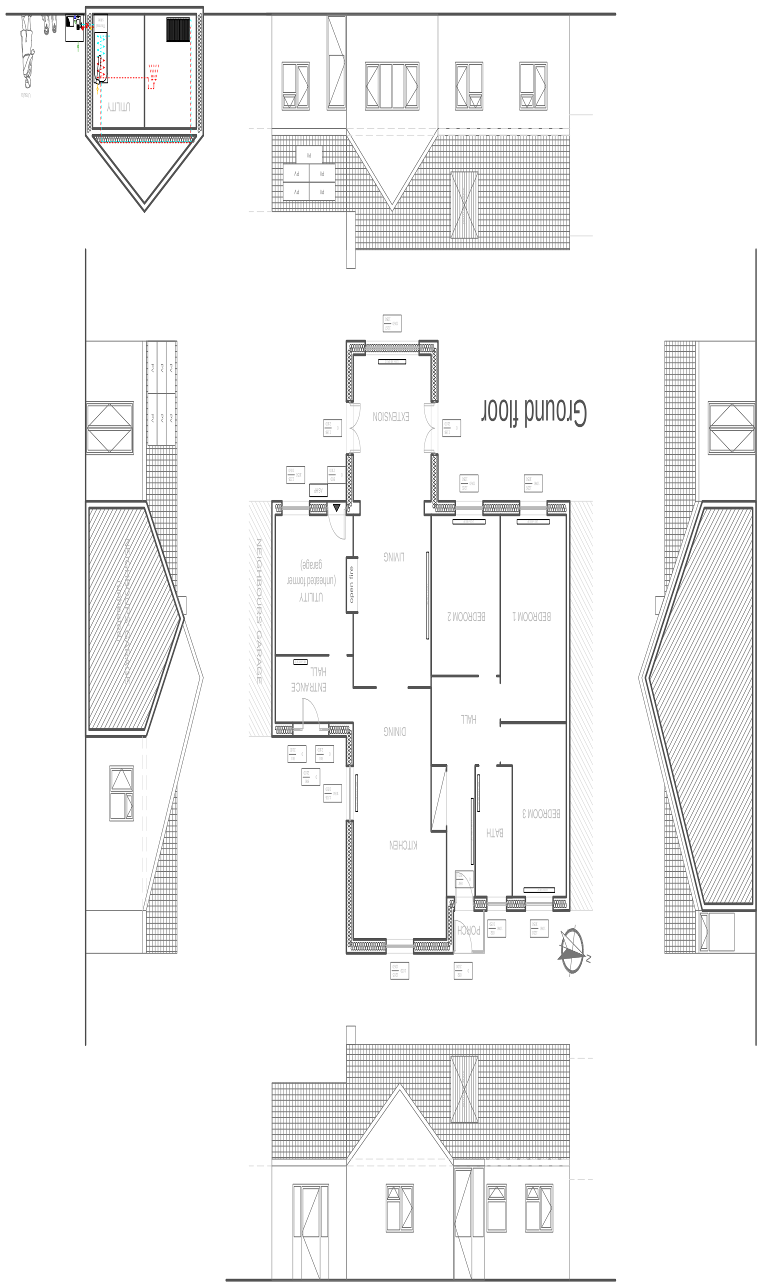


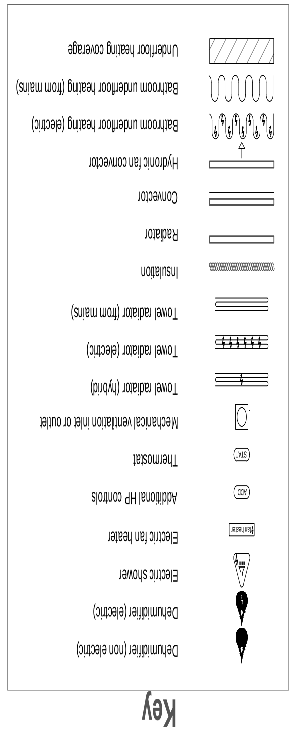
CS20 Drawing not to scale





CS21 Drawing not to scale





E2 Tailored schematics

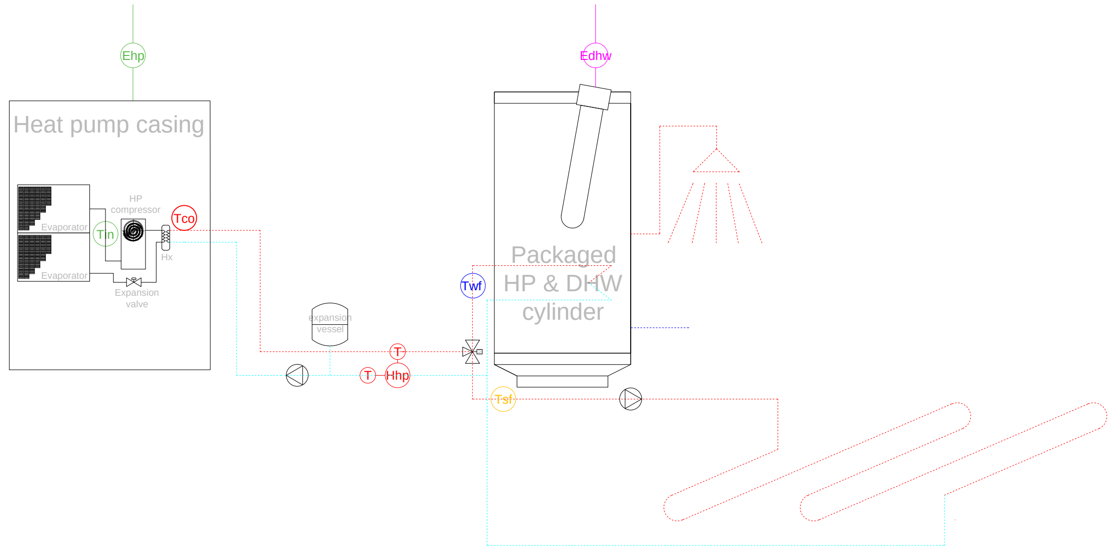


Figure 6: Monitoring schematic of CS01.

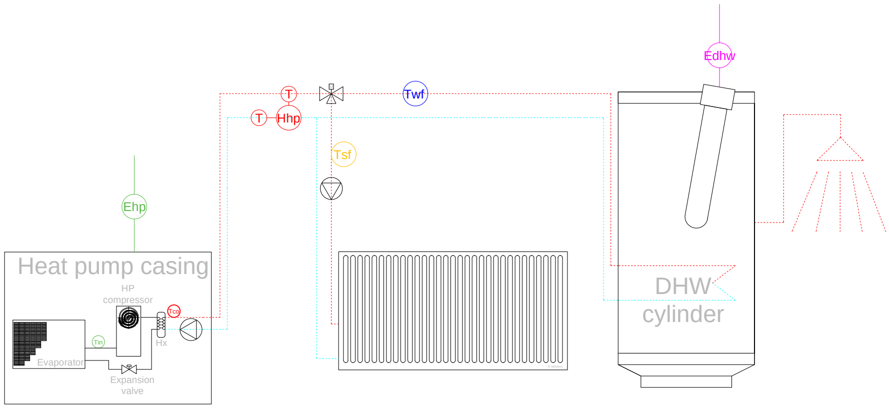


Figure 7: Monitoring schematic of CS02.

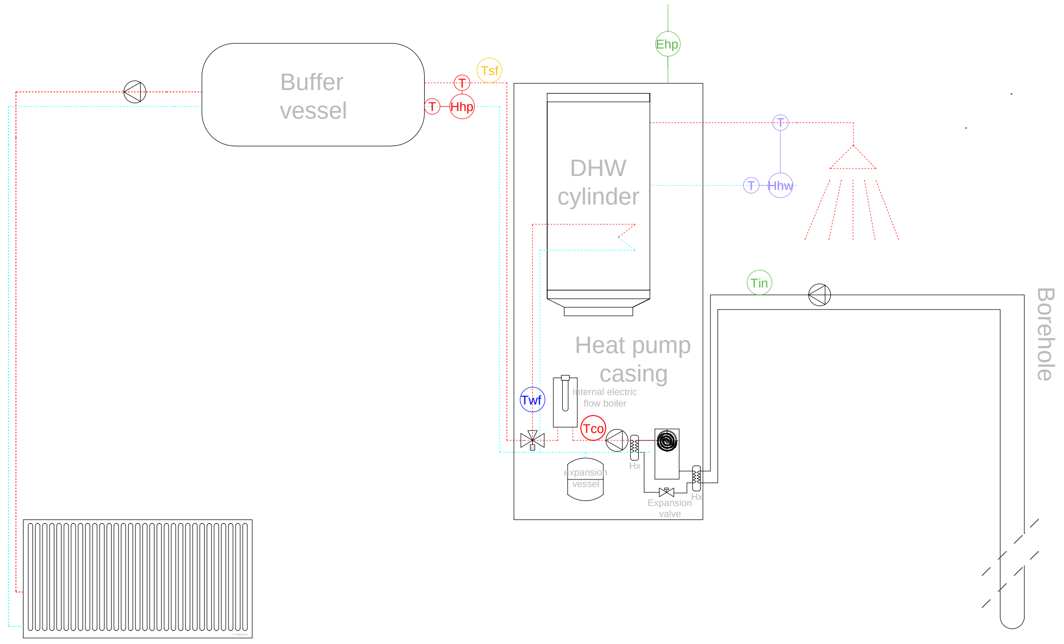


Figure 8: Monitoring schematic of CS03, CS04 and CS05.

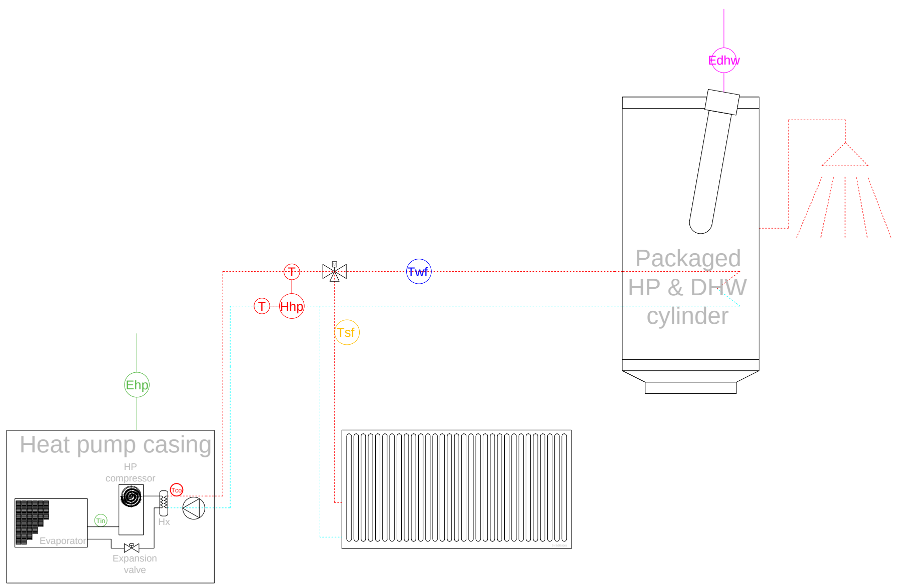


Figure 9: Monitoring schematic of CS06, CS07 and CS08.

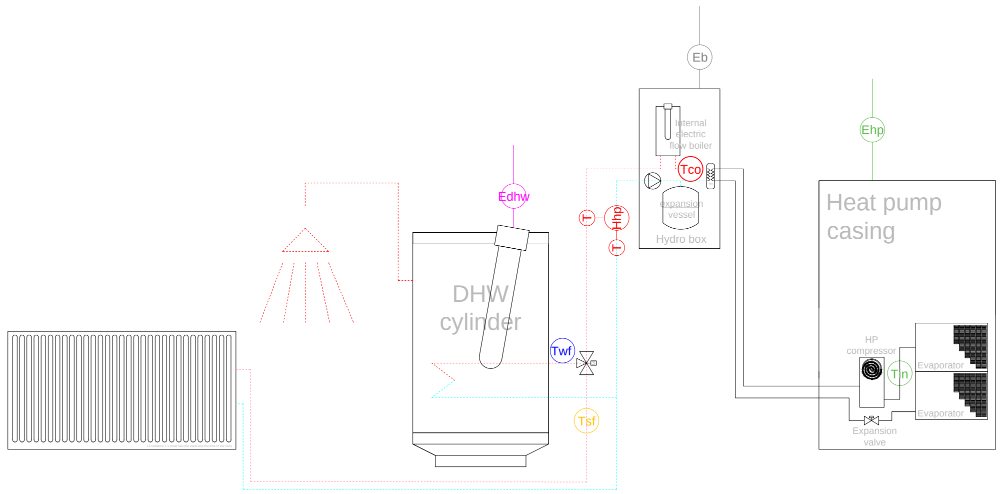


Figure 10: Monitoring schematic of CS09.

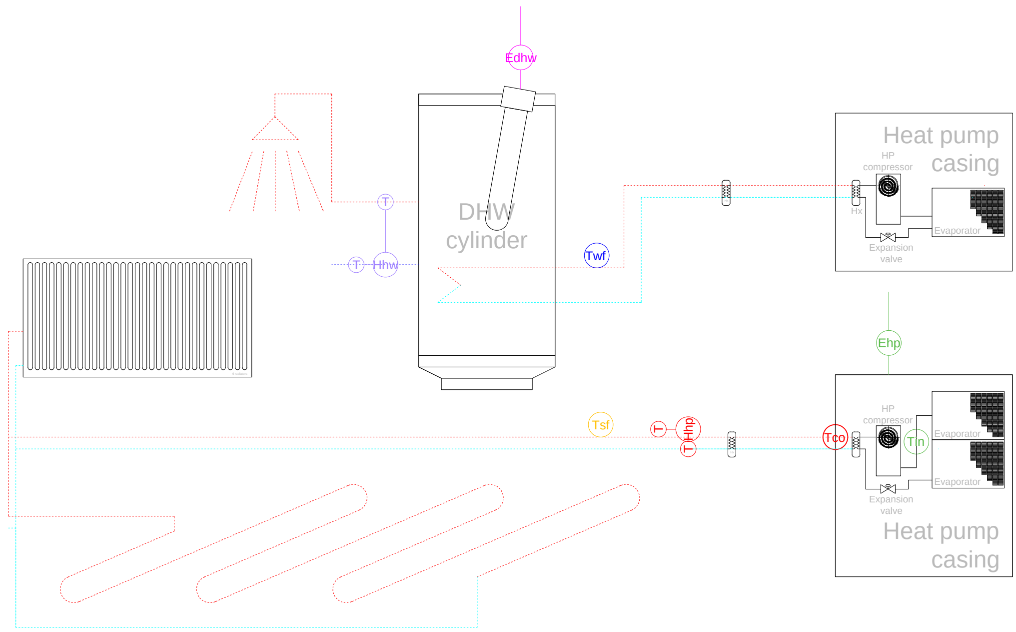


Figure 11: Monitoring schematic of CS10.

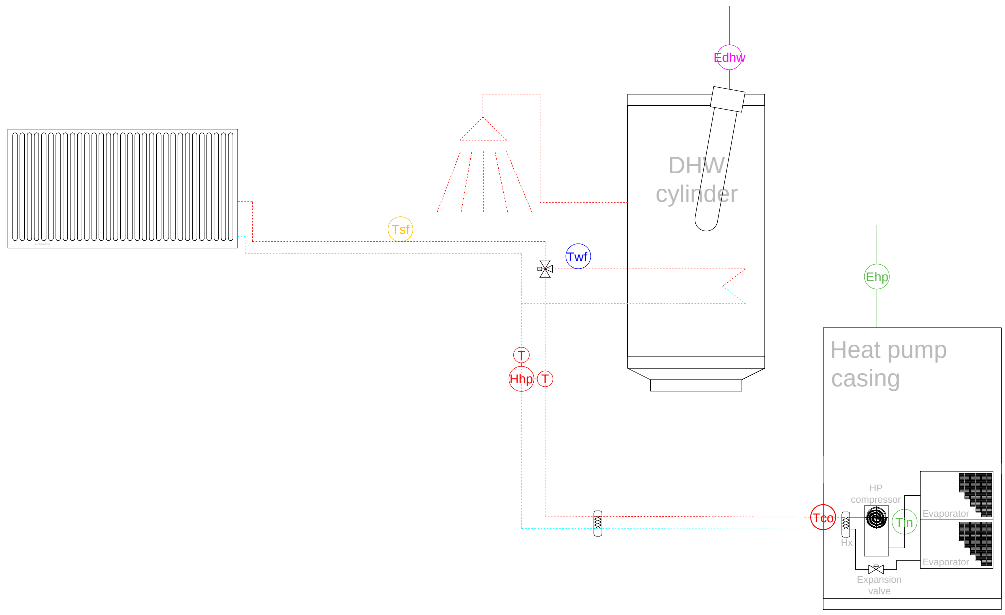


Figure 12: Monitoring schematic of CS11.

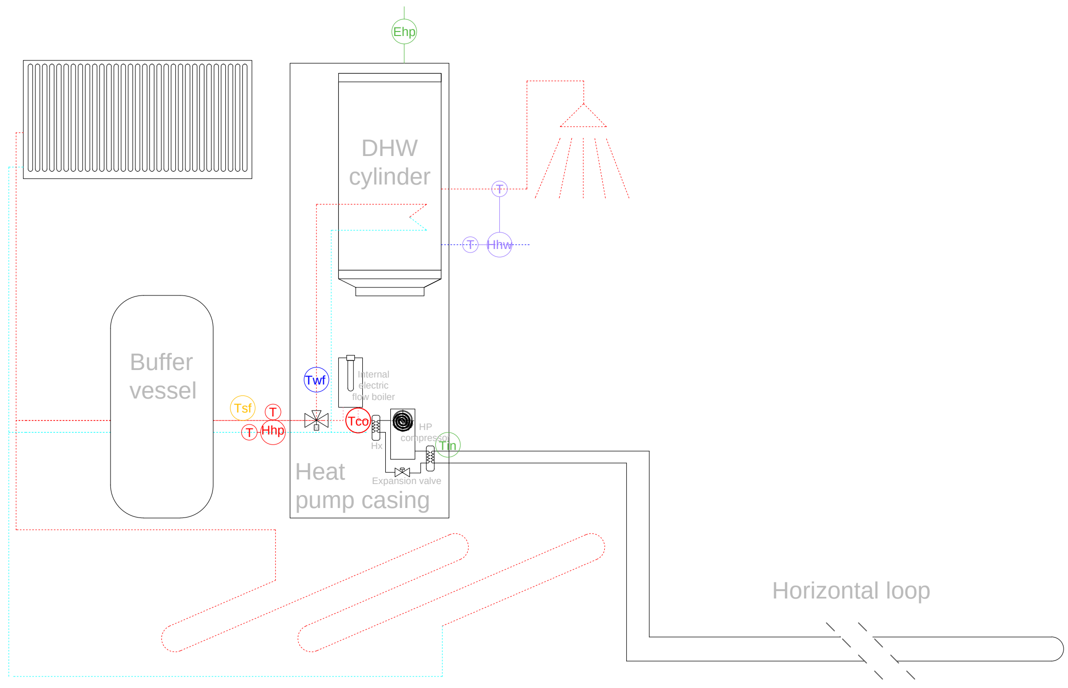


Figure 13: Monitoring schematic of CS12.

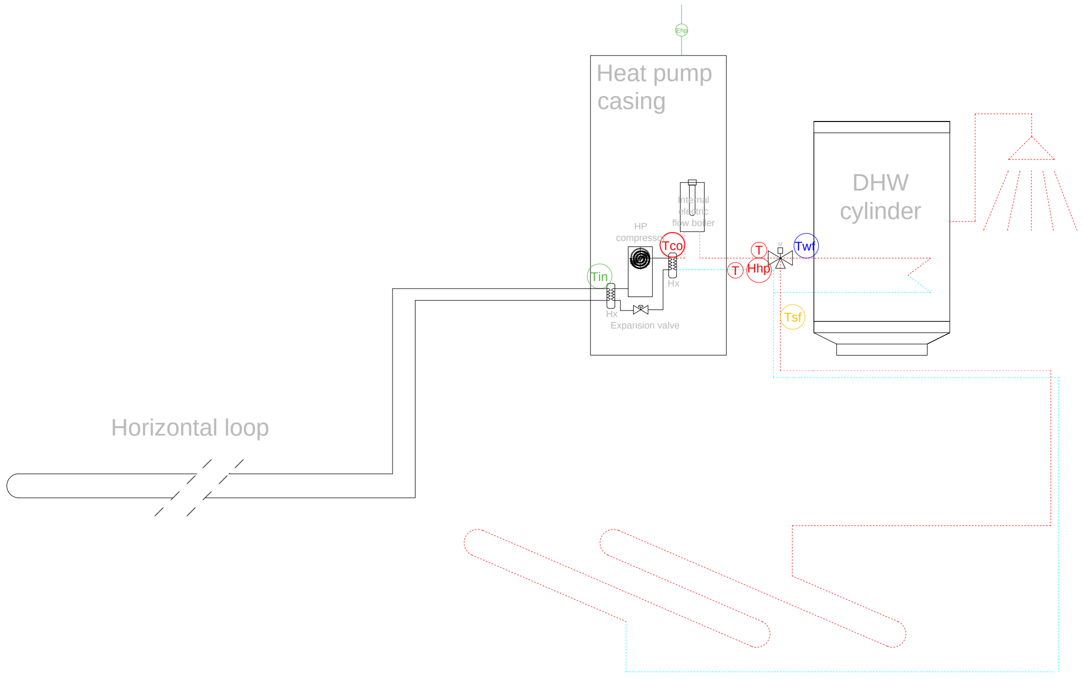


Figure 14: Monitoring schematic of CS13.

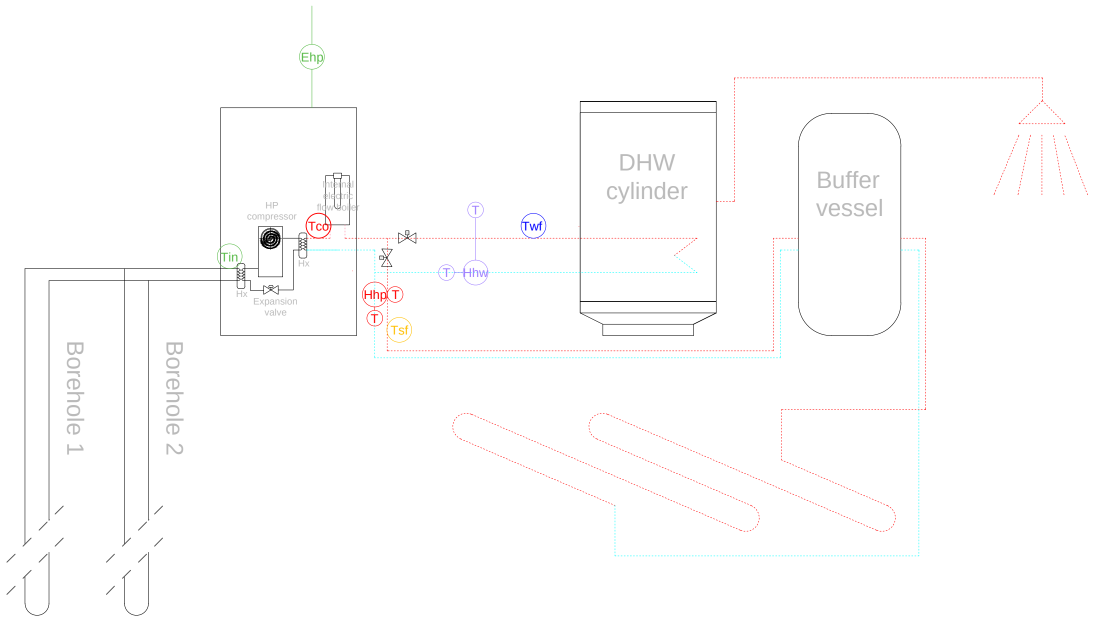


Figure 15: Monitoring schematic of CS14.

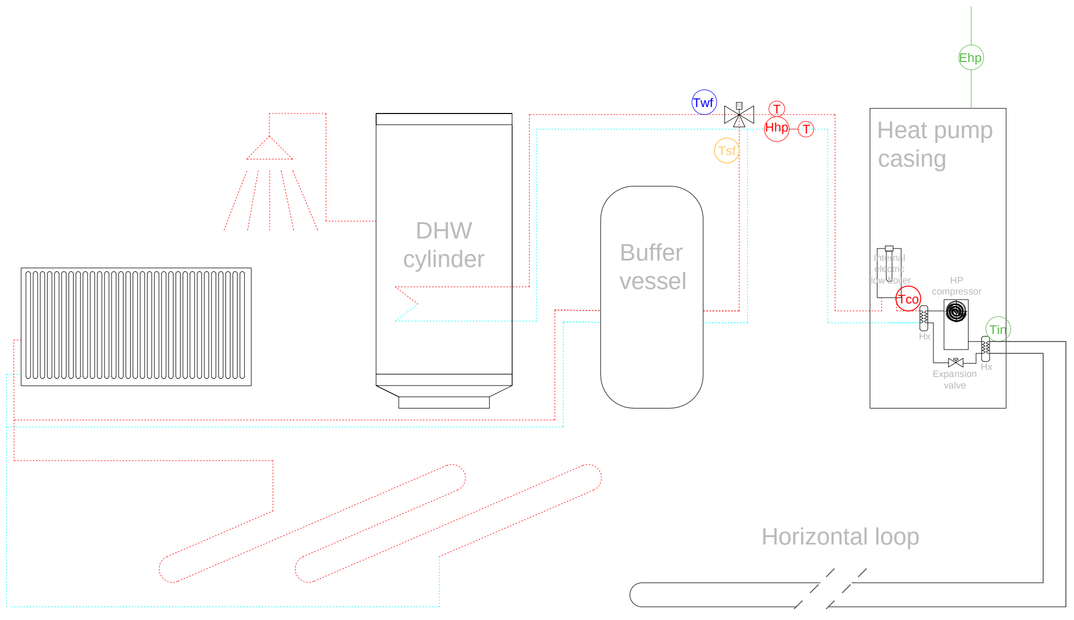


Figure 16: Monitoring schematic of CS15.

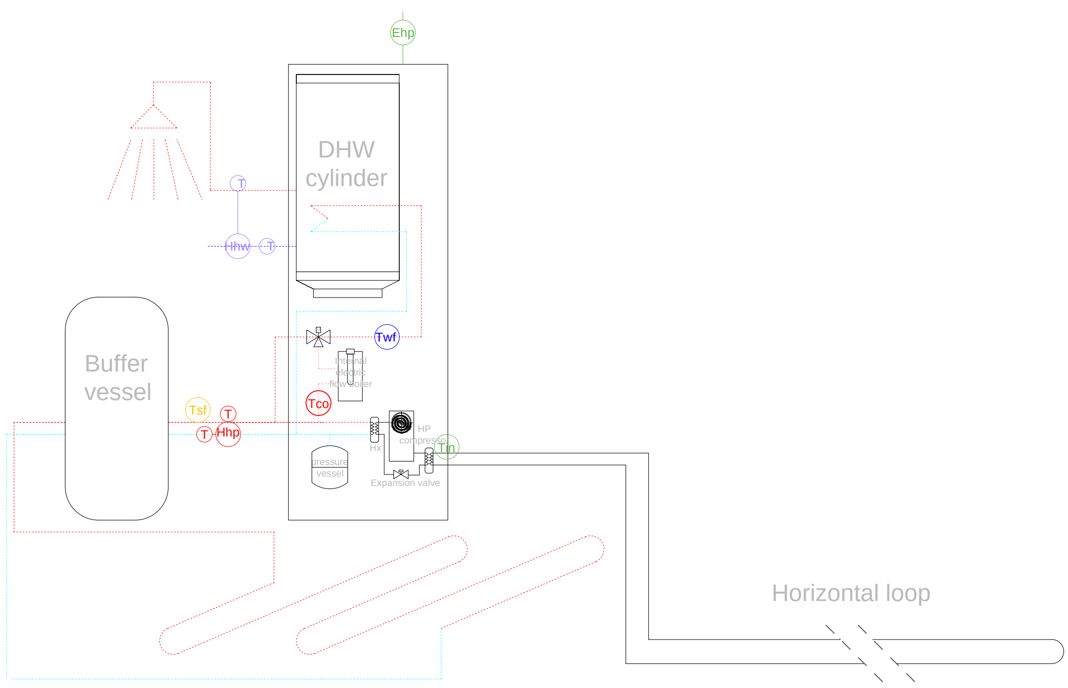


Figure 17: Monitoring schematic of CS16.

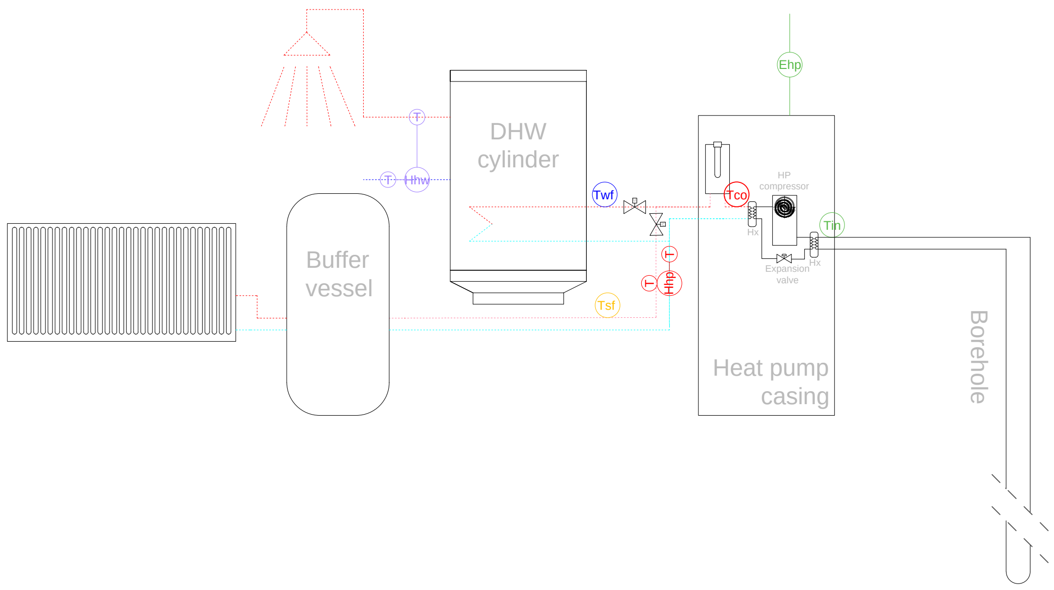


Figure 18: Monitoring schematic of CS17.

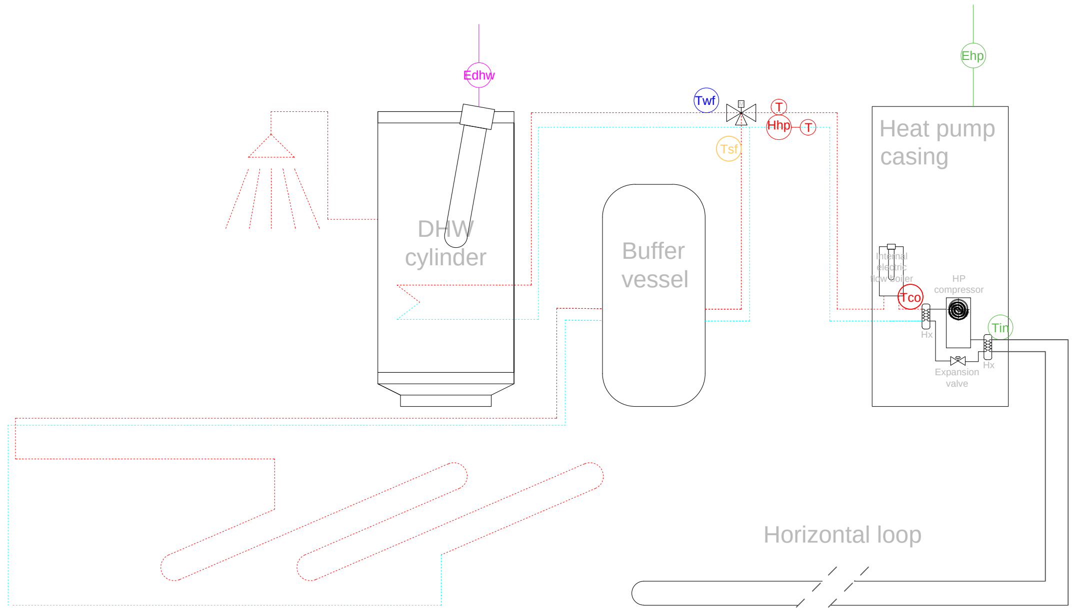


Figure 19: Monitoring schematic of CS18.

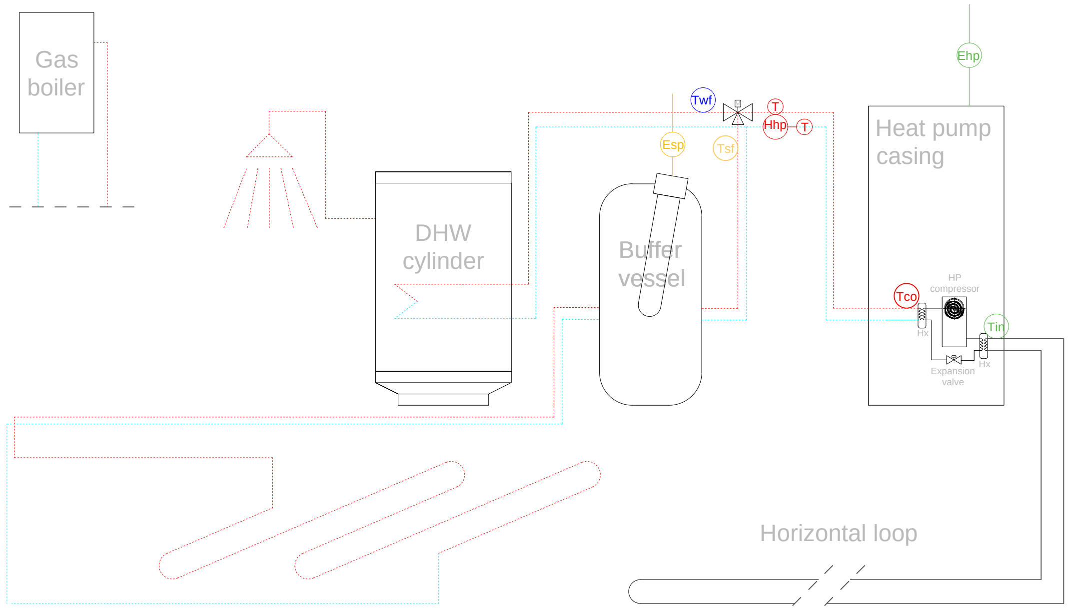


Figure 20: Monitoring schematic of CS19.

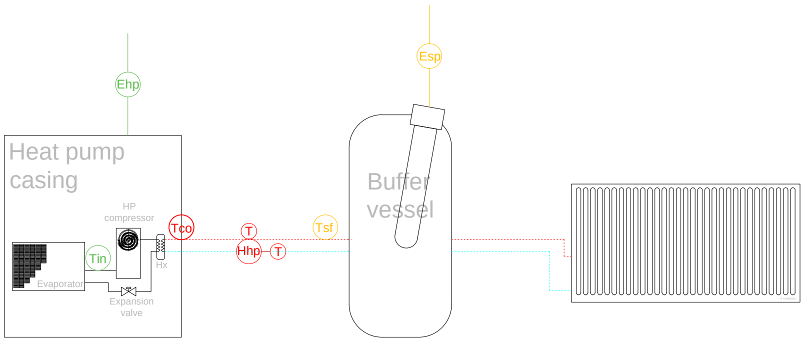


Figure 21: Monitoring schematic of CS20.

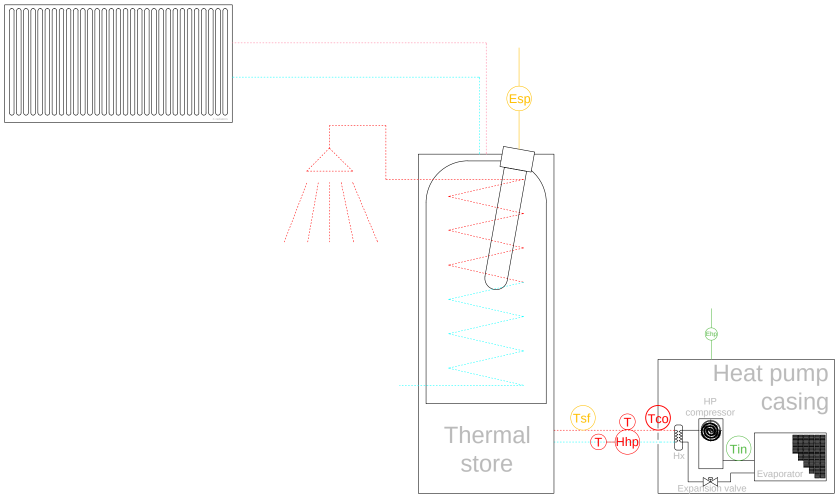


Figure 22: Monitoring schematic of CS21.

Appendix F: The large RHPP dataset

F1 Data cleaning and analysis process

F1 Data cleaning and analysis process

The monitored data were provided in MATLAB matrices with ‘data event’ indicators, where applicable. These refer to a not necessarily exhaustive list of monitoring issues, the identification process of which is described in the RHPP preliminary data analysis report (Wickins, 2014) and which had already been removed from the dataset before its handover to RAPID-HPC. Further data quality checks, led to the identification and elimination of data linked to sensors with a large number of outliers, i.e., over 1000 data points, in 57 sites. The data was eliminated predominantly with the application of the thresholds depicted in Table 23. The outlier thresholds were consistent with those applied in the preliminary RHPP analysis (Wickins, 2014). Stone (2015) also described another outlier type occurring in a small number of sites, where the energy meter appeared to accumulate energy consumption instead of timely reporting it. This led to a series of null time stamps, followed by a seemingly high energy consumption reported that should have probably been distributed over the previous missed periods. Such data anomalies were also omitted from the analysis.

The preliminary analysis was based on the *preliminary and unpublished* subset. As the analysis progressed, different filtering methods were employed that gradually led to the production of more robust subsets, such as sample B2 and B2-cropped, described below:

- **Preliminary and unpublished**: Based on the selection criteria listed in Table 3-4 of the thesis main part, a fixed 12-month period was selected as it enabled the maximum number of sites to be incorporated in the analysis, i.e., with sufficiently complete annual data for the statistical SPF analysis. Any missing data points were accounted for through simple linear scaling, i.e., where x percentage of missing data is substituted by the sum of data present divided by x%.
- **Sample B2**: The requirement for *‘relatively complete and stable data’* over a continuous period of one year and for a sample extending as much as possible across different categories of HP installations (such as emitter type, tenure *etc.*) led the selection of the 418-site strong sample B2, based on the criteria described in Table 3-4 of the thesis main part. The SPF calculation for sample B2 utilised varied 12-month periods between sites and the specifics are also described in Table 3-4. This is advantageous from a statistical point of view as it contributes to balancing out the different weather conditions encountered across sites. No further filtering algorithms were applied to avoid the unintentional removal of valid sites and/or data streams, such as parasitic operation or periods where the HP was deliberately turned off by occupants).

- **Sample B2-cropped**: A significant amount of scatter was detected when looking for relationships between sub-categories of the HP installation, with performance variation between sites being significantly larger than between ASHP and GSHP included in sample B2. Further data quality checks revealed data issues across the range of SPFs and predominantly at the lower and higher ends of the distribution. For this reason, a further restriction was applied by cropping all sites with an SPF_{H4} lower than 1.5 and higher than 4.5, of which 90% were at the lower end of the performance spectrum. The intention was to minimise the effect of sites with considerable metering issues and to increase the detection accuracy of the factors influencing performance variation.

Table 23: Thresholds applied for the removal of outliers in the *preliminary and unpublished* dataset.

Monitored parameter	**Units**	**Threshold**	
		Min	**Max**
Eb	Wh	0	35
Edhw	Wh	0	35
Ehp	Wh	0	35
Esp	Wh	0	35
Fhp	Litres/2 min	0	80
Fhw	Litres/2 min	0	80
Hhp	Wh	0	35
Hhw	Wh	0	35
Tco	°C	-15	80
Tin	°C	0	80
Tsf	°C	0	80
Twf	°C	0	80

Appendix G: Transcript sample

G1 Transcript of semi-structured interview with participants

G1 Transcript sample of semi-structure interview with participants

Study Name: Renewable Heat Premium Payment Scheme (RHPP): Heat Pump Monitoring: Case studies
Depositor: Department for Business, Energy & Industrial Strategy (BEIS)
Interview ID: CS03
Date of interview: 25/11/2015

Key and notations used for transcript:

I1	Interviewer 1
I2	Interviewer 2
MVHR	Mechanical Ventilation with Heat Recovery
TRV	Thermostatic Radiator Valve
[ ]	Personal interpretation of the conversation, not a verbatim report
[…]	Transcript that has been deliberately omitted, such as irrelevant background chat
( )	Denotes non-spoken content, *e.g.,* noises in the background or comments on the mood/tone of the respondent
(**inaudible**)	Unclear words or phrases

Information about interviewee(s):
Clive is a retired male, living alone in a small end-terraced bungalow he is renting from a Registered Social Landlord.

[Recording starts]

I1: How many people live here normally?
Clive: Just me.
I1: And you're a tenant of [a Registered Social Landlord]?
Clive: Yes.
I1: Are you retired?
Clive: Yes.
I1: What kind of job did you used to do?
Clive: I was a pipe fitter.
I1: So, you might have an idea of the system around the heat pump?
Clive: Sort of, yeah...
I1: How long have you been living here?
Clive: It will be two years from December 9th.
I1: Have there been any changes in the number of people living here since you moved in?
Clive: No.
I1: So, the heat pump [manufacturer 675] was here, already installed, when you moved in, right? (Clive nods positively) …okay. Do you know when it was installed?
Clive: No idea. I've never seen one before.
[…]
I1: How many rooms are there in the house?
Clive: Three.
I1: Living, kitchen and there's a small room as well, next to the bedroom.
Clive: Yes, storage in there.
I1: So, three, plus storage.
Clive: That room in there, it's all full of rubbish.
I1: So, you don't really use that room?
Clive: No.
I1: Do you ever feel it's draughty around the house?
Clive: No.
I1: Any other problems, like damp, mould, any internal air quality issues?
Clive: No. The windows are sealed, I can't get them open.
I2: You can't open the windows?
Clive: No, they're all sealed.
I2: Is it because they're too high, or because they're locked, or are they too stiff?
Clive: They're sealed, apparently.
I2: Do you want me to see if I can open one?
Clive: You can do it, help yourself.
I2: Did you mean the big bit, or the top, little bit?
Clive: Just the little, top bit.
I2: I'll just try the kitchen one, should I?
Clive: Yes, fine.
I1: You can open this one?
Clive: I can open that one [pointing at living room double doors].
I1: Only the doors, right.
Clive: The cats come in, I've got five of them.
I1: So, everything with regard to the heat pump was already here when you moved in, radiators *etc.*, nobody ever changed anything while you were in?
Clive: No.
I1: So how do you find the radiators in this room, like hot, cold?
Clive: Very good, I think.
I1: Exactly as you would like them to be?
Clive: Yes, it's nice and warm. I feel the cold terrible now, since becoming ill.
I1: Do you ever feel it's too warm?

Clive: Yes, occasionally.
I1: So, what do you do in that case?
Clive: Turn it off.
I1: Where do you control it from?
Clive: Just on the side of the doorway there, a little thermostat. I turn it down to about number 15 and leave it.
I1: Until you feel it's cold and then you turn it on again. So, you turn it down to 15 when you feel it's cold. What's the normal temperature you set it at?
Clive: 23.
I1: And this controls all the radiators in the whole house?
Clive: Yes.
I1: And you have two radiators, are they both functional?
Clive: Yes.
I1: How often do you use this room?
Clive: I live in here really, so all the time.
I1: You only sleep in the bedroom and spend the rest if the day here, okay. So, I've got this scale here from hot, warm, slightly warm, comfortable, slightly cool, cool and cold (shows scale). How would you rate this room?
Clive: Warm.
I1: In the summer, what's the temperature like?
Clive: Very good, you don't need the heating on in summer. These places are very well insulated.
I1: Do you ever feel too warm in the summer?
Clive: No, not really.
I1: You don’t use a fan, or anything like that?
Clive: No. We've got an extractor up there.
I1: So, do you have them on all the time?
Clive: All the time, from when I get up in the morning until I go to bed at night.
I1: You switch it off in the night?
Clive: Yeah.
I1: And you use it all through the year, summer and winter and that's a pattern, you turn it on by the day, off in the night, okay.
Clive: I smoke and a lot of people get offended by smokers.
I1: They must do a fairly good job because it's not really smelling. I can sense something like tobacco, but very lightly, it's not unpleasant. So how often do you open this door?
Clive: During the summer, perhaps every day in the summer, not at all in the winter.
I1: Only if you want to go out, for some reason.
Clive: Yeah.
I1: In the summer, every day, like when you wake up and sit here, do you have it open normally, or whenever you feel warm?
Clive: As I said, if I leave it open, all the cats come in. They come in if you let them, you know.
I1: But the door, you leave it open in the summer, like pretty much the whole day?
Clive: I go outside and sit outside and (inaudible) the cats away (laughs).
I1: Do you ever use any other heating equipment?
Clive: No.
I1: No, just the heat pump, okay. Do you mind if I take some pictures of this room?
Clive: No. There's an electric heater in the hallway there, but it's never used.
I1: Okay, it was fitted there before you moved in.
Clive: No, it's my neighbours, actually. I borrowed it when I came out of hospital, just to keep the chill off.
I1: Why didn’t you use the heat pump?
Clive: I did, I turned it on, but it took so long to come up.
I1: So, you used the electric heater for a while, but now, you don’t really use it.
Clive: Not at all. I don’t use it at all now.
I1: When was that, when you were using the electric heater?

Clive: February 2015, I'd been in hospital for eight weeks and when I came out, the place was chilly.
I1: And the radiators, do they have any valve you can switch on and off on them?
Clive: Yes, there's that (points at TRV).
I1: Do you ever touch it?
Clive: No …the valve's on the side.
I1: And there is an extractor fan here...
Clive: That's a fire alarm, a smoke alarm.
I1: Ah yes, that's true …But that (points at MVHR system) does bring fresh air in?
Clive: That's the extractor … that takes it out and out through into the open air.
I1: Do you want to come with me to the next room, or I can have a look, take some pictures and ask you about the room, any questions. Whatever you prefer. If you prefer to sit here it's fine.
Clive: I'll sit here.
I1: That's fine. Is it okay if I take some pictures, in the bedroom?
Clive: Of course, yeah.
[Interviewer 1 leaves the room for a while and come back after a few minutes.]
I1: So, the windows were sealed when you moved in, but have you asked them to …?
Clive: Somebody came round and measured up, they were going to put some new glazing in, but that's the last I heard.
I1: I see… So, it's the same set of questions, like the radiators next door in the bedroom, do you find them equally comfortable, as this one is?
Clive: Yes.
I1: How often do you use the room?
Clive: Every night.
I1: Do you sleep at noon as well, sometimes?
Clive: Yes, occasionally. The medication does that…
I1: Again, on this scale (shows scale), how do you find the room next door?
Clive: Warm
I1: Oh when you told me about this electric heater…
Clive: It's in the hallway. I've only used it once.
I1: Alright… can I have a look at the kitchen as well?
Clive: Yes
[Interviewer 1 goes into the kitchen and Interviewer 2 walks into the living room]
I2: You're right, they're locked, all of them. I think the housing association should be able to get … there might be a little screw that they can undo, that means they're openable because that's ridiculous, not being able to open the windows, isn't it?
Clive: I smoke as well, you know?
I2: I agree, because otherwise, you have to open the front door. Can you open those ones?
Clive: Yes, I can open the.
I2: But a woman that we spoke to, she's got her bedroom, the top one, she's got that open, so it is possible for them to open because they all look like the same kind of windows.
I1: They told Clive that they need to change the windows, to bring new ones. Maybe they've lost the keys or something, I don't know.
I2: That might be it, yeah. Sometimes, you find the builders put the windows in, throw the keys in the skip.
I1: So, in the kitchen, the radiator is warm as well. How do you feel the temperature is in the kitchen?
Clive: It's comfortable.
I1: Not warm, comfortable, okay… Do you cook?
Clive: Yes, occasionally.
I1: Do you feel it's getting too warm when you cook maybe?
Clive: No, not really. I use the oven, mainly.
I1: And the window does not open in the kitchen as well…
Clive: No.

I1: Can we have a look at the small room?
Clive: Of course, you can. Be careful in there... the tools and (inaudible) that I used to use… There is one radiator in there, I think.
I2: Yeah, there is in the other house as well.
Clive: A lot of people have got them down for a spare bedroom.
I2: It's like a little box room, isn't it?
Clive: Yeah, occasional visitors.
[Interviewers leave the room]
I1: So, the radiator is working in that small room as well, but you don't really use it because it's like storage space, right?
Clive: Yes.
I1: Can I have a look at the bathroom as well?
Clive: Yes, of course you can.
[Interviewer 1 leaves the room for a while to have a look at the bathroom.]
I1: Clive, in the bathroom, you have a heater on the side, do you use that?
Clive: No, never used it. In the morning, I always put the heating on first for about an hour.
I1: You switch the heating on in the morning and then you switch it off before you go to bed?
Clive: Yes.
I1: There is no radiator in the bathroom, is there?
Clive: No, just the electric one up there.
I1: But you don't use it.
Clive: No.
I1: Do you have an electric shower?
Clive: Yes.
I1: And the window doesn't open, in the bathroom?
Clive: No.
I1: How do you feel the temperature is in the bathroom?
Clive: It's comfortable, it's never too warm in there, it's comfortable.
I1: Even without the heater…
Clive: Yes.
I1: You don't use any other sources of heat, apart from one occasion. Do you control the heat pump from the thermostat?
Clive: Yes.
I1: You said you set it to 15, when you think it's warm and then to 23, like it's the normal temperature, you set up when you wake up in the morning. What time usually, do you wake up?
Clive: Usually about 6 am, 5 o'clock this morning.
I1: What time do you normally go to sleep?
Clive: About 11 pm.
I1: Since you moved here, have you changed your patterns of heating at all, or this is like the standard thing you do?
Clive: This is standard.
I1: How do easy do you find it to control your heat pump?
Clive: Very easy.
I1: Do you know what kind of electricity tariff you have, like standard, economy 7 was cheaper at night, or …?
Clive: I really don't know.
I1: Probably, it's going to be standard, I think.
Clive: It's expensive.
I1: How is your bill? Do you pay monthly?
Clive: I pay quarterly.
I1: Can you remember how much it is, per quarter?
Clive: The last one, I think, was about £146.
I1: When you moved in, did anybody show you how to use your heat pump, or tell you what was the optimum way to use it?

Clive: Just the optimum way, just use it from the thermostat and leave it on all the time.
I1: But you switch it off in the night, but they suggested you leave it on continuously?
Clive: Yeah, continuously. It's too hot though, when you get out of bed, it's too hot.
I1: So, somebody came here from [the Registered Social Landlord] and they told you what to do?
Clive: Yes, from [the Registered Social Landlord] and the chap from the manufacturers.
I1: So, they just told you to keep it on continuously, at a certain temperature?
Clive: Yes.
I1: Did they suggest a temperature as well?
Clive: Yes, 23.
I1: Any written instructions, any leaflet or anything?
Clive: No.
I1: And how satisfied are you with the level of instructions you were given, from very satisfied, satisfied, neutral?
Clive: Satisfied.
I1: Would you have liked more instructions, or more information about how the heat pump works, or you are happy?
Clive: I'm happy, yeah.
I1: You're happy, you don't necessarily want to know more...
Clive: Except for the manufacturers, he explained it to me, the coil underground… the borehole…
I1: So, is it in your back yard?
Clive: No, it's over there somewhere, not in my back yard.
I1: Have you got one for all three?
Clive: I should imagine so.
I1: How satisfied are you with your heat pump, from very satisfied, to very dissatisfied?
Clive: Very satisfied. It's nice and warm.
I1: And in terms of cost? Do you feel it's worth the money you spend for the heating?
Clive: Yes.
I1: Have you ever had any problems with your heat pump?
Clive: No. Sometimes it makes a noise.
I1: Is this annoying for you?
Clive: It does when you first … you get used to that after a while.
I1: Yes, it's quite noisy (a continuous buzzing sound can be heard on tape) but it may be [worse] because the [cupboard] doors are open.
Clive: It bangs when it stops as well, yeah.
I1: And when it starts?
Clive: It comes with a non-return value that stops it.
I1: Do you know who you would get in touch with if you ever had a problem with your heat pump?
Clive: I'd get in touch with the housing association.
I1: And they would direct you, they would call…
Clive: They would call the people in… I forgot what they're called now.
I1: So, since you moved in, there have been no changes in the heat pump, in the radiators, pipes, or structure of the house, nothing…
Clive: No.
I1: They didn’t change the windows, of course. So, if you were to advise other people that were thinking to install a heat pump, what would you tell them?
Clive: I would advise it, yeah. It's clean and it's efficient, so… but the electricity bills are a bit dear.
I1: What kind of heating did you have in your previous house?
Clive: A gas boiler.
I1: Compared with your gas boiler that you had previously, could you tell me what you liked, or disliked about the gas boiler?
Clive: It worked, it was okay. I much prefer this type.

I1: And in terms of how easy, or how hard it is to control them, do you find there's a difference between the two systems?
Clive: This is much easier.
I1: Didn't you have a thermostat with the boiler?
Clive: Yes, it was thermal controlled, but it was forever going wrong. You had to turn two little valves inside to get the water pumped in, I couldn't do it properly and kept calling people out.
I1: Maybe the thermostat was problematic then, but would you leave it on for the whole day?
Clive: Yes, leave it on during the day and switch it off at night.
I1: So more or less, the same pattern.
Clive: Same pattern, yeah.
I1: Do you think it's cheaper to run the heat pump, or was it cheaper with the boiler?
Clive: I think the gas boiler was a bit cheaper. This is all electricity.
I1: Do you remember what your quarterly bill was, when you had the gas boiler?
Clive: The highest winter bill I had was £119, but this, but this is consistently over £140-£300 at first, when I came here, when I first moved in.
I1: In the winter?
Clive: Mm (nods positively).
[Clive shows his last electricity bill]
I1: Yes, £121 a quarter. Okay, the summer is like £121, but in the winter [quarter], it's £146.
Clive: Yes.
I1: So, you use the electric heater for showers, but then in the kitchen, the hot water comes from your heat pump?
Clive: Yes.
I2: So, you've got an electric shower as well?
Clive: Yes… I've got the washing machine out there, as well.
I1: Which appliances do you think you use the most electricity in your house?
Clive: I should imagine the washing machine, the television. I don't know.
I1: Is there any microwave?
Clive: No.
I1: The oven, as well? Do you use it?
Clive: It's a gas oven.
I1: How often do you use your washing machine?
Clive: Once a week. I hang it in the bedroom to dry.
I1: They must dry very quickly because it's so warm… and how often do you cook?
Clive: Every other day. I use ready meals and just warm them up.
I1: And you smoke, but you smoke inside because you cannot open any windows… My other question is what do you use hot water for? So you've got an electric shower…
Clive: Hot water is for washing up.
I1: How often do you wash up?
Clive: Every day.
I1: How long does it last?
Clive: It's extremely hot when it comes out. It takes me about 10 minutes.
I1: Do you keep the tap running, or do you use a bowl?
Clive: I use the sink.
I1: Do you fill it up with hot water?
Clive: Yes …and there's washing and shaving.
I1: How many times a week do you use the shower?
Clive: Most mornings, at least five times a week.
I1: Are you away for long periods of time, like in the summer?
Clive: No, no.
I1: Have you got any visitors coming over and staying here?
Clive: No.
I1: So, in general, how warm or cool do you like the house to be?
Clive: Nice and warm.

I1: And did you say it normally feels warm overall, like the whole house?
Clive: Yeah, it's good.
I1: When you feel you need to cool down, you just lower the thermostat?
Clive: Yes.
I1: Do you ever open the door, if you want to cool down?
MI: No.
I1: But you're warm enough, so you don't feel you want to use something extra to warm up, unless you are away for long periods.
Clive: Yes.
I1: That's it, basically. If you don't mind, I would like to take some pictures of the front [of the house].
[Interviewer 1 leaves the room and Interviewer 2 comes in after a while.]
I2: Can I ask you, how long have you lived here?
Clive: Two years.
I2: Oh, only two years, right. They might have done them all up and moved people in, did they?
Clive: I think they did. They're very well insulated.
I2: I'm dying of the heat.
Clive: Turn it off.
I2: No, no, no I'll adjust. Do you mind if I have a quick look up in the attic, just to see how much insulation is up there? I'll do that and then I'll come back and have a chat.
[Interviewer 2 goes up into the loft and they discuss about taking pictures]
I1: Are all your light bulbs energy efficient?
Clive: Yes.
I1: Good.
Clive: 110 watt lasts two years.
[…]
I2: Do you know where the borehole is for this?
Clive: No idea.
I2: It's probably in your garden.
Clive: There's a concrete square in the middle, it might be under there.
I2: That looks like quite an old slab and it would only be a two-year-old slab, they're hardly likely to have used somebody's old slab. Can I have a quick look out?
Clive: Of course, you can.
[…]
Clive: I think it's a bore system.
I2: It would be because you've only got a little bit of garden and that's somebody else's, isn't it, behind your fence, so you've almost certainly got a bore hole. I'll go and see if I can spot it.

[Interviewer 2 goes outside and the recording concludes]

Appendix H: Fuel cost and carbon intensity assumptions

H1 Underlying assumptions behind Table 4-1

H1 Underlying assumptions behind Table 4-1 of the main document

Table 24: Fuel costs and carbon intensities utilised in the determination of the SPF_{H4} required for heat pumps to outperform alternative fuels.

Fuel	Carbon intensity (gCo2eq/kWh)*	Fuel cost (p/kWh)***
Electricity (standard)	324**	13.86
Electricity (economy 7)	324**	7.21
Coal	366	3.94
Oil	268	3.58
LPG	215	6.66
Gas	184	4.18

* Source: DECC, 2015 ** Source: EST, 2016 ***Value refers to a long-run marginal value and not a 2015 grid average, which was significantly higher at the time of the study. DECC (2015) suggested the carbon intensity of the electricity grid will be declining continuously in the following decades and that marginal and average values will converge.

Appendix I: The case study monitoring profiles

I1 Approximate statistics

I2 Notes from the visual inspection of the monitored data

I3 Suspected faults in the case study sample

I1 Approximate statistics

Table 25: Indicative temperature sensor readings based on a visual inspection of the data.

ID	HP in operation	Tsf winter max (°C)	Tsf swing season max (°C)	Typical Tsf hysteresis (°C)	Twf max (°C)	Twf cycles per day	Twf cycle duration (min)	Tin max (°C)
CS01	Oct to May	45	35	10-12	52	2-3	30	40
CS02	Oct to May	40/45	Unknown	2.5/12	55!	0	N/A	40
CS03	Oct to May	40/45	40	5	67	0.3-0.5	?	30
CS04	annual	55	55	10-15	55	0-2	?	30
CS05	annual*	40/45	35/40	5	55	1-2	30	30
CS06	annual	35/40	35	2.5	40	2-3	30	45
CS07	annual	60/70	55	10	65	1	?	(80)
CS08	annual	35/40	30/35	5	52	2	30-60	50
CS09	annual*	45	45	5-10	50	2 -3	30	X
CS10	Sep to Jun	35/50	35/40	5-12	52	2	30-60	35
CS11	annual	35	33	3	50	2	25	50
CS12	annual	35	35	8	55	~10	30	35
CS13	annual	50	40	12-13	60	~5	25	38
CS14	annual	45	30	10	60	4	60	30
CS15	Sep to May	43	38	7-8	55	4-5	30-60	43
CS16	annual	40/45	Unknown	12-15	55/65	2-3/ 12-20+	90/15 or less	23
CS17	annual	45	32	10-12	58	~3	20	25
CS18	Sep to May	40/45**	35/40**	13**	58	1-2	70	23
CS19	annual	45	40	10	48	3	20	25
CS20	Sep to Jun	35/40**	35**	8**	N/A	N/A	N/A	35
CS21	annual	45	35	2.5-4	45	varies	Instant	42

* Rare SH occasions during summer ** Values based on Tco as Tsf implausibly low
/ Different periods present distinctively different temperature settings ( ) Value limited by sensor upper limit

Table 26: Indicative flow rate and heat meter readings based on a visual inspection of the data.

ID	Fhp max (lt/min)	Fhw max (lt/min)	Hhp winter max (kW) in SH mode	Hhw winter max (kW)	Ehp max (kW) in SH	Eboost max (kW)	Edhw max (kW)
CS01	29	X	12	X	4.5	N/A	3 (4.5)
CS02	14	X	3.9	X	1.5	N/A	2.7
CS03	24	3.5	6.7	12.6	2.1	X	N/A
CS04	18	8	8.1	16.2	2.4	X	N/A
CS05	24	X	7.8	X	2.1	X	N/A
CS06	12	X	4.8	X	1.8	[5]	X
CS07	16	X	5.7	X	2.3	[5]	X
CS08	16	X	4.5	X	1.5	[3.3]	X
CS09	30	X	13.5	X	4.5	5.5	3
CS10	20	X	9	X	3.6	N/A	3
CS11	30	X	7.5	X	3	N/A	X
CS12	7.5	2.5	3	15	3	X	N/A
CS13	29	X	(18)	X	4.5	X	N/A
CS14	25	15	15	13.5	3.6	X	N/A
CS15	16.5	X	13.5	X	3.3	X	N/A
CS16	29	7.5	16.5	19.5	4.5	X	N/A
CS17	27.5	16	13.8	13.5	3.8	X	N/A
CS18	23	X	13.8	X	3.75	X	X
CS19	24	X	10.5	X	3	N/A	N/A
CS20	25	N/A	11.3	X	3	N/A	N/A
CS21	28.5	X	8.4	X	3	X	N/A

[ ] Edhw possibly misreported as Eboost.

I2 Notes from the visual inspection of the monitored data

The visual inspection of the monitored data was a useful tool in better understanding their quality and validity on an individual basis. This section utilises eyeballing of the monitoring profiles and the statistics presented in Table 25 and Table 26 to discuss emerging aspects of the monitored variables.

Temperature sensor anomalies and uncertainties

Tco sensors are always placed after the condenser and preceding Tsf and Twf, however, Tco readings were often found to be lower than those of Tsf and Twf, either throughout the whole monitoring period or during certain periods or recurring instances. This could have been due to a range of reasons, including faulty sensor configuration, data transmission issues, sensor interchange or use of Eboost (suspected in CS03, CS04 and CS05).

Space heating availability throughout the year

SH seems to be available throughout the year in approximately two-thirds of the case studies, with the remaining suspending it during the summer period. Table 25 provides detailed information on the suspension periods.

Flow temperature towards the SH distribution system

With the exception of CS07, maximum Tsf during winter time ranged from approximately 35 to 55 °C, with UFH-only systems presenting temperatures of between 40 and 50 °C and radiator and mixed emitter systems ranging between 35 and 55 °C. The radiator-only CS07 system appears to have reached excessively high Tsf, peaking at 60 or even 70 °C, which, given that the occupants complained about the radiators never feeling warm, is likely to reflect a data-quality issue.

Weather compensation

Tsf temperatures in most cases were found to be lower towards the end of the heating season by approximately 5-15 °C, indicating weather compensation was in place. Weather compensation could not be detected in CS04, CS09 and CS11 due to the negligible DT of maximum Tsf between winter time and the end of the heating season. The weather compensation application could not be ascertained in CS16 due to the limited heating available during the end of the heating season and in CS02 and CS12 due to the unreliable data.

Hysteresis

Hysteresis in the case study sample ranged between 1.5 and 2.5 °C, with CS06, CS11, CS21 on the lower end, CS01, CS03, CS13, CS16, CS17 and CS18 on the higher and CS02 presenting a stark contrast after a change in settings dramatically increased hysteresis from 2.5 to 12 °C in October 2014. As shown in Table 12 of Appendix C, of those cases that a calculation of the median monthly on-to-on cycle duration was possible, a link between short-cycling (10-minute gap between cycles) and hysteresis of approximately 3 °C may apply in CS11.

Flow temperature towards the DHW distribution system

Maximum Twf in the case study sample presented a smaller temperature range in comparison to maximum Tsf, *i.e.,* from 45 to 67 °C. In many cases, this is significantly lower than the 60 °C benchmark required to limit the risk of Legionella (Lévesque, Lavoie and Joly, 2004). However, this may not necessarily mean there was no pasteurisation in place since there could be a DHW immersion heater present or a metering issues involved.

Pasteurisation

Pasteurisation controls, with Twf temperatures reaching approximately 65 °C, were clearly in place once in three days in CS03 and once a week in CS12, CS15 and CS16, following a shift from daily peaks of 65 °C running until early March 2014 in the latter. This does not necessarily mean there was no consideration for Legionella in the remaining sites, as there could have been a sensor issue involved or a DHW immersion bringing the temperature to the required level. This is likely to be the case in CS01 and CS10, where Edhw shows the immersion came on once every 8-9 days at 3-4 kW and once a week at 3-4.2 kW, respectively. In other cases, such as CS18, pasteurisation related operation may be linked to the increased (20 kW) but regular (once a week) heat production (Hhp) at a lower than the usual COP, *i.e.,* around 2.3 rather than 3. The unmetered DHW immersion of CS18 might also have contributed to topping up the heat produced by the HP.

DHW cycles

Overall, a great variation was noted in the number of regular DHW cycles per day, ranging from a few scheduled cycles to heating DHW multiple times a day on demand. Except for the instantaneous DHW of CS21 (the only HP system with a thermal store) and CS16 presenting a striking change in its DHW heating patterns in early March 2014 from two to three 90-minute cycles a day to multiple (12 to 20 or sometimes more) nearly instantaneous and up to 15-minute heat-ups, the remaining sites would heat up water for anywhere from 20 to 70 minutes, usually a few times a day. Twf also appeared to reach pasteurisation temperatures on a daily basis in CS07 but this could be unreliable due to suspected data-quality issues.

Uncertainty around the use of backup resistance heating

Since Edhw was not metered in CS18, it is uncertain whether it played a significant role in the HP's energy consumption. Similarly, Eboost was present in CS03-CS05, CS12-CS18 and CS21 but clearly metered in CS09 only. The latter presented very few non-zero entries and it is uncertain whether this is due to very limited use or missing data. When it came on, it was in SH mode and there was no associated increase in flow temperature or heat output from the HP. This could indicate that the in-line heater was used for the defrost cycle but the lack of indoor temperature measurements makes this hard to confirm.

Declared net capacity in comparison to the maximum measured heat produced by the heat pump

The maximum heat produced by the HP and circulated towards the SH system followed the manufacturer's declared net capacity (listed in Table 9 of Appendix C) fairly closely in all but four cases. Declared net capacity was found to be significantly higher in CS11 and CS12 (by 6.5 kW and 4 kW respectively) and significantly lower in CS13 and CS16 (by 6 kW and 4.5 kW, respectively). A higher Hhp reading may indicate the use of Eboost, otherwise a heat meter issue may have been at play. The same applies to the sensor measuring the heat circulated towards the DHW system, for which data were available in just six cases. The maximum Hhw readings ranged from approximately 12.5 to 19.5 kW, with CS03, CS04, CS12 and CS14 presenting heat production of between approximately 1.5 and 3 times higher than the declared net capacity. The matching Ehp data were generally found to be inconsistent with the Hhw readings, except for CS14, where they clearly indicate the DHW was heated by the HP initially (at a COP of approximately 2.7) and then topped up by the resistance heater at a COP of approximately 1.

Uncertainty around the heat sensor placement

The location of the Hhp sensors in the tailored schematics of Appendix E is indicative, based on the information provided in the assigned schematics, where available, and the configuration of each HP system. However, there is some uncertainty around the placement of the Hhp sensor, *i.e.,* whether before or after the valve directing the water flow towards the SH and/or DHW systems. This is because even through DHW heat production is also expected to be indicated in the Hhp data, this was not always the case.

Water flow rate considerations

Water flow rate to the DHW system (Fhw) was measured in only 7 out of the 20 HP systems providing DHW, with maximum flow rates ranging from 2.5 to 16.5 litres per minute and data not being always consistent with other matching variables, *i.e.,* Hhw and/or Twf. Maximum water flow rate to the SH system (Fhp) presented higher flow rates of between 7.5 and 30 litres per minute.

External temperature seasonal fluctuations in relation to the temperature of the heat absorbing medium

Overall, Tin, *i.e.,* the temperature of the refrigerant leaving the evaporator (ASHP) or the temperature of the fluid returning from the ground loop (GSHP) followed the seasonal fluctuations of external temperatures (Tex) fairly closely, with the majority of monitored data lying above Tex, with maximum Tin ranging between 25 and 50 °C. Two sites diverged significantly from this pattern. In CS07, the range of Tin stands significantly higher than Tex, both in winter (45-80 °C[1]) and summer (45-80 °C[1]). In the SH-only HP of CS20, Tin extended significantly beyond both the upper and lower Tex limit in the winter and the lower limit in the summer. Only very limited or no Tin data were available in CS01 and CS09, respectively. Tin fluctuations were generally higher with ASHPs (≥30 °C) than GSHPs (5 to 20 °C). The GSHP Tin data available presented no indication of source depletion from year to year.

[1] Temperature sensor upper limit is set at 80 °C.

I3 Suspected faults in the case study sample

Table 27: Monitoring profiles with extensive periods of missing or implausible data.

	Description of data in question	Period in question	Plausible explanation	Time period coinciding with representative SPF calc. period
CS01	Missing Tin	12/13 – 03/15	Unknown	12 Months
CS02	Missing or too low Hhp, Ehp, Tco, Tsf and Twf; few consecutive days of HP DHW production at a COP of just over one	01/13 – 09/14	Unknown	7 Months
CS03	Ehp but not Hhp, missing Fhp	10/14 – 12/14	Unknown	½ Month
CS07	Hhp but no or invalid Ehp/ abnormally high Tin, Tco, Tsf	12/13 – 03/14	Unknown	2 Months/ 12 Months
CS08	Hhp but no Ehp	10/12 – 02/13	Unknown	4 Months
CS09	Missing or extremely low Hhp and Fhp	04/13 – 09/14	Hhp sensor flat battery	None
CS10	Inconsistency between Twf and the remaining monitored data	04/12 – 11/14	Except Twf, all monitored parameters relate to SH-only HP	12 Months
CS12*	Invalid Hhp and Hhw/ Twf significantly higher than Tco	09/13 – 11/14	Unknown/ Variation in temperature installation quality	12 Months
CS13	Regular Hhp incidents at 1 kW while Fhp active but no Ehp/ Hhp limited to 18 kW	06/13 – 03/15	Unknown/ Heat meter pulse frequency limitations	12 Months
CS15	Ehp but no Hhp	07/13 – 03/14	Hhp/Fhp integrator replacement reported by metering installation team	1 Month
CS16	Regular Ehp but no Hhp incidents	09/13 – 03/15	Unknown	12 Months
CS18	Regular Hhp incidents at 1-1.5 kW while Fhp active but no Ehp	05/13 – 03/14	Possibly linked to buffer tank	12 Months
CS20	Hhw present but no DHW supply	04/12 – 03/15	Unknown	12 months
CS21	Abnormally high Ehp readings	12/12 – 02/13	Unknown	3 Months

* Of all case studies, CS12 is the only case, where the problematic data extended throughout the whole monitoring period. The DHW heat meter showed output up to 15 kW without any associated electricity use. The temperature data indicated apparent DHW cycles at a corresponding 3 kW electricity input but no associated heat meter output. There was no associated output for the 7 kW DHW pasteurisation cycles running once a week either, leading to a faulty DHW heat meter assumption. In SH mode, the Hhp and Ehp readings did coincide (COP=1), with the output and electricity use being both only 3 kW, as if the system were in Eboost mode. The circulation pump data was also very low, with Fhp of up to a maximum of 7.5 L/min. The Tin ground loop temperature data show that the HP operated when SH was provided, suggesting that the system was not in resistance heat-only mode. However, the 3-kW heat output does not seem sufficient to heat a large, detached house, only constructed around Part L 2006 insulation standards and the occupant appeared to be content with the HP's heat provision. This leads to the overall conclusion is that neither the SH nor DHW heat monitoring data can be trusted, making it impossible to draw any conclusions from this dataset.

Appendix J: Additional information and insights from the socio-technical analysis

J1 Additional information on emerging topics

J2 Occupant quotes

J1 Additional information on emerging topics

Drivers of occupant satisfaction

In this study, the occupants' overall satisfaction with a heating system was found to depend on the relative influence of a wide range of parameters. These were distilled from the narratives of case study occupants as a whole, including responses to questions requesting a comparison between the experience of the HP and the occupants' previous experience with heating systems (see Table 18 of Appendix C). The HP's ability to fulfil the occupants' fundamental needs, i.e., the affordable provision of sufficient heat was identified as the primary driver. Table 28 lists the full range of the primary and secondary drivers of occupant satisfaction. These may apply to any heating system and are categorised in 6 main groups, all of which reflect the occupants' perception of the desired characteristics and qualities.

Table 28: Primary and secondary drivers of occupant satisfaction with heating systems.

Type	Driver name	Related desired features
Primary	Ability to fulfill fundamental needs	Sufficient and uninterrupted (*i.e.*, free of technical faults) SH and DHW availability at an affordable cost
Secondary	Economy	Cost-effectiveness; capital cost competitiveness; fuel cost competitiveness; fuel cost stability; no need for fuel cost negotiation; economic incentives.
Secondary	Ease of installation	Minimal disruption.
Secondary	Ease of control	Straightforward and intuitive instructions and controls; zone control and control aggregation.
Secondary	Conveniences	Quiet operation; discreet visual presence; aesthetic value; minimal maintenance requirements; continuous and whole-house warmth; physical heat; ability to dry clothes indoors; high system responsiveness; compatibility with pre-installed systems or energy saving technologies.
Secondary	Confidence and desirability boosters	Highly esteemed manufacturer reputation; highly esteemed technology reputation; cooperative (non-forcing) decision making; environmental friendliness; keeping up to the stated promises and expectations.

Influencers of the occupants' desired space-heating availability

The table below provides additional information on the causal loop diagram variables that are thought to influence the occupants' perception with regards to space heating.

Table 29: Variables influencing the occupants' perceived space heating performance shortfall.

CLD variable	Related information	Case studies affected
Air movement	Draught due to structural defects	CS07, CS10, CS14, CS18
	Draught due to open flues	CS10
	Draught from faulty MVHR unit	CS04, CS05
	Convection currents due to highly glazed walls	CS01
Metabolic rate	Retired households expected to have a low metabolic rate due to old age and limited mobility.	CS02-CS09, CS11, CS17, CS19, CS21
Health issues	Continues warmth important.	CS03, CS06, CS12
Time spent at home	Houses occupied throughout the day.	CS01-CS17, CS19-21
Preference for cooler night-time temperatures	Achieved via daytime only heating schedule	CS04, CS09, CS11
	Achieved via differentiating individual room/radiator thermostat settings.	CS01, CS13, CS21

Thermal comfort and gender

In at least four cases (CS01, CS09, CS13 and CS14), the female partner was generally felt colder than the male partner and would have liked more warmth. Andrew (CS01) explained that it was not sensible to make instant changes to the HP due to its slow responsiveness and Gabi (CS07) noted that raising the thermostat temperature above a certain threshold was not an option due to the fear of high electricity bills. For others (CS05, CS06, CS09 and CS11), choosing between additional clothing or a change of HP settings depended on the time of the day and their physical activity, or even the room into which they would move. For example, Francis (CS06) would add clothing layers upon entering the kitchen and bathroom, because of his dissatisfaction with the hydronic fan convectors present. Adding clothing layers was also a necessity for Gabi and Greg (CS07), who ended up with a very cold bedroom in their attempt to save energy by isolating the living room, *i.e.,* the only room with a thermostat in their house (Quote 15, Appendix J). Any action taken, whether a change in HP settings, clothing level or supplementary heating method also depends on the equipment available, as well as their impact, both timely and economic, as perceived by the occupants.

In terms of ventilation patterns, in CS15 and CS20, it was the female partners that would prevent the windows from staying open, due to their sensitivity to cold or draughts. On the contrary, in CS07, it was Gabi that was keener to open a window occasionally. Even though both partners were very energy conscious, Greg presented an even higher level of *energy consumption awareness*. Thus, there appeared to be a tendency of the latter to act (by closing windows) to limit the energy-consuming behaviour of the former. In addition, both occupants in CS11 appeared to have a high level of *energy consumption awareness* that led them to adopt their so-called *"closed-door policy"* (Quote 37, Appendix J2).

Reducing the usable heated area served by the heat pump

A reduction of the usable heated area to total usable area was noted in the following cases:

- Elva (CS05) switched off heating in the box room due to heat gains from the freezer/tumble drier present.
- Beatrice (CS08) switched off the kitchen/wet room hydronic fan convectors due to the draughty and unfamiliar technology. However, she felt that the cooking heat gains and allowing the air to move freely from the radiator-heated areas of the small bungalow would make up for this.
- Gabi and Greg (CS07) reported that the thermostat setting would ideally need to be set higher than the stated 21 °C comfort setting to accommodate their heating needs, however, they were not willing to do so in the fear of high electricity bills. As a result, they isolated the living room (the only room with a thermostat in the house) so as to have access to at least one sufficiently warm room. The remaining rooms of their small house felt cold, thus reinforcing their *perceived SH availability gap* that was balanced only through the addition of *clothing insulation* [B8] [Clothing rebound].

Unresolved concerns and actions taken in relation to a perceived building fabric performance gap

- **Implementation of provisional measures –** In cases CS07, CS13 and CS17, provisional measures were employed, *i.e.,* thick curtains hanging over the windows and/or front door. Even though Francis (CS06) expressed no complaints in terms of the thermal efficiency of his glazing, he utilised thick curtains as an additional insulating measure during the winter.

> *We shut those curtains at night and the temperature goes up by two degrees. You know, it's just shut the windows. I said them before about the windows,. "oh no no no triple glazing is no good (Greg, CS07).*

- **Planned measures –** Jennifer described their Georgian home's energy efficiency improvement as an ongoing process with 'lots of holes to plug'. Marvin (CS13) also had a plan for fixing the draughty front door by building a porch that was part of the original building design. In CS19, at least Samuel expected a part of the imperfectly insulated wall to be bridged by the installation of a conservatory, soon to be built on that side.

> *The original design had the porch on it, but we ran out of money and time and effort and interest […] That, I reckon, will make a huge difference […] it's not just that it [the door] didn't fit properly because [...] when they supplied the front door, they couldn't read the documentation that was*

send, I think it had to be 100 wide, they sent it at 101, so it has a fake frame round it and so it's not fitted properly, so the air flow inside the wall shouldn't be there because the frame doesn't fit […] …with the new, double glazed porch and a new door, the air flow will go out even further […] that will make a huge difference […] it's an air lock […] that's why [I put a curtain over the door] because it helps with the draught, also for privacy reasons (Marvin, CS13).

- **Unresolved concerns –** Gabi and Greg (CS07) were sceptical of the level of their dwelling's insulation, particularly due to the limitations posed by existing building elements. Indeed, there is a limit to the amount of insulation that can fit into 150 mm walls. Gabi and Greg also felt their home was draughty, with a particularly strong draught coming through the front door and into the living room. For Rafael (CS18), the draughts resulted from technical imperfections in the building fabric insulation, despite it being a newbuild and in CS10, Jennifer stated the draught was related to the presence of open fireplaces. In CS11 and CS19, there was also no plan for improving the perceived as imperfectly insulated building fabric, due to the technical difficulties associated with the application of insulation in existing cavity walls and/or roof spaces.

We've always had draughts and we couldn't understand why […] so I've just got to the bottom of it, so yes, there are draughts, but it was because it [the timber frame house] was not built properly […] if you look at the garage roof, that's the roof cavity there, it's pulling the heat from the house into the roof – some of the cavities aren't sealed […] if it's windy from one direction, one room will be colder where the prevailing wind is coming from and there are slight draughts (Rafael, CS18).

For this to have worked anywhere near decent, we need wooden front door and back door and triple glazing. The cold that comes into the front passage from the front door is unbelievable. So, what's the point? What's the point of the 'so-called' efficient heating when you've got the cold coming in around from every other direction? There is no point […] But these houses were never built for this type of heating (Gabi, CS07).

Roof insulation, when we had the survey done, they were happy with what we'd done but there is fibre glass insulation and it is flawed […] When the guy came to do the cavity wall insulation, he was checking the depth of the cavity in various places and it wasn't consistent (Kevin, CS11).

Radiator-sizing concerns in retrofit installations

Of all retrofit installations in the case study sample, CS19 was the only case where the heat-emitter system was originally designed with a future HP installation in mind. In the remaining cases, the system was either deemed adequate or was adapted to some extent, however, not always without problems or reservations. Ursula (CS21) in particular, explained that the designer had mentioned the likely need for a radiator upgrade in the open plan kitchen/diner area. In both CS21 and CS09, occupant descriptions reveal a rather superficial radiator assessment by the contractor.

He looked at this radiator and he said there is a possibility that I might have to have a bigger one, but said to leave it how it is to see how I get on with it and I have been beginning to think that

> *perhaps I ought to get a bigger one, but it's got so warm and I think… until it gets really cold and because it's a double one, that's why he was a bit wavering, whether to change it or not.. (Ursula, CS21)*

> *…when they came in to assess it - not as good as it should have been assessed - because they just go round and say "oh, you ought to have bigger radiators in there" and he looked round and he said, "I reckon you've got well enough radiators in here". So we left that, that's why we didn't upgrade any of the radiators [in the living and dining area]. (Ian, CS09)*

CS07 were the only occupants dissatisfied with the heat provided throughout the house but there were at least five other cases, whose occupants complained about the insufficient heating provided by radiators in specific rooms. By contrast, in only one case (CS09) did the occupants feel that the upgraded 520x2000 mm double panel-double convector was too big for their 13 m^2 TV room and thus they kept it at a lower temperature *via* a lowered TRV setting. Overall, the perceived insufficient heating provided may have been the result of the radiator's size, type and/or location, depending on the case.

- **HFC-related perceived emitter inadequacy** - In the kitchens and/or bathrooms of CS06, CS07 and CS08, a different (compared to traditional radiators) heat emitter was offered to the occupants, by means of hydronic fan convectors. These were mounted high up on the wall and were likely to be offered as a solution to the lack of space available in the particularly small kitchens and bathrooms of these social houses. None of the occupants seemed to be content with it since they were either not using it (SC08) or reported that it did not meet their heating expectations (CS06 and CS07). This could be either the result of the convective heat that comes from this type of emitter and/or its insufficient heat output.
- **Suspected radiator sizing inadequacy** – Both Elva (CS05) and Quianna (CS17) would also have liked more heat in their bathroom and living room, respectively, which they thought related to improper emitter sizing. Even though Elva's bathroom emitter had been replaced with a radiator of approximately double the size of the original and running at its full capacity (in terms of TRV settings), it was still not able to provide sufficient heat. Jennifer and James (CS10) were also not content with the heat in their attic and were planning to install an additional radiator.
- **Suspected improper emitter location –** In addition to the perceived as improperly sized living room radiator, Quianna believed that it did not meet their needs also due to its placement in the corner of the room.

> *I find the radiator in the bathroom is so small, it doesn't heat the bathroom. It's ok for me, I can run in and out quickly, but when my husband was here, we used to have to rely on an electric wall heater that we've got, just to make it warm enough for him […] The only room I have problems with is the bathroom, I don't know if the radiator's not big enough or what […] it does feel really quite chilly in there when you go in. (Elva, CS05)*

This [the living room] is the most disappointing room of them all […] it's partly because like today, it's quite cool, because the wind's blowing this way and there's a lot of glass […] We asked them, after we had gone through like the first winter, if they would move the radiator over there because it would make more sense to us to the room like that […] and a bigger radiator there and they said they would do it. That's been the one disappointment of the whole thing is that the company that did it are too busy doing other things and they can't be bothered to come back and do things for you (Quianna, CS17)

User awareness of the presence and operation of a HP's backup resistance heater

Of the 15 case study occupants (CS01-CS02, CS04, CS06-CS09, CS11-CS15, CS17-1CS9) with which a discussion about the HP-incorporated resistance heating was initiated, the majority stated they were aware of its presence in their system. Only Ian (CS09) and Patricia (CS15) were uncertain but eager to find out. Of the remaining cases and excluding any technical problems and unexpected circumstances triggering the backup heater operation, none of the occupants thought the resistance heater was operating often, if at all. In particular, Andrew (CS01) was the only occupant to state that the immersion heater was utilised whenever a DHW boost was needed. Francis (CS06) and Kate (CS11) were confident they knew how to operate the backup heater but stated they had never done so and Beatrice (CS02) was certain it had been switched off by the technicians. At least six occupants expected an automatic but limited operation of the backup heater. Unlike Andrew of CS01 who believed that the HP alone could reach pasteurisation temperatures, Greg (CS07), Kate (CS11), Marvin (CS13) and Samuel (CS19) thought that the resistance heater had to be utilised for the DHW to reach the required temperature for Legionella control. At least two occupants expected that the backup heater would kick in automatically due to high heat demand (CS14) and the heat source not being able to supply sufficient heat, *e.g.,* due to weather conditions (CS19). Excessive resistance heater use was noted in the following cases:

- In CS08 and CS12, the resistance heaters might have been turned on accidentally during the renovation and plumbing work that took place, however, their respective occupants Helen and Lynn were not as lucky in spotting the resistance heater operation early on, perhaps due to the lack of easily read signaling.

…she [Helen] did have a power cut a couple round about November time and then, in the February [the RSL] came in, they put a new kitchen, new bathrooms, so the electric was on and off, on and off for three weeks and unbeknown to us, the immersion heater had kicked in, it had been running and that's how she's ended up with that big bill. So out payments now have gone from £45 to nearly £75 a month […] My mam did say there's two lights on in there [cupboard] and we thought… it's not that we don't just believe you, but is she mistaken? We weren't sure until these big bills started coming through (Hilda, Helen's daughter, CS08).

The booster heater is never used but once plumbers came in and they left it on by mistake (Lynn, CS12).

- A similar situation seems plausible in CS02, where even though Beatrice was certain the resistance heater was off, to her surprise, both the researchers' visual inspection and the monitoring data revealed the opposite. However, neither occupant complained of high bills nor did the bills appear high in comparison to other cases of similar size and heating patterns (see Table 17 of Appendix C).

Yes, there's one [immersion heater] in there, but it don't' work […] It's been on! […] The only time I've had them there is I had trouble with my heating coming on, but only once, I don't think they touched the immersion (Beatrice, CS02).

- For Quianna and Quentin (CS17), resistance heater use and the associated surge in energy consumption appeared to be the result of their HP failure. Luckily, Quianna's electricity consumption-recording practices enabled her to identify the problem early enough to avoid high electricity bills but not poor comfort, since it took three winter weeks for the problem to be fixed and to reduce costs they were only using the backup heater for DHW.

… we didn't notice for a couple of days. It was only when I had checked the electricity usage […] and it was like "how come we're using that much electricity?" […] it must have been using the immersion heater. It must have gone automatically onto [this emergency setting]. And then… when we realised that, it was a massive amount! […] So during that time we were keep on going with the wood burning stove, which just heated the house. We kept that room warm [living room] and heated the water [with immersion] for a short time every day so that we had hot water… occasionally […] And we were frozen! You don't realise… we hadn't appreciated how cold it can get when there was no heat […] 'cos it was costing a fortune (Quianna, CS17).

- A similar but more extended period of discomfort was the result of HP technical failure in CS04, where Dawn was left without heating for 2 months during winter and the backup heater never did not kick in, as expected.

…I have found recently, there's supposed to be an immersion heater put in there […] and we couldn't understand why the immersion heater wasn't kicking in, for hot water they didn't connect it (Dawn, CS04).

Examples of possible effects from uninsulated pipework within buildings

- In CS12, the uninsulated pipework may have influenced the kitchen room thermostat, in addition to the cooking heat gains, since the kitchen and the utility room, in the cupboard of which the installation was placed, were next to each other with no doors to isolate them. However, this is not expected to have affected heat availability in the rest of the house, since its ground floor UFH and the upper floor radiators were controlled by multiple room thermostats.

- On the contrary, in the underfloor-heated ground floor of CS19, there was no room thermostat present, thus the heat losses from the uninsulated pipework surrounding the DHW cylinder in the drying room were expected to increase heat demand.

Examples of severely delayed resolution of technical issues

- **Extensive resistance heater use** – Unknown to Helen (CS08), the backup heater was active during approximately four months, resulting in high electricity bills, however, the RSL had to send several technicians before the immersion heater operation was identified and deactivated.

> *…she was paying £45 a month and it was fine, but what's happened is, she did have a power cut a couple round about November time and then, in the February [the RSL] came in, they put a new kitchen new bathrooms, so the electric was on and off, on and off for three weeks and unbeknown to us, the immersion heater had kicked in, it had been running and that's how she ended up with that big bill. So out payments now have gone from £45 to nearly £75 a month […] We couldn't get anybody to understand… there's one boy, one lad, he's from the council. If you get him, he's good. He knows, but the others… they only get half a training, or something on it, they don't get training […] the other thing is there's a thing in the cupboard. My mam did say there's two lights on in there and we thought… it's not that we don't just believe you, but is she mistaken? [..] We didn't realise that the two lights that were on were the immersion heater. […] It was on permanent for about four months. She's [age range 80-90], she doesn't press any buttons unless (Hilda, Helen's daughter, CS08).*

- **DHW priority turning the SH off in the evenings** – According to Gabi and Greg (CS07), the technicians made several erroneous assumptions as to what might have been going on (*e.g.,* a floor lamp too close to the thermostat or flat thermostat batteries) before managing the situation by limiting the DHW heating period to early mornings only.

> *…the man that put it in comes in, cause we had trouble every night […] every night at 5 o' clock the heating would go off in the middle of the winter (inaudible) and he [the technician] would eventually come down and he was gone again. "There's nothing wrong with it, nothing wrong with it". Only it is Gabi used to have a bath at that time and drained the water out of the tank so instead of heating here [the radiators] it was heating the water […] He didn't know what he was doing, 'cos when he came […] he literally said, "oh well, you have to move your lamp 'cos it's underneath the stat, so it's affecting…". You know, silly things… and when it was not working long time, they came out and they said "oh you might need to change the batteries in that stat, it could be the batteries doing it…" Every excuse in the book why it was not working, they hadn't a clue […] But the thing that happened then, the hot water coming on twice a day, 9am to 10am and then 3-5pm and that is when the trouble came in. […] So, we rang them up saying we've got no heating but they didn't know enough to tell us that we shouldn't be having a bath at the same time as the heat […] The stagnation came after we got the new pump. We changed it and the hot water heating now comes on between 1am and 3pm and that's it. Just once (Greg, CS07).*

- **Missing drip tray** – Water dripping can be particularly dangerous in icy conditions, however, this problem was only rectified 7 months after Helen informed the RSL (CS08).

Examples of experts resolving technical issues with occupants' assistance

- **Valve interchange –** Andrew (CS01) realised something was wrong with the valves shortly after the installation as some rooms were not warming up. Upon examination, he was able to identify a valve inlet-outlet interchange, which was then communicated to the installer.

> *The installers' weren't very good. They connected the downstairs manifold back to front on all the valves, it took me three days to sort that out, so none of the valves were reading because the water was going the wrong way through the valves, so the balancing system wasn't working, so I had to get them to come back and re-wire that (Andrew, CS01).*

- **Air trapped in the ground loop –** Marvin (CS13) stated that he ended up doing 90% of the HP design himself, following a series of problems encountered, from the design phase to the HP installation and setup, including the original designer planning to install a three-phase HP without considering the need for a very expensive three-phase line extension to the site, and a non-working HP due to trapped air in the ground loop.

> *The original installation was crap and I had to do a lot of work to get it to behave properly […] We went through six plumbers, a few went bankrupt, a few got chucked out […] and then the last guy was on the panel, he's part of the senior guys who are doing the heat pumps […] so, for instance, once we realised the problem with three phase [i.e., having to pay a lot to extend it until it reaches the house], I forced him [the original installer] to give me he calculation spreadsheet, he worked it all out, and I then used that to work out what we could do to get us down to a level, which is about 10-12 kW […] The original installer […] couldn't' get the air out of the ground loop properly, he didn't have the right equipment. He didn't understand enough about the header tanks and the pressures going on inside it […] there were problems because they got the pressure tank at the wrong level, so we had to move… well, the pipe went round (inaudible) and once he [the senior installer] did that, it was fine and we haven't touched it since, it's been magic […] I actually believe, the reason why is the guys who were doing the charging of the ground loop had the wrong diameter equipment on their pumping equipment, so they couldn't get a flow high enough to push all the air out of the ground loop. So they came and did the same thing, basically, with the right equipment and worked, strangely enough (Marvin, CS13).*

- **Ground loop leakage** – According to Nathan (CS14), the technicians were only able to identify the leakage following his prompt for a ground-loop test and blaming their original inability to identify the leakage on the use of inappropriate equipment.

> *We did have a problem after the installation and it was a major problem, nothing to do with the setup here, but you see that topping up there […] it's your antifreeze, basically which I've got a bottle. That's where I've marked it and I'm going back after they installed it and I noticed it was*

dropping and at first they said "oh, it'll be air in the system" but it kept on dropping after we got the air out – there was a leak […] they had to dig up […] where it comes up as an elbow, or two elbows because it's a huge thing, the pipe that comes to here, they weld it and they do a plastic weld […] it was dripping out of there. So they fixed it and then it took a little while again and it was still going down, it was only the other one was leaking as well […] Process control and instrumentation [is Nathan's expertise] and when the engineer was doing the leak test, when he came back, I said "no reason you didn't find the leak, they're doing a leak test with a little gauge like that". So you need a proper, standard test gauge and you need to give it a good 20 minutes and offshore, we put it on a recorder, so you can see it, straight off (Nathan, CS14).

J2 Occupant quotes

Quote 1: *Well, gradually, before we had this [portable room thermostat], I kept putting it down to see how low we could keep the boiler on and it still be comfortable. If I put it down too low and it wasn't comfortable, then you'd notice and then you'd put it on. At one time, we used to have it on at 50, but then, it was getting too hot and then I quickly realised that it was more efficient to run it all the time, at a lower temperature […] It's 44 [pointing at the flow temperature setting on the controller] at the moment, so I can move it up and down. Normally when it comes on in the morning, its 35 on there, or has been, I don't know whether that new piece of machinery has changed everything yet, we can't tell, but I come and manipulate that. If I'm cold, I will come and put it up. Normally it's on 35, which is fine for us… (Ian, CS09).*

Quote 2: *…we weren't [controlling the room temperature up until the day before the interview took place, when a portable room thermostat was fitted, i.e., four years after the HP installation] because the one [room thermostat] they put in didn't work because it was in the utility room and there's no radiator in there anyway and the old one is on the wall by the fire, which is a ridiculous thing because if you have a fire, obviously, that's controlled to that. So that was disconnected when this one went in* (Irena, CS09).

Quote 3: *If [I am] not [comfortable with the temperature] I'm gonna tweak the graphs […] I just set the [flow] temperature according to the graph and if the house isn't warm enough, I'll go up a graph*. (Quianna, CS17)

Quote 4: *If it gets very cold, I might do it [change the flow temperature], but quite honestly, I haven't had to change it because I'm quite happy with these [settings]…* (Ursula, CS21).

Quote 5: *It's got three places it [the thermostat] lives, it lives in the hall normally. If we're generally too hot, then I move it into here [living room] which is about a degree hotter than the hall even though the door is open and then that means that because the ambient temperature is a bit more, the switch doesn't come on so much and then, if we're too cold, I can put the thermostat into a colder environment, which is out in the porch, and then that will make the heat pump work better. I might do that for a few hours and then I'll put it back in the hall, so that's the way it would work* (Kate, CS11).

Quote 6: *…we're playing with this new, little toy that we've got […] it has got screws to fix it to a wall, but then we're stuck with one room then, whereas we can move, we can walk around with it and it senses what the temperature in that particular room is. I don't know whether we're working it properly or not* (CS09).

Quote 7: *We had it [the HP] on to keep the house warm throughout, it was such a fantastic thing […] the HP does keep the house warm but is expensive and the bills are higher than expected […] [Now] we sometimes put the downstairs hall and upstairs hall on, just to boost the temperature up, but only for a day […] We don't really use it [the HP] that much. We do use it sometimes, obviously, but it hasn't been very cold this winter yet. […] We just wanted to see if it would make any difference to the electricity […] the last two winters have been really high electricity bills, so we thought we'd change it and try not to use it, try something new (Patricia, CS16).*

Quote 8: *It goes off at 11:20 at night […] and it comes on at 7:30 in the morning. Unless I'm having a lie in and I set it for a later time […] so if I'm having lie in until about 9, or half past 9, I'll set it to come on for about 9 o'clock, or half past 9 (Francis, CS06)*

Quote 9: *Normally when it comes on in the morning, it's 35 [the flow temperature] on there […] but I come and manipulate it. If I'm cold, I will come and put it up […] In summer, we get rid of all the controls […] I'll switch the central heating on, sometimes if you get an odd, cold day, because we don't have it going on all the time during the summer, we just go and switch it on. If it's cold, we'll have the central heating on a bit and then we switch it off when we go to bed (Ian, CS09).*

Quote 10: *The wood-burner's in here; without this on in the evening and we hadn't had the doors open, I even open the* *hallway door and the lounge because it gets really warm, so we do let the heat in through them, yeah. It does warm up fairly well […] Yes, this [the wood burners are used] every day… nearly every day, anyway (Patricia, CS16).*

Quote 11: *…that's purely decorative really [the wood stove]. We do use it, it will get warm, but we don't need it, if that makes sense, it's just for show. We do have it on regularly, but it's not the end of the world if we don't (Rafael, CS18).*

Quote 12: *I borrowed it [the electric heater] when I came out of hospital, just to keep the chill off […] I did turn it on [the HP] but it took so long to come up […] I'd been in hospital for eight weeks and when I came out, the place was chilly […] I don't use it [the electric heater] at all now (Clive, CS03).*

Quote 13: *My husband does have extra heating [portable heater] up here [home office in the attic] […] because it gets cold […] we do have plans to put another [HP radiator] in (Jennifer, CS10).*

Quote 14: *We're trying to use the wood-burners to heat the house […] the HP isn't on, it's only on frost protection […] we've got an oven as well, that is on low at the minute, that's never hot, we just turn it up. That is our heat source as well, if you want it to be; so we turn it on snooze, it's on snooze at the moment. Sometimes we turn it off completely, but just to keep the chill off a little bit and then when you want to cook you just turn it up again and away you go. It's not on all the time, but it is on at the moment […] we just wanted to see if it would make any difference to the electricity, we were trying to work it out* (Patricia, CS16).

Quote 15: *Yeah, because the thermostat is in here [living room] and we want to feel warm while we're in this room, we shut the doors. When one of us wants to go on the computer, which is in the bedroom, we literally have several layers of clothes on, because we freeze in the bedroom. If we left all the doors open, maybe we wouldn't freeze in the bedroom but while we spend most of our life in here, we shut the doors to try and keep the heat in. But in that bedroom you would freeze to death, literally (Gabi, CS07).*

Quote 16: Sometimes during the day, Irena will say "there's no hot water", so I'll go and over-ride the system […] Can you see these, with the shower, I just press this. I press the one on the right and then you will get another shower coming up there, another shower, one of these, that is flashing and it will flash all the time it's over-riding (Ian, CS09).

Quote 17: I've got two settings on there, one is on what they call the advanced setting, where it [the HP] heats it [the water] up to a higher temperature and generally, we're okay on normal here, but if we have visitors, I might have to put it on – like you do in any system (Nathan, CS14).

Quote 18: Oh, there's an immersion link as well […] it's only ever on when I've got all the family – there's six of us – and I know they're all going to be having showers first thing in the morning […] when there's six of us here who want a shower in the morning, then it can't cope, even though it's a very big tank, so I just put our immersion heater on, or boost the heating, it could be both (Andrew, CS01).

Quote 19: Yeah, it's [a secondary return] to keep the pressure up, so you don't stand for ages with a cold tap running, so there's a sensor in each bathroom that knows you've arrived in the bathroom and the pump starts going round (Patricia, CS16).

Quote 20: We had that [electric] shower somewhere else and it's just got such a nice power, that why we used it, rather than [the HP]… (Patricia, CS16).

Quote 21: I actually monitor all the power and see how much I'm using. So you look at the green one, which is what we're actually using for the heat pump [...] because you look at the total one, it's the lights, it's not the heating at all. Cause until we got the meter in, at that date then, I was horrified at the amount of electricity we were using and then I found out, it just was my children, before they finally moved out, leaving lights on – and they're not very energy efficient lights – every time they blow, I change them to an LED, but they haven't all blow yet […] I've got a complete 3G communication system in there with data logging, hot and cold water temperature, heat flow rates in and out of the heat pump, separate power meter – so that's where I get all my data from – so I can self-monitor (Andrew, CS01).

Quote 22: I can see it in the data set […] very clearly, summer and winter. The COP at the moment is running 10 to 4 […] [I know that] because it's on the meter […] I think it averages at about 4.2, but it goes well over five in the summer and I've seen it down about 3.1-3.3 in the winter (Samuel, CS19).

Quote 23: *We occasionally turn off radiators in the bedroom from the thermostatic radiator valve. But we actually started to notice the problem with condensation in the bedroom so we put that on again now (Teo, CS20).*

Quote 24: *That one up there [guest room], I think it's [the room thermostat is set at] about 15 [°C] – we don't overheat it because we're not using it – but we don't want it to get damp (Nathan, CS14)*

Quote 25: *To be fare I've never set it [the room thermostat temperature] any higher […] you can put it up to 30, and it will go but we can't afford to pay the bills (Greg, CS07).*

Quote 26: *We rarely use the oven itself, Greg has got […] an infrared thing that sits on the bench and we use that. We never other than the Christmas day, we never use the oven […] That's [the electric bar fire] there for decoration and no other reason. I don't even put the pump on to have the light going on it, because you can hear it worrying away, which is taking electricity […] I wouldn't dare to put the heat on to be honest (Gabi, CS07)*

Quote 27: *We took the bulbs out [of the chandelier] [...] we don't need all these bulbs on. We're just thinking about the energy (Patricia, CS16).*

Quote 28: *The temperature's fine [in bedroom 1], we don't usually have the radiator on unless it gets really cold, but we've had a problem with condensation in the corner there. I quite like the window open and Teresa doesn't like the window open, so… but it's because of the condensation […] Most of the time, there's usually something drying in here [bedroom 2], but only once or twice a week there's a wash […] so you see the problem we've got with damp there as well […] We've only noticed recently because there was a cupboard there before (Teo, CS20).*

Quote 29: *We did use to have condensation in here [dressing room] and dampness because it was all clothes […] We had vents put in the roof because there weren't any air vents in the roof, so we had eight put in (Nicole, CS14).*

Quote 30: *That one up there [guest room] I think [the room thermostat] it's about 15 [degrees Celsius] – we don't overheat it because we're not using it – but we don't want it to get damp (Nathan, CS14).*

Quote 31: *We occasionally turn off radiators in the bedroom from the thermostatic radiator vale. But we actually started to notice the problem with condensation in the bedroom so we put that on again now (Teo, CS20).*

Quote 32: *There is plenty of damp in the house, but I doubt if that's because of heating, that's just because of this house […] Well, you can smell damp, not so much in this room [living room] but in the bedroom… Oh, actually we've got one of these dehumidifiers and it's filled to the top with water (Gabi, CS07).*

Quote 33: *Have you got any idea how much water it [the dehumidifier] exudes overnight? This had been on just today, since I got up this morning. And that's fairly normal… yes, so it's about 100 watts, but the result is no mould and in my last house, it was a fairly damp house, do dehumidifiers solve the problem (Samuel, CS19).*

Quote 34: *Because I like the air to come through, I feel closed, it's too hot. It doesn't matter what the weather, if the wind's blowing, I have the windows open. My mum always used to say to me that I was born inside out, I'm different than everybody else […] [The windows are open] every morning [until approximately] mid-afternoon. The first thing I do in the morning, I open the blinds, I think it's the thicker cardigan I wear (Helen, CS08).*

Quote 35: *I try to [ventilate every morning], I really try to, yeah, but one of them doesn't work, there is only one that* *actually works […] the bottoms don't open just the top (Gabi, CS07).*

Quote 36: *…they [the windows] are all sealed […] somebody came around and measured up, they were going to put some new glazing in, but that's the last I heard […] I smoke as well, you know? […] We've got extractor [fans] up there […] [I have them on] all the time, from when I get up in the morning until I go to bed at night (Clive, CS03).*

Quote 37: *…we go weeks without opening a window, y'know, closed door policy. Well, it's a waste, isn't it? We didn't like using oil to heat our house and don't like using electricity either (Kate, CS11).*

Quote 38: *We don't open the windows at all, only the French door… […] and the dog is in and out of there, anyway (Andrew, CS01).*

Quote 39: *…we have to have the door open for the dog sometimes […] so we just leave the door open for a little while […] summertime, it would be every day […] wintertime, I dunno, half an hour a day, just to let a bit of air in, sort of change the air a little bit (Patricia, CS16).*

Quote 40: *Because it takes so long to heat the house up, we just don't open them [the windows] […] Yes [there are draughts in the house], there are less than there was two weeks ago, thanks to the builder […] we're never going to be airtight because we've got fireplaces in our bedrooms (Jennifer, CS10).*

Quote 41: *The only issue is, if there is, is it's so highly insulated that the air quality has not been a concern, but been a thought process and we have discussed about putting in a mechanical ventilation heat recovery […] put in a system, which would change the air in bedrooms and the bathrooms because one thing that has happened is the air in here is incredibly dry, really, really dry because there's no open fireplaces, there's no draughts, there's no damp, so (inaudible) the wood and the floor upstairs because it's so dry, it's dried so much, that gaps were opening up and that's happened because the floor and the warmth is so… So if I was doing it again, we would put mechanical air system in, up front, to keep the heat quality in, better air quality. It's not bad, you open a window, that's the way round it […] in the wintertime […] we have a window open if we can […] we try and open them sometimes, but that definitely is an issue, the dry air (Marvin, CS13).*

Quote 42: *The old cavity was never filled, so we had it filled about eight years ago. When I started doing the bathroom, we found out that the insulation wasn't in the wall there […] I took the stench pipe out , you looked at the gap, couldn't see any insulation. So I rang them up, they came and a chap came round, went round and drilled holes all the way round, he said "you're fine from here round to there, but all round the back of the house, there's hardly any". So they came and re-did it […] That's what happens if you use contractors, you don't know (Ian, CS09).*

Quote 43: *That [the cavity wall insulation] was done earlier this year. I didn't really want to put it in the first place… there are an awful lot of piercings in that wall, but the company that did it did volunteer me a guarantee that if I've got any water penetration – which I fear, with the quality of brickwork in that is highly likely – then they would pay for the removal, so I said 'okay' and I got it […] It was done really as a prompting of the RHI scheme because they wouldn't accept my architect's written statement that it was no recommended (Samuel, CS19).*

Quote 44: *…actually, that's a new external door, because the door I had on, it had Flemish glass in, it was just one pane. Actually, that door got put on, from [the RSL] and they paid for that door and that door, I don't know if you noticed it, it makes it ten times warmer. I've had that put in and I've got a draught excluder because the draught used to belt in that door, so I've put that right the way round (Francis, CS06).*

Quote 45: *I've insulated the hot one [water circulation pipe] […] I'm pretty sure it's the hot one, there's not actually much difference between them […] There was stuff left over from the guys who put in the heating and so I put insulation because there's quite a lot of pipe, before the water reaches the radiator, there's a fair amount of pipe, so the aim was to get the water to go to the radiator as soon as possible without losing too much heat (Quianna, CS17).*

Quote 46: *Sometimes, you'd come back and there would be no hot water, you'd go and it says it's Motor P error, you just turn if off at the isolator, turn it on and it's fine, so I've no idea what it is […] I did look at it in the manual and it gave no… y'know, turn it on and off, then it works and everything is fine. It's happened maybe three or four times […] when the hot water stops and we think "why is this shower cold", we have a look and that's why […] A couple of times it happened on really stormy nights where the lights were kind of going […] With technology, turn it on and off, that tends to be a good idea, so I did that and it was fine (Rafael, CS18).*

Quote 47: *We did have a problem with it and we had to simply turn it on and off again at one point and I've got written instructions because we get a lot of power cuts here […] this is what I've written, if heat pump not working, e.g., power interruption and this is how to switch it all off, the order you switch it off and how long you leave it and then you switch it all on again […] they were very good, we just said what happened and they told us over the phone, so I wrote it down […] it took us two days to realise the water was cold. Again, a very big tank full… it was gradually cooling off… and then we realised that the heating thermostat, with the heating was calling and the pump wasn't working, and it slowly dropped… "it's not working, it must be something to do with the power cut, two or three days ago" (Kate & Kevin, CS11).*

Quote 48: *Actually, the only time I'd had a problem with it was when the power was off for a while, so the control system turned itself off and it turned back on in 2012, in the middle of summer and it was wintertime, so it didn't know; for some reason, it decided to be in summer, so we didn't realise because you don't touch these things, but it was cold. (Marvin, CS13).*

Quote 49: *…there was one year the [bathroom] heating had gone off and I went round to my friends. I said that I couldn't get it on and he [a friend] came round and he had a look. He said what's happened is that I've got the thermostat in the bathroom […] on the wrong setting. So my friend adjusted it and the heating started coming through and I've had no more bother since (Francis, CS06).*

Quote 50: *Because there is this immersion heater and we knew it straight away! The immersion heater was heating the water! 'Cos it's gone on to this emergency setting […[we didn't notice for a couple of days. It was only I had checked the electricity usage […[and it was like how come we're using that much electricity? […] it must have been the immersion heater […] So during that time we were keep on going with the wood burning stove, which just heated the house. We kept that room warm [living room] and heated the water [with the HP] for a short time every day so that we had hot water… occasionally (Quianna, CS17).*

Quote 51: *I was watching television and heard such a rumble, like an explosion […] there were great, big clouds of smoke, you couldn't see across the field […] So everybody came up from [the local council], they hadn't a clue what they were doing, so eventually, they classed it as an emergency, they sent somebody up from [another area]. So the man came, the engineer, who up a man from [installer company 85] […] he tested it and he said there was a fault in the generator […] the sitting room was freezing cold, we were sitting with the two electric bars on […] So they took the generator away and they brought a new one and it was connected up within a day (Francis, CS06].*

Quote 52: *The people that installed this they put it in the wrong way. The pump (inaudible) lasted less than 12 months […] it burnt itself to death […] And when they came […] they said the water temperature had been set too high (Greg & Gabi, CS07).*

Quote 53: *The heat pump had only been in for one year, when it broke […] they came back once or twice, but they couldn't pinpoint… so they changed the whole lot… They put in an actual motherboard that went in the first one […] that would be about three years ago. Three weeks, four weeks, it was quite a while [before they replaced it] it would have been March time (Hilda, CS08).*

Quote 54: *…last year, I wanted it [the HP] taken out. I was down for two months solid, in the winter […] it went down. Two* *months, I was without hot water and central heating […] it broke down, so outside in our cupboard, we've got a tube […] with antifreeze in it. That cracked and I was using the anti-freeze. Being cold, I suppose it cut me off (Dawn, CS04).*

Quote 55: *Three weeks, and it was the coldest part of that particular winter… and that has been the one… bone of contention we had with the folk that installed, because they just weren't good. Well you see, part of it is that our choice of company was delivering under the impression they were local […] when we had a problem, it took a while for them to get organised and come down here. Because it is a good two hours' drive from [that city] to here […] So there was a big surge in the voltage and the thing… I don't know whether something else in the heat pump was damaged or whether the surge told them the other thing… there was more to it. So 2-3 weeks between… I was on the phone… so they were telling us [manufacturer 755] was the problem. And I was phoning [manufacturer 755] and saying, "what is going on here?" And they were saying "no, we've sent the stuff down to them, they have it", so [manufacturer 755] was saying no, no… And we were frozen. (Quianna, CS17).*

Quote 56: *…we had all kind of problems within the first 12 months and it burnt out […] When they first put it in, like we are doing now, we relied on the settings and everything being correct. Within that first year, I don't know how many times we called the engineer out, because it wouldn't work, it wouldn't go on […] we weren't doing anything wrong; whoever installer the thing, didn't do anything right (Greg & Gabi, CS07).*

Quote 57: *…this has never worked properly since the day it was put in […] the guy that came and he reset it all… and then we had another technician came and then dig it up and it has been good but it still doesn't heat the place properly […] You can put it up to 30, and will go but we can't afford to pay the bills (Greg, CS07).*

Quote 58: *I do think it is using an awful lot of electric; that's one thing, that' being investigated at the minute […] He's being monitoring it two months and now it's been the winter time. He said to write down when I put the oven on… […] So he knows what's happening and we've got three phase electric and which phase it's on because the high readings are on the phase that is to the ground source heating (Patricia, CS16).*

Appendix K: Enlarged images of selected causal loop diagrams

K1 Figure 6-15 of the main document

K2 Figure 6-16 of the main document

K3 Figure 7-1 of the main document

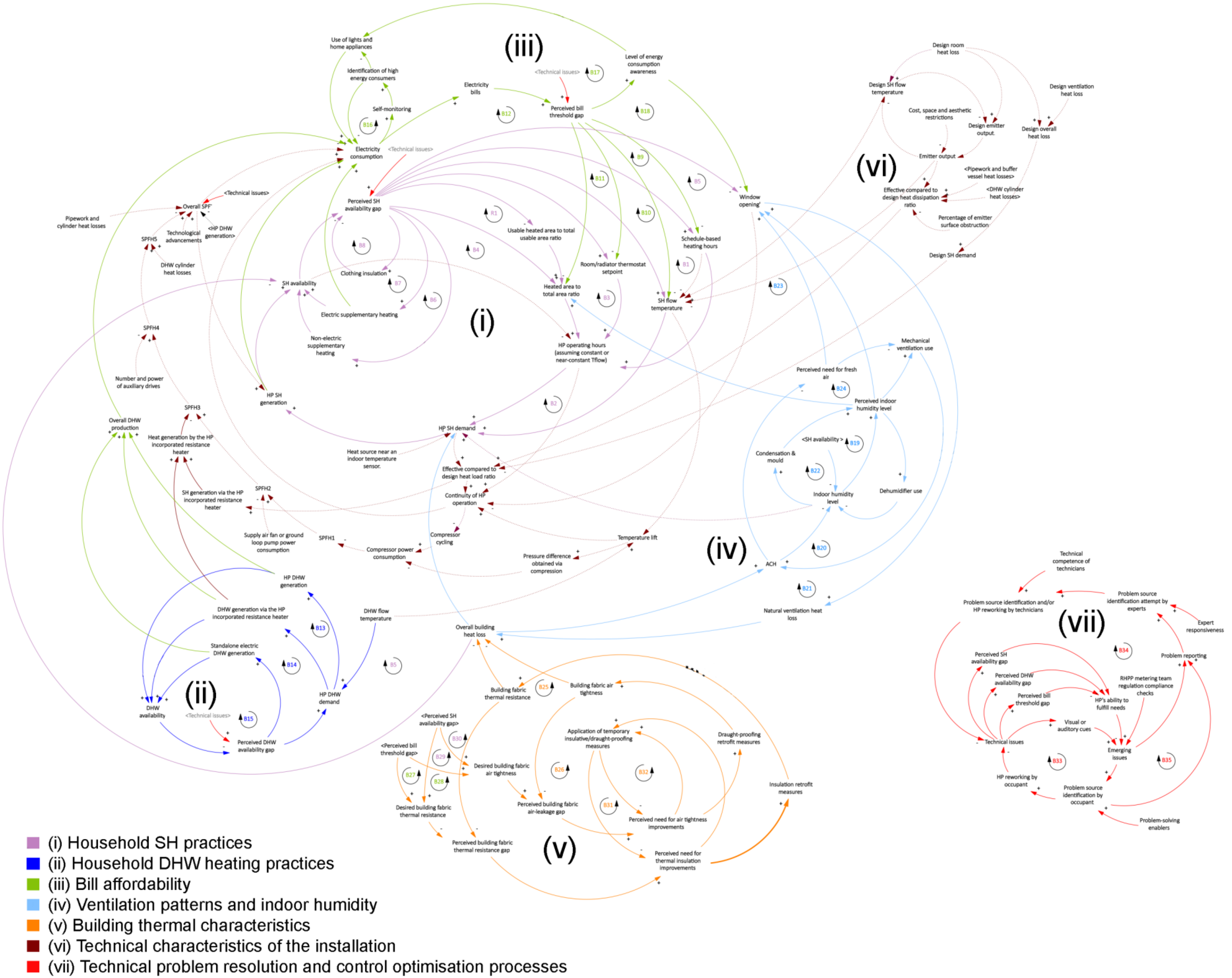
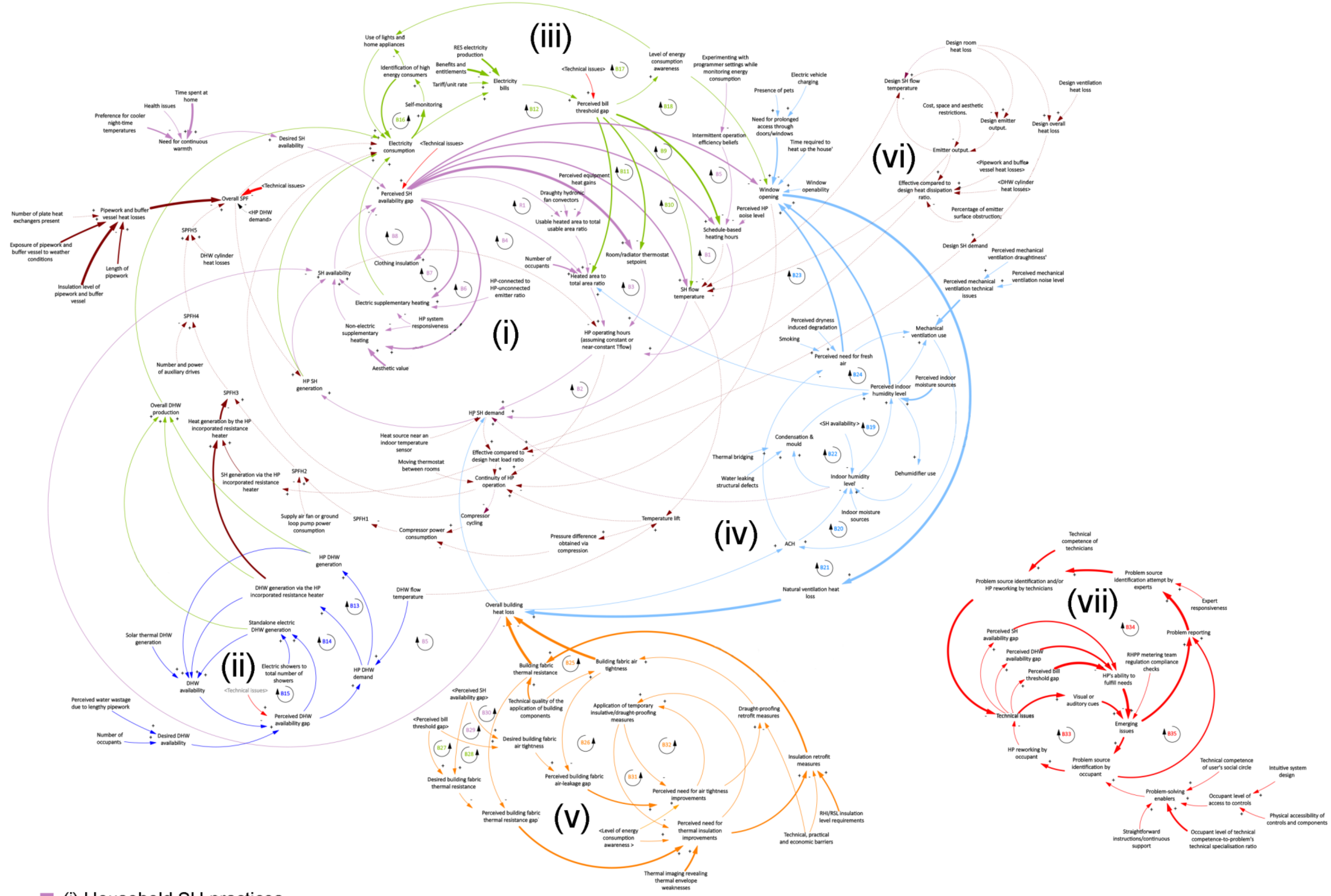


Figure 6-15 of the main document



(i) Household SH practices
(ii) Household DHW heating practices
(iii) Bill affordability
(iv) Ventilation patterns and indoor humidity
(v) Building thermal characteristics
(vi) Technical characteristics of the installation
(vii) Technical problem resolution and control optimisation processes

Width A
Width B
Width C
Width D

Figure 7-1 of the main document