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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University of London
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Declarations

I, Eleni Oikonomou, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Student’s signature

This thesis builds on the work conducted as part of the 'Analysis of Heat Pump Data from the Renewable Heat Premium Payment Scheme' and specifically on the elements the author led on, i.e., the planning and implementation of site investigations for 21 case studies. The findings from conjoined work are described in Chapter 4. The remaining chapters present the results from the additional analysis that was performed by the author under the supervision of four supervisors.

Student’s signature

Supervisor’s signature
Abstract

The UK Government views heat pumps (HPs) as an increasingly important technology able to contribute significantly towards the decarbonisation of domestic stock, with the Government committing to the annual installation of 600,000 HPs by 2028. However, there appears to be a performance gap between predicted and real-life HP performance. A number of studies have highlighted several possible causes of the performance gap but have not investigated these in a structured way. Given the important role of HPs in a Net Zero future and the potential to improve their performance, the aim of this study is to characterise the socio-technical parameters affecting heat pump performance in the field and discuss the implications for their future take up in the UK.

A sample of 21 case studies were selected from 700 domestic HPs monitored across the UK via the government’s Renewable Heat Premium Payment Scheme for the collection of qualitative and quantitative socio-technical data. The data collection process involved in-depth interviews and direct observational methods. The collected material was inductively analysed and corroborated with pre-visit material, including monitored HP performance data. Using systems thinking as an integrating framework, the results were fed into a series of interlinked causal loop diagrams, specifically focusing on the parameters and feedback processes that are likely to be linked to poor HP performance.

The systems model revealed complex mechanisms that are likely to influence HP performance in seven interconnected areas relating to the (i) household space heating practices (ii) household domestic hot water heating practices, (iii) bill affordability, (iv) ventilation patterns and indoor humidity, (v) building thermal characteristics, (vi) technical characteristics of the installation and (vii) technical problem resolution and control optimisation processes. These impact HP performance through different, direct, and indirect paths, the majority of which converge at two points, namely HP space heating demand and continuity of HP operation. The systems analysis identified four leverage points, i.e., places to intervene within a complex system, where small shifts can cause a big impact: ensuring both quality installations and appropriate control through behavioural change, allowing the incorporation of smart controls, carefully reconsidering the rules governing the HP installations and enabling system feedback.

The findings have important implications for policy makers, HP manufacturers and installers by identifying barriers to the performance of domestic HPs in the field. This work can inform future HP related government schemes and incentives, installer, and manufacturer standards, as well as the installation and monitoring practices of future field trials.
Impact Statement

This research investigated the underperformance of domestic heat pumps (HPs) in the UK to gain a deeper perspective on performance influencers and achieve new insights into the requirements for well-performing HPs. The work mapped for the first time the full range of the parameters influencing HP performance based on an extensive range of interacting boundaries. It is also the first study in the field to utilise systems thinking as the integrating framework for the interpretation of data collected through field monitoring and in-depth site investigations, thus enabling the identification of a complex network of underlying interconnections. By identifying key performance influencers and prioritising critical initiatives, the study formulated a suggested course of action. It also offered insights for the improvement of technical monitoring practices and highlighted the importance of a holistic assessment in the performance investigation of complex technologies.

The detailed recommendations formulated based on the study's findings address a wide range of stakeholders in the areas of testing, monitoring, installation, and use of HPs, including practical advice for policy makers, installers, manufacturers, and users. The study prioritises critical initiatives and acknowledges the presence of practical and social barriers. The suggestions provided will potentially also improve public acceptance of the technology. The work will also be of interest to other disciplines, such as the built environment, building services, residential building management and psychology and social sciences. The wider academic community will benefit from the research as it has produced a blueprint for the improvement of HP performance, applicable to studies beyond the UK and populations of different characteristics. These benefits could be brought about through the dissemination of output in conferences and publications of journal articles.

Direct beneficiaries of the research study are UK policymakers, such as government departments and other regulatory agencies, who are responsible for developing and introducing climate mitigation policies, including policies for the incentivisation of HPs and the improvement of their energy performance in the UK. The research output can be utilised to inform and update current industry standards and quality assurance processes, such as those forming the Microgeneration Certification Scheme (MCS). The output may also be of interest to research institutes and testing laboratories investigating HP performance; installers and manufacturers of HP systems and their components; trade associations representing manufacturers and HP distributors; builders, designers and housing associations involved in building retrofits projects and/or the design of domestic developments; social landlords and housing managers who oversee HP installations; as well as users seeking to improve their understanding of HP operation.
Acknowledgements

I would like to express my sincere gratitude to my primary supervisor, Professor Tadj Oreszczyn, for his continuous encouragement, supervision and support throughout the ups and downs of the research process. I am also grateful to my secondary supervisors, Professor Mike Davies, Dr Nici Zimmerman and the late Dr Colin Patrick Gleeson for their valuable insights and suggestions.

This research would not have been possible without support from the Department of Business, Energy & Industrial Strategy that funded the RHPP project and case study work and allowed the use of the data for the purposes of this PhD. I am also grateful for having had the opportunity to work with the RHPP project research team, led by Professor Robert Lowe, for their productive collaboration and for all the inspiring and thought-provoking discussions. I am particularly grateful to Jez Wingfield for his insights into the technical data and to Dr Jenny Love for the technical support provided.

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<th>Full Form</th>
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<tbody>
<tr>
<td>ACH</td>
<td>Air Change per Hour</td>
</tr>
<tr>
<td>ASHP</td>
<td>Air Source Heat Pump</td>
</tr>
<tr>
<td>BEIS</td>
<td>Department for Business Energy and Industrial Strategy</td>
</tr>
<tr>
<td>BRE</td>
<td>British Research Establishment</td>
</tr>
<tr>
<td>CLD</td>
<td>Causal Loop Diagram</td>
</tr>
<tr>
<td>CLNR</td>
<td>Customer-Led Network Revolution</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
</tr>
<tr>
<td>COSP</td>
<td>Coefficient of System Performance</td>
</tr>
<tr>
<td>CWI</td>
<td>Cavity Wall Insulation</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change (now incorporated in BEIS)</td>
</tr>
<tr>
<td>DHW</td>
<td>Domestic Hot Water</td>
</tr>
<tr>
<td>EHPA</td>
<td>European Heat Pump Association</td>
</tr>
<tr>
<td>EPC</td>
<td>Energy Performance Certificate</td>
</tr>
<tr>
<td>ErP</td>
<td>Energy-related Products</td>
</tr>
<tr>
<td>EST</td>
<td>Energy Saving Trust</td>
</tr>
<tr>
<td>ETI</td>
<td>Energy Technologies Institute</td>
</tr>
<tr>
<td>EWI</td>
<td>External Wall Insulation</td>
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<tr>
<td>FIT</td>
<td>Feed-In-Tariff</td>
</tr>
<tr>
<td>GSHP</td>
<td>Ground Source Heat Pump</td>
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<tr>
<td>HEG</td>
<td>Heat Emitter Guide</td>
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<tr>
<td>HFC</td>
<td>Hydronic Fan Convecto</td>
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<tr>
<td>HP</td>
<td>Heat Pump</td>
</tr>
<tr>
<td>HPA</td>
<td>Heat Pump Association</td>
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<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas</td>
</tr>
<tr>
<td>MCS</td>
<td>Microgeneration Certification Scheme</td>
</tr>
<tr>
<td>MIS</td>
<td>Microgeneration Installation Standard</td>
</tr>
<tr>
<td>MVHR</td>
<td>Mechanical Ventilation with Heat Recovery</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RAPID-HPC</td>
<td>Research and Analysis on Performance and Installation Data - HP Consortium</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Systems</td>
</tr>
<tr>
<td>RHPP</td>
<td>Renewable Heat Premium Payment Scheme</td>
</tr>
<tr>
<td>RSL</td>
<td>Registered Social Landlord</td>
</tr>
</tbody>
</table>
SEPEMO-BUILD  A European Project on Seasonal Performance Factor and Monitoring for Heat Pump System in the Building Sector

SH  Space Heating

SPF  Seasonal Performance Factor

TFA  Total Floor Area

TRV  Thermostatic Radiator Valve

UFH  Underfloor Heating
## Monitored Variables Nomenclature

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eb</td>
<td>Electricity used by the whole system boost</td>
<td>Wh</td>
</tr>
<tr>
<td>Edhw</td>
<td>Electricity used by the immersion heater on the DHW tank</td>
<td>Wh</td>
</tr>
<tr>
<td>Ehp</td>
<td>Electricity used by the HP (may include in-line heater and circulation pump)</td>
<td>Wh</td>
</tr>
<tr>
<td>Esp</td>
<td>Electricity used by the SH in-line heater</td>
<td>Wh</td>
</tr>
<tr>
<td>Fhp</td>
<td>Water flow rate to SH and DHW system (if the HP provides both)</td>
<td>litres/min</td>
</tr>
<tr>
<td>Fhw</td>
<td>Water flow to the DHW system</td>
<td>litres/min</td>
</tr>
<tr>
<td>Hhp</td>
<td>Heat leaving the HP as measured on the circulation system</td>
<td>Wh</td>
</tr>
<tr>
<td>Hhw</td>
<td>Heat entering the DHW system from the HP</td>
<td>Wh</td>
</tr>
<tr>
<td>Tco</td>
<td>Temperature of the water flow after the condenser</td>
<td>°C</td>
</tr>
<tr>
<td>Tin</td>
<td>Temperature of the refrigerant leaving the evaporator (for ASHPs) or of the fluid returning from the ground loop (for GSHPs)</td>
<td>°C</td>
</tr>
<tr>
<td>Tsf</td>
<td>Temperature of the water flow to the SH system</td>
<td>°C</td>
</tr>
<tr>
<td>Twf</td>
<td>Temperature of the water flow to the DHW system</td>
<td>°C</td>
</tr>
<tr>
<td>Tex</td>
<td>External temperature, sourced from publicly available databases</td>
<td>°C</td>
</tr>
</tbody>
</table>
Feedback Loop Names

[Ra] [Corrective measures inducing unintended heating-related consequences]
[Rb] [Corrective measures inducing unintended energy-related consequences]
[Rc] [Corrective measures inducing unintended SPF-related consequences]
[Ba] [Appropriate corrective measures improving heating availability]
[Bb] [Appropriate corrective measures improving energy consumption]
[R1] [Usable heated area adjustments to meet heating needs]
[B1] [Programmer adjustment to meet heating needs]
[B2] [Flow temperature adjustment to meet heating needs]
[B3] [Thermostatic setting adjustments to meet heating needs]
[B4] [Overall spatial adjustments to meet heating needs]
[B5] [Balancing SH availability through window opening]
[B6] [Adjusting SH availability with non-electric supplementary heating]
[B7] [Adjusting SH availability with electric supplementary heating]
[B8] [Clothing rebound]
[B9] [Temporal rebound]
[B10] [Flow temperature rebound]
[B11] [Thermostatic setting rebound]
[B12] [Spatial rebound]
[B13] [Balancing DHW availability through the HP]
[B14] [Balancing DHW generation through the HP-incorporated resistance heater]
[B15] [Balancing DHW availability through standalone resistance heating]
[B16] [Balancing energy consumption through monitoring]
[B17] [Light and appliances rebound]
[B18] [Window opening rebound]
[B19] [Balancing humidity, condensation and mould through dehumidifier use]
[B20] [Balancing humidity, condensation and mould through mechanical ventilation]
[B21] [Balancing humidity, condensation and mould through natural ventilation]
[B22] [Balancing humidity, condensation and mould via modulation of heated-to-total area ratio]
[B23] [The perceived need for fresh air as a window opening driver]
[B24] [The perceived need for fresh air as a mechanical ventilation driver]
[B25] [Retrofitting effect on building fabric thermal resistance]
[B26] [Retrofitting effect on building fabric air leakage]
[B27] [Insulation retrofitting as a cost control driver]
[B28] [Draught-proofing as a cost control driver]
[B29] [Insulation retrofitting as an indoor temperature driver].
[B30] [Draught-proofing as an indoor temperature driver].
[B31] [Alleviating the perceived need for thermal insulation with temporary solutions]
[B32] [Improvements of air-tightness with the application of temporary solutions]
[B33] [Self problem-resolving process]
[B34] [Expert problem-resolving process]
[B35] [Occupant-assisted expert problem-resolving process]
Chapter 1: Introduction

Climate change due to anthropogenic carbon emissions is globally recognised as a threat which, if not controlled, could lead to dramatic environmental and economic consequences (IPCC, 2014). Most member states of the United Nations have set legally binding targets for the reduction of greenhouse gases (UNFCCC, 1997) via the transformation of the energy supply and demand network (IEA, 2017; WEC, 2016). According to the recast Renewable Energy Directive 2018/2001/EU (European Commission, 2018), aiming to address both climate change and energy security in the European Union, 32% of the energy produced by 2030 should derive from renewable energy sources, as a minimum. Within this framework, heat pumps (HPs) are seen as an increasingly important technology that can contribute significantly towards meeting national carbon and European renewable energy targets (IEA, 2017; WEC, 2016).

In the UK, the Climate Change Act 2008 (HM Government, 2008) forms the basis of the UK’s plan to reduce carbon emissions, as well as mitigate and adapt to the effects of climate change. The Act set an 80% reduction target in carbon emissions relative to 1990 levels by 2050 that was subsequently increased to 100% (’Net Zero’) on 27 June 2019 (Institute for Government, 2020). To meet the set reduction targets, the UK Government introduced the 5-yearly carbon budgets given in Table 1-1, each providing a required cap on carbon emissions. Individual carbon budgets are set 12 years in advance and describe cost-effective pathways to achieve the required carbon reduction for the period of interest, taking into consideration all carbon-emitting sectors. The UK has met the first and second carbon budgets and is currently in the third carbon budget period (2018 to 2022), which appears to be on track to be met, unlike the fourth and fifth carbon budgets (CCC, 2021).
Table 1-1 UK carbon budgets (CCC, 2021).

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Carbon budget level (MtCO$_2$e)</td>
<td>3,018</td>
<td>2,782</td>
<td>2,544</td>
<td>1,950</td>
<td>1,725</td>
<td>965</td>
</tr>
<tr>
<td>Total reduction below 1990 levels</td>
<td>25%</td>
<td>31%</td>
<td>37%</td>
<td>51%</td>
<td>57%</td>
<td>78% by 2035</td>
</tr>
</tbody>
</table>

Heat decarbonisation in the building sector, where the uptake of 19 million HP is suggested by 2050 to meet the UK’s Net Zero target, is one of the main focus areas of the carbon budgets (CCC, 2020b). As of 2019, the residential sector accounted for almost 30% of national energy use and approximately 15% of UK carbon emissions, deriving primarily from space heating (SH) and domestic hot water (DHW) (BEIS, 2020b, 2021a). In 2020, the coronavirus (COVID-19) pandemic and the preventative measures put in place resulted in a sharp decrease of overall carbon emissions in the UK, driven primarily from the transport and business sectors. The provisional BEIS estimates (BEIS, 2021b) place the overall reduction to over 10% in relation to the previous year or just under 50% relative to the 1990 UK levels. At the same time, carbon emissions from the domestic sector presented an approximate increase of 2%, as people spent longer at home.

The UK Carbon Budget low-carbon scenarios (CCC, 2010, 2015, 2020b) and several other strategy documents (e.g., BEIS, 2018; CCC, 2019b; IEA, 2021) identified the need to use low-carbon heating sources and heat networks. Within this framework, HPs are seen as a key technology in achieving the decarbonisation of domestic heating, given that the proportion of renewable electricity (either from the grid or decentralised energy sources) to power them is growing. The electricity grid carbon intensity is currently similar to gas, at around 0.18 kgCO2/kWh, while grid carbon intensity predictions set electricity at approximately 0.1 kgCO2/kWh in 2030 (BEIS, 2019d; National Grid ESO, 2021).

The sixth carbon budget advocates for a significant scaling-up of the UK HP market within the next 10-15 years. In particular, it recommends the annual installation of 600,000 HPs annually in existing houses by 2028 (CCC, 2020a). In turn, the UK government has committed to such an uptake in the domestic sector through the Ten Point Plan (HM Government, 2020). By 2033, all buildings in the UK are expected to be energy efficient, all boiler replacements to be made with low-carbon technologies and the industry to be able to support the installation of over a million
domestic HP annually (CCC, 2020b). For 2021, the Heat Pump Association’s (HPA) roadmap to zero (HPA, 2019) had called for a fourfold increase in HP installations in comparison to 27,000 HPs in 2018 (EHPA, 2021a).

While HPs provide a great opportunity for the decarbonisation of domestic heat in the UK, care must be taken so that HP-related electricity does not burden the grid by further increasing peak demand, which currently occurs in the mornings (6am-9am) and evenings (4pm-8pm) (Durham Energy Institute & Element Energy, 2015). Hybrid HPs and smart controls are technologies that could help achieve demand-side management (Carroll, Chesser, & Lyons, 2020; CCC, 2020b). Hybrid HPs could serve as a low cost and flexible interim solution during the transition to full electrification, with possible benefits including greater public acceptability, and accelerated and extended deployment, even in off-gas properties and low-efficiency existing houses, which currently stand at approximately 29 million across the UK (CCC, 2019b). However, for hybrid HPs to be cost-effective, they should run in HP mode for a significantly higher fraction of time (Bennett, Watson, Wilson, & Oreszczyn, 2021; CCC, 2020b).

The Committee for Climate Change (CCC) also stresses the importance of offering financial support and flexibility to prospective buyers and minimising retrofit disruption in relation to HP installations, while concerns arise in relation to the weak supply chain status for insulation and HPs (CCC, 2020a). In order to ensure the legally binding net zero target is met, the UK government is seeking to identify barriers associated with the uptake of HPs (e.g., high capital cost) and ways to overcome them (BEIS, 2018a). The main focus so far has been placed on offering financial incentives and raising consumer awareness of low-carbon technologies and potential savings (BEIS, 2019b), improving the energy efficiency of new and existing dwellings [e.g., through the introduction of the Future Homes Standard by 2025 (BEIS, 2019c)], phasing out off-gas grid carbon-intensive heating (BEIS, 2017), and testing the feasibility of the large-scale deployment of HPs incorporating innovative technologies (BEIS, 2020a).

Domestic HPs will play an important role in future low-carbon domestic hot water (DHW) and space heating (SH). Policy is focusing on the scale-up of the UK market to help achieve the 2035 carbon budget. This deployment needs to be accompanied by the large potential improvements in performance that can be achieved as evidenced by field trials in Europe (Boait, Fan, & Stafford, 2011; Delta Energy & Environment, 2011; Stafford & Lilley, 2012) and the UK ['Analysis of Heat Pump Data from the Renewable Heat Premium Payment Scheme' (RHPP project) (Lowe et al., 2017c)]. The focus of this thesis is to investigate the drivers behind underperformance and identify pathways to improved performance in the UK from a socio-technical perspective.
1.1 Rationale for the Study and Research Background

1.1.1 The RHPP project

The Department of Energy and Climate Change (DECC, subsequently known as BEIS) first introduced the RHPP grant scheme for the installation of domestic air-source heat pumps (ASHP) and ground-source heat pumps (GSHP), among other technologies, in 2011. BEIS assigned British Research Establishment (BRE) and Energy Saving Trust (EST) with the installation of metering equipment and the associated data collection in approximately 700 out of the 14,000 HPs installed (the 21 case study sample selection is explained in subsection 3.1.1), with a view to inform renewable heat policy development, including the Microgeneration Certification Scheme (MCS) standards, and supporting advances in the HP industry to improve HP system performance. The specific aim was the collection of a reliable set of data that would enable the efficiency assessment in a segment of the HP population installed under the RHPP scheme and provide insights into their performance.

After the end of the monitoring period (2011 - 2014), data collected on almost 700 sites and the associated metadata were passed on for analysis to RAPID-HPC, a UCL and University of Westminster joint research team, consisting of eight members including the author and led by Prof. Robert Lowe. RAPID-HPC work spanned just over 2 years, (2014 – 2017), including the case study work that was conducted between 2015 and 2017, and produced a series of RHPP project reports, including the following primary output, on which further information can be found in Chapter 4:

- The RHPP Performance Variations Report (Love et al., 2017) - utilised exploratory statistical analysis of the monitored data to investigate variations in the performance of HP in the RHPP trial by means of Seasonal Performance Factor (SPF).

- The RHPP MCS Compliance Report (C. Gleeson et al., 2017) - investigated the compliance level of the monitored HPs with Microgeneration Installation Standard (MIS) 3005.

- The RHPP Case Study Report (Lowe et al., 2017a) - provides an overview of the case study investigation performed on 21 sites monitored as part of the RHPP field trial and provides insights on selected cases within this sample.

- The RHPP Bias Errors Report (Lowe et al., 2017b) - describes categories of systematic error and their effect on the SPF estimation.
The RHPP Final Report (Lowe et al., 2017c) - provides a summary of the work undertaken by RAPID-HPC and the insights gained from the RHPP data analysis performed in all previous reports.

For the greatest part, the RHPP project work focused on the statistical analysis of monitored data to assess HP efficiency and investigate performance variation. During the process, significant monitored data and metadata issues and limitations were identified, which may reduce confidence in the validity of the monitored data collection. The detailed data filtering applied was thought to have increased finding accuracy, however monitored data are not expected to be perfect, and this is more relevant to sample sizes large enough to support statistical analysis (Lowe et al. 2017c). The statistical findings indicated a wide range of performances across the sample, consisting of real efficiency differences and metering errors. However, the statistical analysis provided only limited insights into the reasons behind performance extremes. To overcome the limitations of the statistical analysis and to better understand HP performance and user satisfaction, an in-depth socio-technical study was commissioned. The work that started in November 2015, which ran for approximately 1 year closely examined 21 case studies (including one pilot) from the large RHPP sample. The limited RHPP case study work revealed a level of complexity that could not be understood by physical monitoring alone and highlighted several metadata inconsistencies. It also drew attention to HP resistance heating and heat load, two issues involving socio-technical considerations. However, time and resource restrictions did not allow comprehensive analysis of the full range of the qualitative and quantitative data obtained and thus, the study focused primarily on specific case studies and aspects of the data collected.

1.1.2 The author’s role in the RHPP project

From the start of the RHPP work in 2014, the author of this thesis had a key role of project managing and coordinating both the large-scale analysis of the technical monitoring and the more focused socio-technical case study RHPP work. The work was completed in 2017 with the publishing of the project reports, in the majority of which she acted as a co-author. The author also contributed to a number of unpublished internal project reports (Andew Stone et al., 2016; Andrew Stone, Lowe, Gleeson, Oikonomou, & Summerfield, 2015; Andrew Stone, Summerfield, Gleeson, Oikonomou, & Lowe, 2015; Andrew Stone, Summerfield, Gleeson, Paterson, et al., 2015; Summerfield et al., 2016; Summerfield, Lowe, Stone, & Oikonomou, 2014). The role of the author was even more prominent during the case study work phase by being involved as a key member in the planning of the site investigation and the on-site technical and social data collection during the site visits, where she acted as the main interviewer. The research team involved in the site visits consisted of three members. The author and Dr Colin Gleeson
(University of Westminster), with an architectural and engineering background respectively, dealt with both the social and technical aspects of all site visits. Dr Lai Fong Chiu (UCL) also participated in the first three site visits, *i.e.*, the pilot and the first of the social and owner-occupied case studies, to offer guidance as an experienced social researcher. The remaining sites were covered by the author and Dr. Colin Gleeson, aiming to minimizing the intrusion into case study occupants' personal space.

The author was responsible for the high-level analysis, involving a first exploratory attempt to organise and analyse the wealth of qualitative (see subsection 3.2.2) and quantitative (see subsection 3.2.1) material collected, *i.e.*, by partially transcribing audio recordings from interviews with occupants in the form of summary notes, scanning through and swiftly organising written and photographic evidence, filtering and corroborating with the pre-visit material available (monitored data and metadata, see subsection 3.2.1) and then feeding the themes identified into a master matrix¹ (see subsection 3.3.3) that facilitated further analysis required as part of the RHPP project. The data was methodically organised and fully analysed for the purposes of this PhD study only after the end of the RHPP project by the thesis author.

**1.1.3 Building on the RHPP case study work**

The work undertaken for this thesis focused on the elements the author specifically led on during the RHPP project, *i.e.*, the site investigations, both in terms of planning and implementation. The work involved fully processing the data collected via the qualitative (see subsection 3.2.2) and quantitative (see subsection 3.2.1) RHPP field trial on the 21 case studies to expand the master matrix (see subsection 3.3.3), as required, and feed a systems thinking qualitative model that revealed a complex network of interrelationships influencing HP performance. The quality issues of the monitored data were found to have influenced the case study selection in some occasions (see sections 4.4 and 5.2.3), however this did not undermine the case study research as, overall, the wealth of information deriving from different sources enabled triangulation (see subsection 3.2.3), and the findings were found to be largely saturated. The analysis was performed by the author with inputs from all four supervisors and builds on the analysis undertaken as part of the RHPP project reports.

Even though many of the RHPP field trial HPs were installed as early as 2011 (and monitored between 2012 and 2015) and the technologies are expected to have improved since then, *e.g.*, due the incorporation of technological advancements, the accumulated experience of installers

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¹ The RHPP case study work utilised additional analytical matrices to perform low-level analysis on selected case studies. These were designed by members of the RHPP team other than the author and were not utilised in this PhD.
and the improving MCS procedures, the technologies involved are still relevant today as their core technology and operational principle remain the same.

1.2 Research Questions, Aims and Objectives

Given the important role of HPs in a Net Zero future and the potential to improve their performance, this research aimed to investigate their underperformance on the hypothesis that it derives from a network of complex socio-technical system interactions between manufacturer/installer assumptions, building installation, system integration and occupant behaviour. An additional hypothesis is that field tests of complex heating systems, such as HPs, are currently not fit for purpose.

This study was undertaken in the specific context of domestic HPs installed under the RHPP scheme and intended to gain a deeper perspective on performance influencers and achieve new insights into the requirements for well-performing HPs in the UK. The thesis aims to answer the following two research questions:

- Which factors drive the discrepancy between the performance of the HPs ‘as predicted’ and in the field?
- In what way can the field tests for HP installations be improved?

By characterising system complexity and reflecting on the technical and social limitations, the specific objectives of the study were to:

- Identify key variables influencing the performance of HPs and discuss the implications on the future uptake of HPs in the UK.
- Examine the reliability and suitability of existing rated efficiency indicators and field measurement practices.
- Examine the role of key actors (e.g., manufacturers, installers, and users) and offer best practice considerations.
- Prioritise the emerging recommendations and propose a future course of action.

Through this process, the current study envisaged to making an original knowledge contribution that will address the emerging barriers to high-performing domestic HP stock in the UK.

1.3 The Delimitations of the Study

The delimitations of the study refer to the boundaries arising from the "limitations in the scope of the study and by the conscious exclusionary and inclusionary decisions made during the
development of the study plan” (Simon & Goes, 2013). This study investigated the socio-technical drivers influencing the performance of domestic ASHPs and GSHPs in the UK, based on a sample of 21 case studies whose HP installation was deployed as part of the RHPP scheme. The monitoring required as part of the RHPP scheme enabled some initial insights into the performance of HPs and provided an excellent opportunity for the purposeful selection (see subsection 3.1.1) of case studies for in-depth investigation. However, drawing the case studies from the monitored RHPP population carries some inherent limitations as it inevitably restricts the type of HP installation and services offered to those allowed under the scheme. This concerns electric-only HPs in receipt of the RHPP fund against the cost of their installation and, generally, in combination with the Renewable Heat Incentive (RHI) fund. The services provided by the RHPP HP concern water-based SH and DHW but not cooling. Thus, the cooling potential of HP was not considered as part of this study and neither was any other type of HP other than standalone electric, e.g., gas-fired, hybrid or communal systems utilising multiple HPs. In addition, this study examined HP performance from a socio-technical perspective and was not concerned with exergy analysis and the investigation of technical improvements in stand-alone components. Obtaining detailed specifications of the system components was beyond the scope of this study, which examined HP performance from a more holistic perspective, taking into consideration the wider environment a HP is installed within.

1.4 Research Structure and Chapter Layout

The research is structured into three main parts: background, core, and synthesis. These are connected to each other as illustrated in Figure 1-1, and a brief overview of each chapter is provided below:

Part 1 - Background

- Chapter 1: Introduction

Outlines the rationale for the study, discusses the relevant research background and sets the main research questions, aims and objectives, alongside any scope, methodological and design limitations. It also provides an overview of the thesis structure.

- Chapter 2: The Study Context - Heat Pump Technology and Performance Complexities

A literature review of the relevant background positions the study in context of the current knowledge, theory, and practice. This includes a discussion of the technological, operational and performance principles and current testing and installation practices. National and
international experience with HPs is discussed, focusing on performance and the identified areas for improvement.

Part 2 - Core

- Chapter 3: Study Methodology

A definition is presented of the framework and methods utilised to test the research hypothesis, based primarily on a case study approach and a mixed-methods design. The data management and analytical process is described and an overview of the basic concepts and principles of systems thinking is included, alongside the rationale for its use as an integrating tool.

- Chapter 4: RHPP Heat Pump Field Trial Project

An overview is provided of the main findings of the RHPP project, based on the project’s published reports, to which the author of this thesis acted as a co-author. These discuss performance variation, cost and carbon savings, compliance with the Microgeneration Certification Scheme (MCS) and present the project-stage case study analysis and output.

- Chapter 5: Results of High-level Analysis – The Case Study Sample and Variables

An overview of the case study characteristics, deriving from qualitative and quantitative collection methods after triangulation, is presented. The common themes described here formed the building blocks of the socio-technical analysis.

- Chapter 6: Socio-technical Factors Affecting Heat Pump Performance in the Case Study Sample

The chapter describes the nature and interrelations of the systems thinking-driven socio-technical analysis. Each step is accompanied by sequential causal loop diagrams (CLD), linked to a final aggregate CLD.

Part 3 - Synthesis

- Chapter 7: Discussion

A critical analysis is presented of the findings reported in the core chapters, in the light of the background chapters of this thesis. The study’s contribution in theory development, lessons learnt, future implications and consequently recommendations arising from this research are also discussed.
Chapter 8: Conclusions and Recommendations

This chapter reflects on the significance of the main findings, as they arise from the discussion section and respond to the study aims. It discusses the research’s original contribution to knowledge and highlights implications for stakeholders and their practical applicability through dissemination activities. It also identified knowledge gaps and provides recommendations for future work.

Figure 1-1: Thesis structure and information flow.
Chapter 2: The Study Context - Heat Pump Technology and Performance Complexities

The HP is a complex but promising technology that can significantly contribute towards the UK’s future decarbonisation goals, providing it performs well. It is the only single technology that can massively reduce a home’s total energy use because HP efficiency can be four times better than current practice (e.g., comparing to a 90% efficiency rate for gas boilers) and it impacts the two major forms of energy use in homes, i.e., SH and DHW. This chapter lays out the context required to understand HP operation and performance assessment. It reviews current installation practices and requirements, as well as the parameters currently seen as influencing performance, based on national and international evidence. This chapter is structured into four parts: Section 2.1 - Heat Pump Technology, Operational Principles and Performance Metrics, section 2.2 - Performance Prediction and Installation, section 2.3 - National and International Experience with Heat Pumps and section 2.4 - Summary of Evidence from Literature and Knowledge gaps

2.1 Heat Pump Technology, Operational Principles and Performance Metrics

HPs transfer heat from one environment (source) to another (sink) rather than generating heat directly, thus delivering considerably more heat than the energy required to drive the heat from source to sink. The HP working principle, illustrated in Figure 2-1, relies on the pressure-temperature relationship of the refrigerant, which is pumped through an evaporation-condensation cycle. The main HP components are: (a) the compressor, lifting the pressure of the refrigerant and as a result its temperature; (b) the condenser, an internal heat exchanger releasing the heat to internal air or the water circulation of the heat dissipation system; (c) the expansion valve, releasing the pressure of the refrigerant and thus lowering its temperature; and (d) the evaporator, an external heat exchanger absorbing heat from the external environment (Staffell, Brett, Brandon, & Hawkes, 2012). In winter, the compressor receives cool, low-pressure refrigerant vapour, which is then pumped onto the high-pressure side of the system. The hot, high-pressure gas passes through the condenser, where heat is removed and released to the indoor environment causing the refrigerant to condense into liquid, which is then forced into the expansion valve. This valve partially restricts the flow of the refrigerant creating a decrease in pressure and thus initiating the evaporation process of the refrigerant, which is able to absorb heat from the heat source. It then flows back to the compressor and the process is
repeated. This process can be fully reversed in the summer, with the HP extracting indoor heat and dissipating it outdoors, just like refrigerators do. (EnerGuide, 2004; Roy, Caird, & Potter, 2010; Staffell et al., 2012).

2.1.1 Thermodynamic principles and applications

Both HPs and refrigerators are essentially heat engines running backwards, i.e., transferring heat from a cold source (Q_{source}) to a hot sink (Q_{sink}). According to the first law of thermodynamics, concerning energy conservation, energy cannot be destroyed or created but it can take different forms without any change in the total amount of energy (Dincer & Cengel, 2001). In the case of HPs, the transfer of heat requires work input (W), which is also converted to heat and thus the operation of the HP is expressed by equation [1].

\[ Q_{sink} = Q_{source} + W \]  \[1\]

The more energy a HP delivers to the heat sink (Q_{sink}) in relation to the work required for the transfer (W), the more efficient the HP is. This is described by the HP’s coefficient of performance (COP) by equation [2].

\[ COP = \frac{Q_{sink}}{W} \]  \[2\]

The maximum theoretical performance of a HP depends on the temperature difference between the heat source and the heat sink as described by equation 3 – deriving the COP of the Carnot cycle in degrees Kelvin (Nordman et al., 2012). Thus, the lower the temperature of the heat sink, the higher the efficiency of the HP.
\[ \text{COP} = \frac{T_{\text{sink}}}{T_{\text{source}} - T_{\text{sink}}} \quad [3] \]

\( T_{\text{sink}} \) = average temperature supplied at the heat sink during HP operation (K)

\( T_{\text{source}} \) = average temperature supplied at the heat source during HP operation (K)

The second law of thermodynamics states that energy has both a qualitative and quantitative aspect and that a quality degradation occurs as a result of energy processes, such as thermal transfer from a higher- to a lower-temperature body. The concepts of exergy and entropy represent the quantification of the energy’s quality or its work potential. Unlike energy, exergy is destroyed (proportionally to the generation entropy) every time an irreversible process takes place. The exergy destroyed or the entropy generated is responsible for the gap between the theoretical performance of a HP and its real cycle performance (Byrne & Ghoubali, 2019; Dincer & Cengel, 2001). Exergy analysis can be a useful tool for the detection of system losses and the improvement of the HP cycle components. Morosuk and Tsatsaronis (2009) for example, distinguished between unavoidable and avoidable exergy destruction and developed a method for the identification of components with the highest potential for efficiency improvement.

2.1.2 Heat pump types and applications

HPs can extract heat from various sources, with the outdoor air and ground (geothermal) being the most common in domestic applications in the UK and Europe, albeit the latter to a much lesser extent (Euroobserver, 2020). Other heat source types include water bodies and exhaust heat. GSHPs that benefit from more stable underground temperatures, converging towards the annual average air temperature with increasing depth (Kalogerou & Florides, 2004), can source heat from the ground using open or closed loop configurations (Staffell et al., 2012). A loop is considered open when water is extracted, circulated through the HP’s evaporator, and then reinserted into water bodies, such as rivers and groundwater resources. Closed loops involve direct (expansion) or indirect circulation of a heat-absorbing medium through buried pipes, in a horizontal (straight or slinky) or vertical (boreholes) configuration. Within the ground loop of a HP with indirect circulation, a mixture of cold water and antifreeze is pumped to extract heat from the ground and is then taken to the HP’s heat exchanger. Direct circulation requires more refrigerant but no circulating pump or heat exchanger. This option is subject to strict environmental regulations and thus rarely seen in the UK (HPA, 2021c; Staffell et al., 2012).

The heat sink of any HP type can be air or water, with the latter being the most commonly used in domestic applications in the UK. The air- and ground-to-water HPs that this study is concerned with transform low-temperature heat from the external air or ground to high-
temperature heat, delivered to a water medium. ASHPs can usually operate at external temperatures as low as \(-15^\circ C\) or even \(-20^\circ C\) if an incorporated resistance heater is used to top up the heat output. However, the evaporator of an ASHP is likely to freeze at low external temperatures and in damp climates, a process highly dependent on usage patterns, which is more likely to be avoided if the outdoor unit is sheltered or exposed to the sun (Staffell et al., 2012). Should freezing occur, defrost cycles that temporarily supply heat to the evaporator usually act by reversing the operation of the normal HP cycle (Klein, 2012).

Both ASHPs and GSHPs come in two main types: indoor or outdoor single-packaged (monobloc) and split-system HP. Monoblocs, where the entire circuit is installed outdoors, require insulated water pipes running between the HP and the building. Single-packaged HPs installed indoors usually require a ducted air inlet and/or outlet if the source is air and refrigerant pipework running between the HP unit and the collector if the source is the ground. Split systems have both an indoor (condenser) and an outdoor unit (evaporator, expansion valve, compressor), connected with refrigerant pipework (HPA, 2021c; Roy et al., 2010).

HPs can provide SH and/or DHW, with SH usually being their main application. There are several categories of water heat emitters available, such as underfloor pipework, radiators, and fan coils, all of which can be combined in a single installation. Underfloor heating (UFH) can operate at the lowest temperatures, \(i.e.,\) 30-45 °C, fan coils at 35-55 °C, low-temperature radiators at 45-60 °C and high-temperature radiators at 60-75 °C. Air room heaters can operate at temperatures even lower than those required by UFH, \(i.e.,\) 25-35 °C (Staffell et al., 2012). DHW is usually heated at around 50-60 °C but can be as high as 65 °C, depending on the HP model. No direct electric top-up is needed for a HP able to take DHW up to temperatures of 60-65 °C. Even if pasteurisation temperatures cannot be reached by the HP alone, the HP should still be set to provide the bulk of water heating. Reversible HPs can also provide space cooling in the summer by passing cooled water through fan coils or underfloor heating pipes, in which case flow temperature is limited to approximately 18 °C to avoid the risk of condensation (EnerGuide, 2004; HPA, 2021c).

Except for electrically driven HPs, the variations of gas-driven and solar-assisted HPs are thought to be promising for some applications (Staffell et al., 2012). For example, internal combustion gas engine HPs utilise the benefits of combined heat and power, allowing them to work on full power even at extremely low external temperatures of less than \(-20^\circ C\). Thus, they may be appealing in countries with colder climates and lower gas than electricity tariffs. The resulting carbon emissions may also be lower where grid electricity derives predominantly from coal, however, this is not the case in the UK any more (Ofgem, 2021a). The most common application of solar-assisted HPs involves solar thermal panels heating up a store jointly with the
HP (parallel system). Alternative configurations concern thermal panels acting as a HP heat source (series) or where summertime solar heat is used to restore ground heat so that it can be used more efficiently as a heat source in the following heating season (hybrid system). Solar-assisted HPs have the potential to double the output and efficiency of a typical HP, especially during the coldest part of the year, providing an optimised installation (Staffell et al., 2012).

The main benefits and considerations around the installation of ASHPs and GSHPs are presented in Table 2-1. Both present longer lifetimes than traditional boiler systems and require minimal maintenance, e.g., once in 3-5 years, mainly due to performance loss relating to refrigerant leakage. The lifecycle of the compressor is around 15-20 years and ground collectors are expected to last approximately 50 years (Staffell et al., 2012). However, the MCS Best Practice Guide (MCS & RECC, 2018) acknowledges the existence of some ambiguity around maintenance guidance and differentiates between the minimal maintenance requirements of a sealed HP unit and the periodic (typically annual) service inspection needs of the system it is attached to.
Table 2-1: Benefits and considerations for domestic air-to-water (ASHP) and ground-to-water (GSHP) heat pumps (Euroobserver, 2020; Fawcett, 2011; HPA, 2021c; Roy et al., 2010; Staffell et al., 2012).

<table>
<thead>
<tr>
<th></th>
<th>ASHP</th>
<th>GSHP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital cost</strong></td>
<td>Relatively low, more expensive than the traditional heating systems they usually replace</td>
<td>Relatively high, more expensive than the traditional heating systems they usually replace</td>
</tr>
<tr>
<td><strong>Running cost</strong></td>
<td>Low, if installed and operated appropriately</td>
<td>Low, if installed and operated appropriately</td>
</tr>
<tr>
<td><strong>Installation</strong></td>
<td>Easy; possible adverse impact on building’s appearance</td>
<td>Disruptive installation; unobstructive once installed</td>
</tr>
<tr>
<td><strong>Heat source</strong></td>
<td>HP operational at external temperatures as low as -15 °C; a backup resistance heater steps in for temperatures lower than that</td>
<td>Land area (horizontal loop ground collectors); access for drilling equipment (vertical closed-loop ground collectors); water quality and minimum flow (vertical open-loop ground collector)</td>
</tr>
<tr>
<td><strong>Operative conditions</strong></td>
<td>A short interruption of operation may be required in cold weather to allow defrosting of the evaporator</td>
<td>Less prone to efficiency fluctuations in cold weather due to thermal inertia of the ground</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>High; influenced by external temperature fluctuations and defrost cycles</td>
<td>High</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Noise disturbance</strong></td>
<td>Possible</td>
<td>Relatively low; less noisy than ASHP and boilers</td>
</tr>
<tr>
<td><strong>Max output for single phase electricity</strong></td>
<td>12 kW</td>
<td>12 kW</td>
</tr>
<tr>
<td><strong>Supplementary heating</strong></td>
<td>Use of resistance heaters should be carefully controlled to avoid efficiency reduction, e.g., through appropriate sizing</td>
<td>Use of resistance heaters use should be carefully controlled to avoid efficiency reduction, e.g., through appropriate sizing</td>
</tr>
<tr>
<td><strong>Heat source maintenance</strong></td>
<td>Possible air intake fouling; possible freezing of outdoor unit</td>
<td>Possible thermal depletion of the ground, gradually over decades of use; long life of ground collector (50+ years);</td>
</tr>
<tr>
<td><strong>Durability and system maintenance</strong></td>
<td>Long lifetime, high reliability, low maintenance</td>
<td>Long lifetime, high reliability, low maintenance</td>
</tr>
</tbody>
</table>

2.1.3 **Advanced technological features of heat pumps**

HP performance has improved and is bound to improve further with the inevitable development of design and controls, some of which have already been widely adopted into the HP market. One such example is the gradual transition from fixed-speed to fully modulating (inverter) compressors that has led to significant efficiency improvements at part load conditions, albeit at
a higher initial cost, by enabling the system to run at different speeds and thus reducing cycling and power consumption as needed, as long as the system is not oversized (MCS & RECC, 2018). Inverter compressors can typically adjust output between 30% and 100% of the HP’s maximum capacity (GLA, 2020). Similarly, the market change from single- to variable-speed circulation pumps with motor redesign and capping of their energy consumption, following the introduction of Ecodesign requirements (European Commision, 2009) and the subsequent further tightening of the regulations, is expected to drive a significant decrease in energy consumption.

Other innovations concern advanced cycle designs incorporating multiple compression stages (known as compound or cascade systems), improved cycle components, such as new types of compressors or refrigerants, and novel hybrid HP systems and applications that perform more efficiently (Mota-Babiloni et al., 2018). As an example, a CO₂ refrigerant HP can provide sink temperatures as high as those provided by traditional heating systems, i.e., above 90 °C, and can be highly efficient when utilising waste heat (Arpagaus, Bless, Uhlmann, Schiffmann, & Bertsch, 2018). Among refrigerants with a low-global warming potential, as dictated by the Montreal and Kyoto Protocols (UNEP, 1987; UNFCCC, 1997), CO₂ refrigerant is particularly attractive for various reasons, including its practical applications, zero ozone depletion potential and easy availability (Dai, Dang, Li, Tian, & Ma, 2015).

The incorporation of smart controls into HP systems is another promising technology. It offers to hide the complexities relating to HP controls from the user and assist demand-side management. Optimisation controllers that can learn from the building’s behaviour in response to heating and are capable of adjusting heating times according to indoor and outdoor temperatures to achieve optimum comfort and efficiency are already being incorporated by many HP manufacturers (MCS & RECC, 2018). Smart controllers that interact with signals from grid suppliers are thought to be a particularly useful at minimising future running costs with time-of-use tariffs. Field trials testing advanced smart controls to achieve demand-side management are encouraging (Parrish, Hielscher, & Foxon, 2021; Shah, Wilson, Huang, & Hewitt, 2018; Sweetnam, Fell, Oikonomou, & Oreszczyn, 2018).

Another option for load shifting would be utilising the technology of smart hybrid HPs, which promise to offer energy savings through smart controls and enhanced user learning. Smart hybrid is a special category of HPs that can automatically switch between using electricity and gas by responding to signals from the user and the electricity system (demand response). As well as the potential reduction in running costs and putting less stress on the electricity grid, smart hybrid HPs come with benefits in terms of capital cost, since smaller HP capacities are needed and they are also thought to work well with existing heat distribution systems and in
moderately insulated homes (Parrish et al., 2021). Hybrid HPs, which can burn methane hydrogen or biofuels, are seen by CCC as an attractive near-term solution that comes with carbon savings that can be easily adapted for operation in a fully electrified or in a hydrogen gas grid (CCC, 2018, 2020b). The expected increased familiarity of the public with HP technology is also seen as an important element for the wider future uptake of HPs.

2.1.4 Practical efficiency measurement methods

There are several metrics for HP performance, all offering a representation of the heat output to energy input ratio, differing in terms of the time period or the energy-consuming components considered in their calculation (BSI, 2018a, 2018c; HPA, 2021c). The simplest measure is the COP, which only takes into consideration the energy consumed by the compressor and fans. It is a steady-state metric and is typically employed over short operational periods for the measurement of HP performance in testing chambers. The Coefficient of System Performance (COSP) also refers to the proportion of heat output to energy input but includes the energy input from internal control circuits and pump power, in addition to the compressor and fans. According to the HPA (HPA, 2021c), this has become the standard COP measure in practice. Since the temperature of the heat source varies throughout the year, COP and COSP do not provide a good representation of a performing system under real conditions. The Seasonal Coefficient of Performance (SCOP) refers to the COP measured over the heating season to take into consideration the temperature variation of the heat source.

Unlike SCOP that is utilised under testing and theoretical conditions, the SPF is project-specific, i.e., measuring the efficiency of a specific installation (MCS & RECC, 2018). It also takes into consideration the temperature variation of the heat source but there does not seem to be a strict rule in terms of the energy-consuming components included. Therefore, there may be significant discrepancy between predictive SPF measurements based on the definition of COP or COSP and those deriving from field studies, which may also include the energy consumed by bespoke components, such as separate hot water tanks, supplementary resistance heaters and additional pumps and fans, that cannot be predicted beforehand (Klein, 2012). While SPF may include DHW, SCOP is typically an indicator of SH efficiency only (MCS & RECC, 2018). The equivalent indicators to COP and COSP for cooling are the Energy Efficiency Ratio (EER) and the Seasonal Efficiency Ratio (SEER) respectively (EnerGuide, 2004).

The need for unified performance reporting through the application of specific boundaries that provide a more reliable comparison of output across field trials has been highlighted by (C. P. Gleeson & Lowe, 2013). The SEPemo-Build (European Project on Seasonal Performance Factor and Monitoring for HP system in the Building Sector) set boundaries H1-H4 (Riviere,
Coevoet, Tran, Zottl, & Nordman, 2011), shown in Figure 2-2, and their significance in SPF calculation is highlighted by Miara et al. (2011) and Gleeson and Lowe (2013). Boundary levels H1, H2, H3 and H4 take into consideration the energy consumed by the HP unit, the heat drawing equipment, the incorporated resistance heater and the system circulators or pumps, respectively. The SEPEMO-BUILD boundaries were also used in the second phase of the EST HP field trial (Dunbabin, Charlick, & Green, 2013). A fifth boundary named ‘system efficiency’ was introduced for comparison purposes with the first phase of the EST field trial (Dunbabin & Wilkins, 2012), i.e., to allow the DHW cylinder heat losses to be accounted for. This was named boundary H5 for the first time by Gleeson and Lowe (2013). The 2009/28/EC Renewable Energy Directive (European Commision, 2013) and its recast (European Commission, 2018) also adopted the SEPEMO-BUILD methodology. Boundary level H2 was judged to be suitable for HP-related renewable-energy calculation purposes. It is also best suited for comparison with previous heating systems, such as condensing gas boilers (C. P. Gleeson & Lowe, 2013).

Figure 2-2: The four SEPEMO-BUILD system boundaries as seen in Riviere et al., 2011, with the addition of boundary H5, including domestic hot water cylinder heat losses (Source: Lowe et al., 2017c).
2.2 Performance Prediction and Installation Requirements

2.2.1 Heat pump testing and certification

European standards

The test conditions for the rating and performance of HPs throughout Europe are specified by the standards EN 14511 (BSI, 2018b) and EN 14825 (BSI, 2018c). However, this does not apply to HPs for DHW even though certain definitions can still be applied. Both packaged and split unit systems are considered but not those units consisting of several parts, i.e., those not designed and supplied as a complete package. A manufacturer’s design COP is steady-state and determined in a testing facility based on the EN14511 standardised operational conditions and at the manufacturer’s maximum output. Depending on the HP category, e.g., air-to-water or ground-to-water, the standard specifies a range of testing boundary conditions, taking into consideration the inlet temperature of air and brine, and the outlet temperature of the water flow. Taking the standard rating conditions for ASHP and GSHP as an example, manufacturers refer to A7W35 and B0W35, respectively, where the temperature of air is at 7 °C, brine is at 0 °C and water flow at 35 °C. The standard corrects COP for the effect of defrosting, as well as the presence of fans and pumps. Up to three defrost cycles within a 3-hour testing period are taken into consideration and formulas are provided for an estimated fan and pump power, which is then added to or subtracted from the total energy input depending on the presence or not of an integrated circulation pump and/or fan. The conditions for the determination of SCOP and part load are described in EN 14825 (BSI, 2018c). Since SCOP depends on the local climate, the standard provides a selection of three climate zones: average, colder, and warmer, whose bin temperature distribution depends on length of the heating season selected. The calculation of SCOP is particularly important for ASHPs, whose efficiency is more sensitive to outdoor air temperature (Klein, 2012). The requirement for manufacturers is for a single COP value to be released per model, however, many voluntarily provide additional COP or SCOP values (required by MCS and other product certification schemes), measured at different inlet and/or outlet temperatures (Haglund Stignor & Walfridson, 2019; Staffell et al., 2012).

In terms of DHW, standard EN 16147 (BSI, 2017) sets the requirements for testing the performance of DHW units of HPs, which are based on instantaneous COP measurements. While source testing temperatures are the same as those defined by EN 14511 for SH, DHW output takes the form of a range of DHW load profiles, measured in kW/day. The COP of DHW is determined by the chosen reference profile and takes into consideration the DHW cylinder heat losses, as well as the effect of pumps and fans. Should the HP not be able to achieve the set peak temperature, which is often the case for temperatures of 55 °C or higher, then the
incorporated resistant heater is assumed to kick in. Other HP-related standards include EN 15879 and EN 12102, specifying the testing conditions for direct evaporation HP and sound power level.

According to Klein (2012), the testing conditions laid out in the standards, which necessitate specialised laboratories, may not always be followed diligently by manufacturers. Another source of lack of confidence in the declared COP is that tests are not always carried out by independent testing centres that offer rating certification, such as the MCS or the European Heat Pump Association (EHPA) Quality Label (EHPA, 2021b) described in the following paragraphs. The test laboratories employed should be United Kingdom Accreditation Service accredited.

Product certification

Throughout Europe, there are several certification schemes for HP, including the EHPA Quality Label, the Eco-label, and the Heat Pump KEYMARK. These schemes are voluntary and not linked to financial incentives. In the UK, MCS-certified HPs, in line with the requirements of the European Union Directive 2009/125/EC, are a prerequisite for governmental incentives, such as the RHI. In addition, top performing HPs in the UK market can be identified through the government’s Energy Technology List. Further information on these product certification schemes is provided below. Detailed information on the MCS and RHI can be found in subsection 2.2.2.

The EHPA Quality Label (EHPA, 2021b) is available in 12 countries across Europe, including the UK. It concerns standardised, electrically driven HPs with a maximum capacity of up to 400 kW that provide SH, with or without DHW provision, sourced from the air, ground or water. The tests are performed by independent testing centres, namely Building Services Research and Information Association for the UK. Among other criteria, the minimum SH SCOP values required for air-to-water and ground-to-water HP are 3.5 and 4.1, respectively. There is no minimum COP requirement for DHW-providing HPs but there is a minimum DHW reference temperature of 52 °C. A local servicing network, including a 24-h customer service reaction time to consumer complaints, and a 2-year full warranty are also required.

The European Union Ecodesign Directive 2009/125/EC (European Commission, 2009) sets the framework of requirements for Energy-related Products (ErP), providing minimum performance criteria and a standardised methodology for the comparison of efficiencies between HPs. Under this Directive, all HPs need a minimum SCOP of 2.5 at boundary level H3 (MCS & RECC, 2018; Ofgem, 2016). This eligibility criterion is also shared with the MCS for certification purposes. The associated Energy Labelling Directive 2010/30/EC (European Commission, 2010)
introduced mandatory product labels, displaying key environmental information about the HP, including efficiency. The MCS online Product Directory provides a list of all ErP compliant HP (MCS, 2020).

Ecolabel is the European Union’s official certification scheme, marking Green Products, i.e., focusing on the life-cycle environmental impact of a wide range of products, including HPs (European Commission, 2021). The criteria used are evaluated by independent and accredited third parties. HPs up 100 kW are covered but not those utilised for DHW only. The KEYMARK certificate (CEN, 2018) is another European Union scheme based on independent, third party testing. It utilises the Ecodesign efficiency requirements and applies to all HP types, including combination and DHW-only HPs. While Great Britain no longer participates in the EU Eco-label scheme post Brexit, the KEYMARK certificate is still recognised by the MCS.

The BEIS Energy Technology List, run by the Carbon Trust and ICF, is a list of marketed products, including HPs, that make it to the top 25% in terms of energy performance (BEIS, 2019a). The publicly available list is based on independent assessments and aims to promote equipment with higher environmental performances. The standards are regularly reviewed and raised to match market changes and performance improvements and to remove any equipment that cease to meet the requirements for inclusion (BEIS, 2019a).

### 2.2.2 Installation process and quality assurance

#### Selection and sizing

Prospective HP owners need to do their own background research to identify their preferred type of HP as well as a suitable installer. MCS-accredited installers can be identified through the scheme’s online platform. The selection of a HP based on specific characteristics requires knowledge of the building’s heat loss, the physical size of the HP and the location for its prospective installation, the HP’s efficiency at a specific operating boundary (as per EN 14511), and the operating temperature range of the heat source and the heat distribution system, including any water storage arrangements (HPA, 2021c). According to an MCS-certified installer (Leedman, 2020), the following steps are suggested for the correct sizing of a HP, with the heat-loss calculations being placed at the heart of the process:

a. ensuring the building fabric is well-insulated and performing a heat loss calculation,

b. establishing the location-specific peak heat load of the building on the coldest day of the year,

c. sizing the heat emitters according to the heat losses of each room and the design flow temperature,
d. selecting a HP based on the comparison between the HP’s heat loss capability and the building’s heat loss and by ensuring the former exceeds the latter.

There is currently no generally agreed HP sizing method for the provision of adequate DHW, which is based on specific DHW load profiles. Control strategies also vary, with many HPs set to switch between SH and DHW provision every 30 minutes under concurrent demand and others providing DHW until the demand has been met or a set time has elapsed. However, DHW heat load is becoming more prominent with increasing building insulation levels. In any case, the DHW patterns should always be discussed with users (MCS & RECC, 2018).

In terms of HP manufacturers, there is a wide range to choose from, some of which are MCS-certified, which is a requirement for those signing up with incentive schemes, such as the RHI. The rules relating to quality assurance schemes, all HP SH and DHW installations are also subject to local building regulations and standards (e.g., Building Regulations and Domestic Building Services). Permitted Development Rights, for example, dictate that outside ASHP units should be placed at least 1 metre away from the property boundary, without having any impact on external appearance. The quality assurance schemes and financial incentives available currently in the UK are discussed in the following paragraphs.

**Microgeneration certification and requirements**

The MCS is the UK's national scheme for the quality assurance of microgeneration technologies, including domestic HPs (MCS, 2020). It provides the standards for products and installers and is a prerequisite for certain governmental financial incentives. HPs of a maximum heat output of 45 kW that source heat from the air, ground or water and can heat and/or heat and cool are included in the scheme. As part of the MCS, there are several standards (MIS 3005, MCS 021 etc.), guides and tools covering different aspects of the HP installation process, as well as installer certification. Further details on these can be found in Appendix A.

MIS 3005 v5.0 (MCS, 2017) provides specific guidance on HP sizing, including tables listing the minimum required internal temperatures per room (18-22 °C) and assuming regional standardised external temperatures to be used in the heat loss calculations. MIS 3005 was made compulsory starting March 2012 (v3.1a) but several updates, some of them incorporating significant changes, have been released between then and 2017, when its latest version (v5.0) was released. For example, an approved heat-loss calculator was introduced by MCS at the end of 2015 and its latest version (v1.10), released in 2021, incorporates a room temperature selector to correct for a previous critical error in the room-by-room calculation of upwards heat flow between floors. Another important addition in late March 2016 was the requirement for HP
installers to calculate the SPF using the SCOP values provided by the MCS Product Directory (MCS, 2019b).

Alongside the release of the standard method for heat loss calculation, MIS 3005 v3.0 in 2011 released emitter specific guidance, including the Heat Emitter Guide (HEG) (MCS 021), the latest version of which was released in 2019 (MCS, 2019a). The concept of Temperature Star Rating, a function of the flow temperature and the radiator oversize factor, provides an indication of the proposed system’s efficiency. In order to improve the Temperature Star Rating, the Heat Emitter Guide (MCS 021, v2.2) (MCS, 2019a) suggests the improvement of building fabric and ventilation heat losses and/or the heat emitter upgrade to achieve higher outputs. MCS advises against high flow temperatures unless there is no alternative, in which case a max of 65 °C is allowed. From its guidance on the HPs and radiator sizing, it is clear that building fabric and ventilation heat loss calculation are key for successful application.

Energy Performance Certificates (EPC) play a significant role in the MCS compliance process as the obligatory calculation of predicted system performance requires an EPC issued within the previous 2 years and any recommendations on loft or cavity insulation must be implemented before the HP is installed (MCS & RECC, 2018). A new EPC is required following any building thermal upgrade interventions. At the end of the process, the client is informed of the maintenance requirements/services and an MCS Compliance Certificate is issued. This is a checklist including summary information about the HP installation and confirming its compliance with the MCS standards. The contractor is also responsible for informing the client of the flow temperature effect on the HP’s performance, energy consumption and running cost, as well as any income options available from incentives. Guidance on the RHI metering requirements is also available through the MCS (Ofgem, 2018c).

Financial incentives available

Currently, there are two main governmental schemes promoting the use of domestic renewable heat with a view to cutting the UK’s carbon emissions and meeting renewable energy targets: the Green Homes Grant: Local Authority Delivery (LAD) and the Domestic RHI, which is expected to be replaced by the Clean Heat Grant in 2022. Further information on these is provided below and in Table 2-2. A brief overview of the RHI-linked Assignment of Rights (AoR) and Kensa’s Shared Group Array Funding is provided in Appendix A.

The Domestic RHI (Ofgem, 2021b) is offered to all homes with electric SH with or without DHW air-to-water or ground-to-water HP (among other heating technologies), no matter whether on- or off- gas grid. Hybrids and reversible HPs are allowed but payments are based on the renewable proportion of heat produced, i.e., the electricity input is subtracted from the heat.
delivered, without taking into account the energy associated with the fossil fuel heating source in the case of hybrids. Even though the scheme has run since 2014, electricity metering (Ofgem, 2018a) distinguishing between the energy consumed by the HP and incorporated resistance heaters only became mandatory from 22 May 2018 onwards. MCS certification (explained in detail in the “Microgeneration certification and requirements” paragraph of this section) is required for all HPs funded under the RHI scheme. Additional requirements include: the RHI applicant must be the property owner or occupant; the HP should be installed after the property was first occupied. Newbuilds can only be funded if they are ‘custom-built’, owned by individuals and occupied only after the HP is installed. The RHI is linked to the property, thus if it is sold, the previous owner will lose the payments. (Ofgem, 2018b).

While the Green Homes Grant voucher scheme (see Table 2-3) has now been scrapped (BEIS, 2020c), the Green Homes Grant: LAD is available until 2021. LAD is being delivered in three-phases, with the third phase ending in December 2021. It concerns the installation of energy efficient improvements since 2020, including ASHPs, GSHP and hybrid HPs utilised solely for domestic SH/DHW. The funding targets low-income and low thermal efficiency houses, subsidising a maximum of £10,000 for low-income owner occupiers and up to £5,000 for social or private landlords. The Green Homes Grant cannot be combined with other government schemes, such as the RHI (BEIS, 2020d).

It has been proposed that the Clean Heat Grant scheme (BEIS, 2021c) will provide funding for the installation of HP and other low-carbon heating technologies from April 2022. The final requirements and details of the scheme have not yet been disclosed as the imminent publication of the ‘Heat and Buildings Strategy’ has been delayed (UK Parliament Committees, 2021) but it is thought that it will build on the existing RHI requirements, prioritising the importance of a well-insulated building in improving the efficiency of low carbon heating systems.
Table 2-2: Currently active and upcoming governmental financial incentives for the installation of domestic heat pumps in the UK.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Description</th>
<th>Prerequisites</th>
<th>Status and applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic Renewable Heat Incentive (RHI), including the Assignment of Rights (AoR) option</td>
<td>Government grant (developed by BEIS, run by Ofgem) providing quarterly payments for 7 years (RHI) and option for funding towards the upfront cost (AoR)</td>
<td>MCS/EPC certificate, electricity metering arrangements, minimum SPF of 2.5</td>
<td>Active since 2014 (RHI) and 2018 (AoR), applies to Great Britain</td>
</tr>
<tr>
<td>Green Homes Grant – Local Authority Delivery (LAD)</td>
<td>Government grant for low-income and low EPC rated homes</td>
<td>Household income ≤£30,000, EPC rating prior to improvement: E, F or G</td>
<td>Active since 2020, applies to England</td>
</tr>
<tr>
<td>Clean Heat Grant</td>
<td>Government grant based on voucher application process</td>
<td>Valid EPC, minimum insulation requirement (proposed)</td>
<td>Upcoming in 2022, applicable to Great Britain</td>
</tr>
</tbody>
</table>

2.2.3 Performance gap

There are several sources of uncertainty leading to discrepancy between the performance measured in laboratories, predicted by design calculations, and actual in-situ performance. Thus, there tends to be a mismatch between real-life performance and the extremely high COPs that are often advertised by manufacturers. COPs are based on certain testing conditions, involving a limited number of components (i.e., those included in boundary level H2) and not taking into consideration the variable source and sink temperature conditions. While the SCOP calculation utilises a methodology which takes into consideration seasonal variations, it is also calculated at boundary level H2 and thus does not include the total energy consumed by all system components, many of which are uniquely selected to match the specific design of each installation (C. P. Gleeson & Lowe, 2013). Thus, the interpretation of testing results is a complex task that, unless an expert themselves, prospective users will need specialised advice to calculate the expected system’s efficiency under their specific circumstances, including environmental, technical and building characteristics (Carroll et al., 2020; Staffell et al., 2012).

Even then, the efficiency of a HPs in real life is often very different to that predicted by technical design experts due to the variable nature of many influencing parameters, such as the dynamic/unpredictable user behaviour and the variation in installation practices. Gram-Hanssen et al. (2017) and Fahlen (2008), for example, stressed the need to examine HP performance from a wider perspective. This includes the HP’s interaction with the building and its users, as
well as the utilisation of additional heating arrangements, with Gram-Hanssen et al. (2017) placing particular emphasis to the competencies of the whole household in relation to the HP.

In addition to HP efficiency, the performance gap is also relevant to HP energy consumption. As with many other energy-efficient technologies, the HP rebound effect has also been found to feed the performance gap, with a significant part of its theoretical savings transforming to increased comfort (K. Gram-Hanssen, Christensen, & Petersen, 2012; Winther & Wilhite, 2014). These and other influencing parameters identified through literature are discussed in subsection 2.3.5.

2.3 National and International Experience with Heat Pumps

2.3.1 Uptake and market drivers

Starting from a very low base, the UK HP market showed significant growth in 2009-10 and then remained stagnant around 2011-12, probably due to the sharp rise in electricity prices (Euroobserver, 2013). As shown in Table 2-3, the first government schemes supporting the growth of renewable energy technologies (Community Energy Savings Programme, Carbon Emissions Reductions Target and Low Carbon Building Programme) achieved a fairly small number of HP installations, with the RHPP scheme, of all closed schemes, achieving the largest, and Green Deal the lowest uptake of HP (DECC, 2011, 2015c, 2015b; Ofgem, 2013a, 2013b). In addition, the Green Homes Grant voucher was closed early due to administrative issues, leading to a significantly smaller uptake of energy efficient measures than expected (HPA, 2021a). In 2012, roughly 14,500 ASHPs, 2,300 GSHPs and 1,000 exhaust air HPs were sold in the UK, with more than 85,000 already in operation throughout the country (Euroobserver, 2013). Since then, UK HP installation numbers have been growing steadily (Statista, 2021) with 35,000 HP sold in 2019 and the HP market projected to nearly double by the end of 2021 (HPA, 2021b). This compares with 1.67 million domestic gas boilers sold in 2019 (Rosenow et al., 2020). Currently available incentives are described in subsection 2.2.2.
Table 2-3: Heat pump installation numbers for closed schemes supporting the installation of domestic heat pumps.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Type</th>
<th>Time period</th>
<th>Installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Homes Grant</td>
<td>Government grant offering voucher towards the HP’s capital cost</td>
<td>2020 – scrapped in March 2021</td>
<td>Unknown, overall less than 5% of vouchers used</td>
</tr>
<tr>
<td>Green Deal (GD) finance, complemented by the Energy Company Obligation (ECO)</td>
<td>Market driven loan (GD), Market driven subsidy (ECO)</td>
<td>2013 - 2015</td>
<td>7 (up to 31/10/2015)</td>
</tr>
<tr>
<td>Renewable Heat Premium Payment (RHPP)</td>
<td>Government grant</td>
<td>2011 - 2014</td>
<td>10,979 (private housing), 5,762 (social housing), 94 (community schemes)</td>
</tr>
<tr>
<td>Community Energy Savings Programme (CESP)</td>
<td>Energy company obligation (low-income areas only)</td>
<td>2009 – 2012</td>
<td>594</td>
</tr>
<tr>
<td>Carbon Emissions Reduction Target (CERT)</td>
<td>Energy company obligation</td>
<td>2008 - 2012</td>
<td>7,454</td>
</tr>
<tr>
<td>Low Carbon Building Programme (LCBP)</td>
<td>Government grant</td>
<td>2006 - 2010</td>
<td>3,034</td>
</tr>
</tbody>
</table>

Historically, the installation of domestic energy efficient measures has proven most successful when regulated and/or heavily incentivised (Jaffe, Newell, & Stavins, 2001; R. Newell, 1997; R. G. Newell, Jaffe, & Stavins, 2006). Incentives, such as subsidies and tax credits, require a substantial amount of money to be spent by the government or utility service, however this may be restricted in times of fiscal constraint. This also raises questions on the size of the economic motivation that would have the desired effect, e.g., in many cases, consumers otherwise willing to purchase the product themselves will still be granted the money (Jaffe, Newell, & Stavins, 1999). Interestingly, a US study on upgrading existing ASHPs, found that energy savings decreased with the provision of larger incentives towards the HP capital cost, as these seemed to feed an extreme rebound effect (Alberini, Gans, & Towe, 2016).

Parrish et al. (2021) suggest that commonly used uptake practices based on the principles of engineering and economics alone may not provide sufficient motivation for the wider uptake of HPs. Thus, in addition to financial incentives and information provision, they drew attention to the theory of domestication as seen by Sorensen (Sorensen, 2006), placing people at the heart of new technology uptakes. Moore et. al (2015) also recognised the need to focus more on a user-centred HP design to increase acceptability of the technology, particularly in relation to social housing. Social norms and compatibility with daily routines are generally seen as significant drivers for the installation of new technologies (Hafner, Elmes, Read, & White, 2019;

From a consumer’s point of view, the additional service offered by an energy-efficient technology is often an important driver for its widespread uptake (Mills & Rosenfeld, 1996). From consumer’s point of view, the additional service offered by an energy-efficient technology is often an important driver for its widespread uptake (Singh, Muetze, & Eames, 2010). This is likely to change in the near future due to climate change and increasing summertime discomfort. A small pilot study on the use of air-conditioning in UK dwellings showed there is considerable potential for growth in the sales of active cooling systems as they are linked with high user satisfaction and low running and maintenance costs (Pathan, Young, & Oreszczyn, 2008). The cooling function of HPs may prove beneficial for their uptake, increasing at the same time carbon- and energy-related security risks, thus highlighting the need for demand-side management and a decarbonised electricity supply (CCC, 2016).

According to Staffell et al. (2012) HPs owe their worldwide popularity to their twofold function, at least in part. Reversible ASHPs are extremely common in Asian and southern European countries. Notably, Italy and France experienced a steep rise in HP installations during 2006-2007, linked to a substantial requirement for both summer cooling and winter heating (Singh et al., 2010). Whole-house integrated heating ventilation and air conditioning systems based on ASHPs are preferred in America (Hepbsi and Kalinci, 2009, as cited in Staffell et al., 2012), whereas GSHPs are most popular in northern Europe, e.g., Austria, Germany, Switzerland and Sweden (Ozgener and Hepbasi, 2007, as cited in Staffell et al., 2012).
Figure 2-3: Estimation of total numbers of heat pumps operating in European Union countries in 2019 (Euroobserver, 2020).

The capital cost of HPs is much higher than that of gas boilers and their annual running costs at current fuel prices are unlikely to deliver financial savings compared to most gas systems. However, they may be more favourable when replacing oil, coal or resistance heating as their running costs are much higher (CCC, 2020b; HPA, 2019; Staffell et al., 2012). Targeting such niches within the domestic stock would be another way to stimulate market growth (CCC, 2020b; Foxon, 2002). The utilisation of market areas where HPs could be installed at least cost and disruption and with fewer social barriers could assist technological improvement, relevant skills and unit cost reduction due to increased competition and cumulative production. Lessons
learnt from other European countries highlight the importance of policy interventions regarding carbon taxes and subsidising upfront costs that together with the widening of the skills base and robust certification could help overcome growth barriers to reduce carbon emissions in the heating sector (Hannon, 2015; HPA, 2019; Peterhans & Rognon, 2005).

2.3.2 UK-based evidence to date

Until recently there had been little publicly available data on the performance of HPs in the UK. Figure 2-4 shows the largest UK domestic field trials and surveys conducted by publication date and sample size. The Energy Saving Trust (EST) conducted the first large-scale domestic HP field trial in the UK in two phases. The first phase (Dunbabin & Wilkins, 2012) involved 56 ASHP and 27 GSHP, of which 44 were selected for the second phase (Dunbabin et al., 2013), where interventions were applied. The Customer-Led Network Revolution (CLNR) project (Durham Energy Institute & Element Energy, 2015) utilised monitored data from a field trial involving 381 ASHPs, making it the largest ASHP field trial in the UK to date. The largest monitored study of both ASHPs and GSHPs is still the RHPP field trial, with 699 HPs in total (Lowe et al., 2017c). Despite the large number of sites included in both, the sites yielding data of sufficient quality for analytical purposes proved to be much lower, i.e., 89 and 418 for the CLNR and RHPP projects, respectively. These are also depicted in Figure 2-4. A description of the large scale RHPP study is provided in sections 1.1.1 and 3.3.2 and its main findings are presented in Chapter 4.

Figure 2-4: The largest domestic heat pump surveys and field trial studies in the UK to date, listed according to study publication date.
Table 2-4 summarises the methods and key findings of the largest domestic HP surveys and field trials conducted in the UK, most of which focused on the performance of HPs in terms of heating provision, running cost and/or energy and carbon savings. In 2006, the data published from Pither and Doyle’s surveys of 18 HP users revealed high levels of satisfaction with heat provision but slightly less with running costs (as cited in Singh, Muetze and Eames, 2010). The installation of eight GSHPs installed in council houses off the gas grid yielded both financial and carbon savings, while occupants did not seem to be prepared for the changes arising from the slow responsiveness of the HP (Harrogate Borough Council, as cited in Singh, Muetze and Eames, 2010). Building fabric characteristics and occupant behaviour were thought to be a significant source of performance variation in both the Harrogate Borough Council GSHP and the Westfield ASHP monitoring field trials (Blois-Brooke, Matthews, & Willson, 2013; Stafford & Bell, 2009). The largest Scottish field trial, involving 73 ASHPs and GSHPs, proved that HPs can be an effective tool against fuel poverty, providing a high-quality of design and installation, as well as educated users (Clear Plan UK & Logan Project Management, 2008). In the Energy Technologies Institute (ETI) Micro Distributed Energy field trial on six HPs, the identification of several design and installation technical issues, as well as the users’ tendency to operate their systems in short bursts and high temperatures were likely to be the cause of their underperformance (Patterson, Preston-Barnes, & Oreszczyn, 2011).

Table 2-4: Brief overview of selected UK heat pump surveys and field studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Methods</th>
<th>Key findings</th>
</tr>
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<tbody>
<tr>
<td>(Durham Energy Institute &amp; Element Energy, 2015)</td>
<td>Customer-led Network Revolution project 12-month monitoring (2013-2014), investigating electricity use patterns in 381 domestic ASHP installations across the UK, including user interviews.</td>
<td>HPs are likely to introduce a significant burden onto the electricity grid by doubling demand at peak times. This could be eased by diversifying heat loads, e.g., through the use of hybrid HPs, heat storage and randomization of SH/DHW production. Users perceived HPs as a complex technology they poorly understand.</td>
</tr>
<tr>
<td>(EST, 2013)</td>
<td>Follow up research on EST field trial data (phases 1 and 2) to improve HP installation guidelines and training. Interviews with users were included.</td>
<td>Well designed, installed, commissioned, and operated HPs can perform extremely well. Users were generally satisfied with the SH/DHW provision but their understanding of how to achieve best performance varied. Performance relies on several aspects of the system and users may benefit from relevant feedback. High performing HPs may be linked to various control strategies (even non-continuous operation).</td>
</tr>
<tr>
<td>Reference</td>
<td>Details</td>
<td>Findings</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Dunbabin et al. (2013)</td>
<td>Analysis of the EST field trial (phase 2, 2011-2012) monitored data involving interventions to 44 HPs from phase 1 to improve their performance.</td>
<td>Good performances can be achieved providing appropriate design and installation practices. 20/21 of the HPs presented an improved post-intervention efficiency. Reduced post-intervention efficiencies were often attributed to higher proportion of DHW heating and extensive use of the internal electric cassettes.</td>
</tr>
<tr>
<td>Patterson et al. (2011)</td>
<td>Studied 4 ASHPs and 4 GSHPs providing SH or SH/DHW, monitored in 2010-2011 as part of the ETI Micro Distributed Energy project, investigating the potential for energy and carbon reduction through DE technologies. Interviews with occupants were included.</td>
<td>Most HPs were underperforming. Issues identified include extensive use of supplementary heating, sizing, and installation issues, including insufficient pipework insulation. Operating patterns often stemmed from experience with previous heating systems.</td>
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<tr>
<td>Stafford &amp; Lilley (2012)</td>
<td>Monitored data from over one year (2009-2010) to 10 similar cases of GSHP installations in social houses, where the performance of one case study is compared against the remaining to explore performance prediction potential based on easily obtained data.</td>
<td>The findings suggest that the monitoring strategy for performance prediction in similar HP case studies should involve detailed monitoring of sample installations and limited data gathering for the remainder, including living room/external air temperatures, ground loop fluid and DHW tank temperatures, and HP electricity consumption to observe compressor cycling patterns.</td>
</tr>
<tr>
<td>Caird, Roy, &amp; Potter (2012)</td>
<td>In-depth user surveys with participants from 78 EST field trial (phase 1, 2009-2010) sites, investigating characteristics, behavior and satisfaction of owner occupiers and social tenants.</td>
<td>Interviews revealed satisfaction with the system’s reliability, SH/DHW and warmth. Higher efficiencies were linked to better understanding of the system and more continuous operation. Owner occupier systems were more likely to present higher efficiencies than social tenants, possibly due to the dwelling type and size, system characteristics and user knowledge.</td>
</tr>
<tr>
<td>Dunbabin &amp; Wilkins (2012)</td>
<td>Detailed analysis of HP performance in the EST field trial (phase 1, 2009-2010) on a site-by-site basis.</td>
<td>Average SPF&lt;sub&gt;5H&lt;/sub&gt; for ASHPs and GSHPs was 1.82 and 2.39, respectively. Performance could be improved with improved installation practices. Changes to MIS 3005 suggested in terms of HP and ground loop sizing and emitter selection.</td>
</tr>
<tr>
<td>Roy et al. (2010)</td>
<td>Analysis of 12-month monitored data looking into performance and user behaviour in the EST field trial (phase 1, 2009-2010), involving 83 sites across Great Britain, with SH or SH/ DHW provided ASHPs and GSHPs.</td>
<td>Highly variable performance across sites, even between similar installations. GSHP efficiency was slightly higher than ASHP but lower than equivalent continental. Performance influencing factors include installation and commissioning practices, user behaviour and system understanding. Well-designed systems can operate well and offer carbon savings comparing to resistance- or gas-based heating systems. HP replacing heating systems other than gas-fueled presented noticeable running cost reductions.</td>
</tr>
</tbody>
</table>
(Kelly and Cockroft, 2009, as cited in Blois-Brooke, Matthews and Willson, 2013) 12-month monitoring (2008-2009) of the Westfield Air Source HP Trial of 8 retrofit ASHP installations. COP was found to be closely related to external temperature variations. Other COP variations were attributed to occupant behaviour in relation to HP controls, internal gains, and ventilation patterns.

(Stafford, 2011; Stafford & Bell, 2009) Harrogate Borough Council monitoring field trials of over 1 year (between 2007 and 2011), involving 10 GSHPs for SH and DHW in retrofitted social housing dwellings occupied by older people. A wide range of performance variation was noted, even between similar properties, which is likely to stem from variations in the building fabric performance and occupant behaviour. The studies highlight the importance of long-term monitoring and disaggregated monitoring.

(Harrogate Borough Council, 2007, as cited in Singh, Muetze and Eames, 2010) Ditto, but focusing on 8 pilot GSHPs installed in off-gas dwellings and monitored between 2007 and 2008. Occupants needed time to adjust to the lower DHW (55 °C) and higher night-time temperatures resulting from the HP’s continuous operation. The installations achieved significant carbon and running cost reductions, taking occupants off the fuel poverty group.

(Clear Plan UK & Logan Project Management, 2008) The Scottish Renewables Heating 2-year pilot study (2006-2008), managed by EST, investigated the impact of renewable technologies on fuel poverty programmes, involving 56 ASHPs and 27 GSHPs providing SH or SH/DHW. Fuel poverty can be tackled, providing HPs are appropriately designed and installed, and users educated to operate their system cost-efficiently, e.g., by improving householder manuals and after-care service.

(Pither and Doyle, 2006, as cited in Singh, Muetze and Eames, 2010) Domestic HP user surveys yielding 18 responses, mostly from housing association residents. Most respondents were satisfied with their systems in terms of heat and slightly less in terms of affordability. Approximately 1/3 felt it was expensive.

Phases 1 and 2 of the EST field trial focused on performance improvement through the formulation of relevant MCS guidance. Both the first- and second-phase analyses demonstrated that well-designed and installed HPs can operate well in the UK. The average SPF for phase 1 ASHPs and GSHPs was 1.5-2.2 and 1.6-3.4, respectively. Overall, the system efficiencies were found to be sensitive to installation/commissioning practices and user behaviour (Dunbabin & Wilkins, 2012; EST, 2013). Figure 2-5 depicts a great variation in performance, which could not be explained through the statistical analysis of the technically monitored data alone (EST, 2013). The analysis of householder interviews identified additional influencing parameters relating to the characteristics of the dwelling, the HP system and the household (Caird et al., 2012). The analysis of pre- and post-intervention monitoring data during phase 2 of the EST trial drew attention to the unnecessary energy consumed by supplementary heating and circulation pumps (Dunbabin et al., 2013). A detailed discussion on the emerging influencing areas is included in the paragraph on ‘Influencers of efficiency and energy demand’ later in this section.
Most EST field trial sites were off the mains gas, however, only a small number of HPs managed to achieve the minimum efficiency needed to make this technology competitive with the dominant SH fuel in terms of carbon emissions at the time of the study. Nevertheless, the majority of installations were found to be competitive in terms of carbon savings with traditional heating systems other than gas. Taking into consideration the UK government’s plan for grid decarbonisation, well-installed HPs with higher system efficiencies can offer significant SH and DHW carbon savings compared to electric, oil and gas-fired heating (Delta Energy & Environment, 2011; Roy et al., 2010).

The CLNR project (Durham Energy Institute & Element Energy, 2015) focused on a slightly different aspect, i.e., investigating the impact of HP uptake on the electricity grid. The study highlights the need for effective demand-side management to ease the pressure that the electricity grid is set to face with a widespread rollout of HPs. The EST field trial also acknowledged that the more continuous operation of HPs may make a significant contribution to peaks in the electricity profile, hence demand-side management through the development of smart grids is very important.

Several specific demand-shifting trials have shown promising findings. A smart control system involving a variable tariff through a simple user interface was tested on 31 out of the 76 HPs of a field trial, and showed that reduction of peak demand and shifting is possible (Sweetnam et al., 2018). However, the need to eliminate possible disturbances, such as night overheating, noise and interface usability issues, was highlighted in order to avoid risking future acceptability of the
Another trial of smart controls testing 75 domestic hybrid ASHPs, automatically switching between electricity and gas depending on grid signals, among other variables, was well accepted by its users (Parrish et al., 2021). Testing a retrofitted domestic HP integrated with thermal storage, also indicated a great potential for shifting demand, however, significant design, installation and capital cost barriers were shown to exist in the domestic sector (Shah et al., 2018).

The literature review also identified several more focused UK studies, combining HP monitoring with simulation modelling to answer research questions relating to:

- the effect of system storage capacity on ASHP performance – the investigation was based on a simulation model validated through laboratory and field trial results from two-purpose built archetypes representative of Northern Irish houses, and revealed that continuous utilisation of heat storage was detrimental to HP performance and the converse was true for direct HP heating (Le et al., 2019).
- the impact of retrofitting ASHPs into existing Scottish houses on running cost and carbon emissions – detailed performance simulation and comparison with field trial data from eight sites indicated a 12% reduction in comparison to a traditional gas boiler but with running costs higher by 10%. Interestingly, the validation process revealed that the weather compensation feature had not been enabled at any site, as was originally expected (Kelly & Cockroft, 2011).
- the testing of experimental predictive load-shifting controls though monitoring and modelling – these were carried out on a low-carbon house near Glasgow and the findings revealed higher thermal comfort at a high energy cost in real life, due to the unexpected extended use of the system’s incorporated resistance heater (Allison et al., 2017).

2.3.3 International experience

Detailed information from domestic air-to-water or ground-to-water HP field trials outside the UK, including insights into their performance drivers, is sparse. As mentioned earlier in subsection 2.3.1, space heating and cooling air-to-air HPs are the norm in Asia, Southern Europe and the US, in the form of centralised HVAC in the latter. Within Europe, even though SH providing HP based on water heat distribution systems are common in several Northern European countries, the majority of relevant data identified concerned installations in Germany and Switzerland.
Fraunhofer ISE projects

The Fraunhofer Institute for Solar Energy Systems (ISE) commissioned three field trials across Germany between 2008 and 2014, involving approximately 250 domestic electric-driven ASHPs and GSHPs, coupled with water distribution systems providing DHW at a fraction of 5-15% in comparison to the total heat production (Marek Miara, Gunter, Langner, & Helmling, 2014). These involved large single-family houses (with an average heated area of 190 m²) of various thermal efficiency characteristics. Figure 2-6 depicts the efficiency range in each of the three field trials, the main characteristics of which are briefly summarised below:

- The ‘Heat pumps in existing buildings’ (2008 - 2009) concerns nearly equal numbers of ASHPs and GSHPs, installed in older houses with poor thermal characteristics. Most HP systems replaced oil and utilised high temperature radiators. Buffer vessels were utilised to reduce cycling as HP compressors were non-variable.
- The ‘Heat pump efficiency’ project (2007 - 2010) included more GSHP than ASHP units, all installed in newbuilds.
- The ‘Heat pump monitor’ project (2012 - 2013) involved nearly equal numbers of ASHPs and GSHPs installed in newbuild houses. While the main project lasted 1 year, it also included a group of installations that were installed at a later date, i.e., end of 2013-2014. Their improved mean SPF is attributed to the technological advancements incorporated (Marek Miara et al., 2014).

Figure 2-6: Heat pump efficiency range at boundary level H2 in the three Fraunhofer ISE projects.
Efficiencies were found to be higher in newer buildings with UFH. GSHPs presented a wider range of efficiencies that were overlapping in part but were generally higher than those of ASHPs. GSHPs were found to perform particularly well in the real world, however, the design, installation and operational errors were found to have significant influence. Thus, Miara et al., (2014) concluded that simplicity and robustness are key for high performance.

Performance differences were also attributed to the type of heat source, the building type and the period of installation, i.e., the later the installation, the more technologically advanced was the HP system. The selection of heat source and sink type are both very important as they affect the temperature lift, i.e., the temperature difference between the cold source and the hot sink (Huchtemann & Müller, 2012). Except for higher insulation standards, newer buildings were also more often coupled with UFH systems that enable lower temperature distributions. They also utilised weather compensation and variable speed circulation pumps. Circulation and ground collector pumps were found to consume a significant amount of energy in comparison to other HP components, drawing attention to the need for optimisation of components outside the HP unit itself (boundary level H1), e.g., by incorporating their energy efficient counterparts. The marginal difference between SPFH2 and SPFH3, applying to all three projects, indicated minimal use of supplementary heating (Marek Miara et al., 2014).

The study on newbuilds concluded that high efficiencies and carbon and economic savings are possible, however, optimisation is needed, e.g., appropriate HP design and installation that is a good match to the building and heat source. Energy and carbon savings from the application of HPs to existing dwellings were uncertain in terms of competitiveness with traditional heating systems (Marek Miara et al., 2014). Occupant satisfaction was found to rely on both the installer and occupants, and to a lesser extent to the manufacturer (Miara et al., 2011).

Swiss FAWA project

The Swiss Field Analysis of Heat Pump installations (FAWA) project (1996 – 2003) investigated the potential for improvement of domestic HP performance. It was commissioned by the Swiss Federal Office of Energy and involved 236 owner-occupied sites across Switzerland, of which 221 were included in the final SPF analysis. In each year of the study, approximately 30 new installations were added and from 2004 onwards, 121 sites were retained for longer-term observation. The study involved small domestic ASHPs and GSHPs of 20 kW maximum capacity. The majority of HPs were installed in newbuilds (60%) and the remaining in retrofitted dwellings. Approximately half the installations provided DHW, at least in part. The efficiency reported took into consideration the HP unit, source fans and pumps, as well as the pumps circulating heat through the buffer vessel and DHW cylinder and taking into account any heat
losses from the SH buffer storage. The average SPF for ASHPs and GSHPs was 2.7 and 3.5, respectively, with GSHPs presenting a higher range, which was thought to derive from the highly variable performance of the geothermal heat probes (Rognon, 2008).

Based on an early (1997) survey, most occupants were satisfied with their HP and approximately half of those not satisfied were unhappy with the running costs. Faults were rare, especially in the GSHP group and those without heat storage. Efficiency was found to have improved by approximately 15% since the start of the study and this was attributed primarily to technological advancements. The gradual accumulation of knowledge and experience on the installer side was also acknowledged. No efficiency reduction was detected through the years, neither due to ground thermal depletion nor evaporator soiling. Supplementary heating was not required under normal operating conditions and at of temperatures as low as $-10\, ^\circ C$. With regards to buffer vessels, it was concluded that they should be utilised only if necessary, as they can complicate the installation and increase capital costs (Rognon, 2008). It was finally suggested that the recommended improvements could raise the average SPF by 25% for ASHPs and 60% for GSHPs.

### 2.3.4 Comparative performance

Based on the UK EST field trial data, HP efficiency in the UK appeared to be inferior to that of other European countries (Boait et al., 2011; Delta Energy & Environment, 2011; Stafford & Lilley, 2012). The comparison with the RHPP field trial data though indicated improved HP efficiencies, which are comparable with the German and Swiss field trials in the case of ASHPs. Figure 2-7 and Figure 2-8 depict ASHP and GSHP performance in the German and Swiss field trials in comparison to the UK EST study (Delta Energy & Environment, 2011) and the RHPP field trial (Lowe et al., 2017c). However, outputs are not completely comparable as their SPF calculation involved different boundaries that cannot be perfectly mapped onto each other (C. P. Gleeson & Lowe, 2013). For example, while all the components included in boundary level H5 (see subsection 2.1.4) were included in the SPF calculation of the EST field trial, the German and Swiss field trials took into consideration only the resistance heater and buffer vessel, respectively, in addition to the HP unit and source fans/pumps (but not circulators or pumps) and thus cannot be mapped directly to boundary level H4. According to Delta Energy & Environment (2011), this indicates a possible SPF underestimation of the EST field trial output by approximately 0.1. In the RHPP field trial, only measured components were included, thus the associated SPF were calculated at boundary level H4. In addition, the Swiss field trial took place at least one decade earlier than the RHPP and German Field trials and thus the SPF of the Swiss HPs is likely to have improved further, e.g., due to the technological advancements incorporated.
Figure 2-7: Comparative performance of ASHPs between European and UK field trials (Delta Energy & Environment, 2011; Lowe, et. al., 2017c)

Figure 2-8: Comparative performance of GSHPs between European and UK field trials (Delta Energy & Environment, 2011; Lowe, et. al., 2017c)

The three Fraunhofer projects measured HP performance in circumstances very similar to those of the UK trials in terms of annual average temperatures and heat demand (Staffell et al., 2012), however, the Northern European climate tends to be colder and drier than the British (Roy et al., 2010). One of the major differences between the two lies in the thermal qualities of the domestic
stock, with the UK featuring a more extended poorly insulated existing stock in comparison to Northern European houses (Colbourne, 2010; Roy et al., 2010). However, when comparing between existing buildings of the EST and Fraunhofer trials, there does not appear to be much difference in terms of heat losses (C. P. Gleeson & Lowe, 2013). The fact that different countries encompass different types of buildings should also be taken into consideration (Delta Energy & Environment, 2011).

As HP installations have been used in the continent for a long time, installers tend to be more experienced (Roy et al., 2010). In particular, higher quality components and system controls were identified in the Swiss and German field trials (Delta Energy & Environment, 2011). Boait, Fan and Stafford (2011) also suggested that particular attention should be paid to HP controls, as well as their capacity, both of which need to be better matched to the specific characteristics of the UK domestic stock in terms of size and thermal behaviour. The lower proportion of DHW provision and higher proportion of low-temperature UFH in the Swiss field trial may also contribute to higher SPF (Delta Energy & Environment, 2011). User behaviour, which is often linked to the user’s experience with their previous heating system, is another influencing parameter (Roy et al., 2010). Switzerland in particular, has invested much in end-user education, e.g., in relation to optimum operation whereas EST trial users tended to operate the HP in the same way they did their previous traditional heating systems, i.e., intermittently and at high temperatures(Delta Energy & Environment, 2011).

The meta-analysis of data on the performance of domestic ASHPs and GSHPs from eight field trials in Europe (including the EST and Fraunhofer), involving approximately 600 sites, provided some additional insights (C. P. Gleeson & Lowe, 2013). Germany and the UK seem to share similar HP market conditions in terms of HP components/materials, manufacturing techniques and manufacturer penetration to some extent, however, weather compensation and variable-speed circulation pumps were not utilised as much in the UK neither at the time of the EST study nor in the RHPP case study sample. According to the same authors, the extreme ranges in HP performance indicate their sensitivity to design, installation, and control, requiring further in-depth investigation on an individual basis.

### 2.3.5 Influencers of efficiency and energy demand

The literature available to date indicates there is a wide range of parameters that could potentially influence the HP efficiency and energy consumption. The parameters negatively affecting the system’s efficiency are generally linked to increased energy consumption. The likely ambivalent outcome of intermittent heating practices in terms of energy consumption is discussed in the ‘Space heating practices: Modes of operation’ paragraph below. There are also
parameters that can affect energy consumption through alternative pathways. Higher fabric heat loss, for example, may increase energy consumption due to increased compressor cycling, thus lowering the system’s efficiency but will also lead to higher heat demand and possibly higher flow temperatures needed (Caird et al., 2012; Delta Energy & Environment, 2011; Stafford & Lilley, 2012). This section discusses these influencing parameters as identified through various sources, including field trials and best practice guides. This section focuses primarily on socio-technical influencers identified through field trials, which are linked to one or more of the following areas: SH practices, bill affordability, ventilation patterns, building thermal characteristics, technical characteristics of the installation and technical problem resolution and control optimisation processes. Additional parameters identified but not quantified in terms of frequency of occurrence in the EST field trial (Dunbabin et al., 2013) include: undersized ground collectors, undersized hot water cylinders, insufficient pipework or hot water cylinder insulation, too many circulation pumps and oversizing, and specific control strategies leading to increased use of resistance heating.

**Space heating practices: Modes of operation**

Experts’ opinions vary on whether HPs perform best on a continuous or intermittent mode (MCS & RECC, 2018). In the EST field trial and based on a 78-strong sample, there appeared to be a statistically significant relationship between continuous HP operation, i.e., letting systems run during the night and when the house is unoccupied, and higher HP efficiency (Caird et al., 2012). Indeed, units running just 5 hours have been linked to a 30% lower COP (Ida, 2008, as cited in Staffell et al., 2012). However, Winther and Wilhite (2014) argue that a continuous heating pattern may not necessarily be optimal in technical terms. Continuous operation tends to be related to higher efficiencies but there is a trade-off between improved efficiency and additional heat losses resulting from maintaining a higher indoor temperature for longer (Pollard, 2018). Thus, even though it is usually recommended that HPs should operate continuously at low temperatures (Delta Energy & Environment, 2011), it is not certain whether this is the most energy efficient practice. Winther and Wilhite (2014) stressed this “remains an open question” and concluded that “heating practices are formed in the light of ambiguous technical information”. The EST field trial findings (EST, 2013) showed that high-performing HPs can be linked to different control strategies and Lira et al. (2011) suggested that buildings with different fabric characteristics can benefit from different operation strategies.

**Bill affordability: The rebound effect**

The rebound effect is a well-documented phenomenon (K. Gram-Hanssen et al., 2012; Hamilton et al., 2011; Lomas, 2010; Milne & Boardman, 2000; Sorrell, 2009), defined as the percentage
of the expected reduction in energy consumption that is transformed into increased comfort and also applies to HP systems. The different types of rebound are described below, with Winther and Wilhite (2014) introducing for the first time the terms spatial, temporal and multi-purpose rebound:

- **temperature rebound** – maintaining higher temperatures, e.g., through higher thermostat temperature settings, or lower temperatures through the use of a HP in a reverse mode (air conditioning), where applicable;

- **spatial rebound** – increasing the system’s heating coverage;

- **temporal rebound** – expanding the heating times/heating season;

- **multi-purpose rebound** – relating to socially conditioned activities or beliefs that result in increased thermostat/flow temperatures, heating coverage or heating times, such as indoor clothes drying, age-related temperature sensitivity etc.

All of the above fall into the direct rebound effect category, where money saved due to the HP system installation are used to pay for an increased use of the same system (Winther & Wilhite, 2014). There is also rebound in an indirect form, where the money saved is spent on buying energy-consuming goods or services other than those provided by the HP. Through in-depth interviews, three main drivers of direct rebound effect were identified in 28 Norwegian dwellings with HPs: “people’s own practical knowledge”, “expert knowledge” and “the HP embedded script” (Winther & Wilhite, 2014).

Gram-Hanssen et al. (2012) studied the electricity consumption, based on energy supplier electricity data and survey data, before and after the installation of air-to-air HP in 138 permanently occupied and 42 vacation Danish houses with previously direct electric heating. They calculated an overall rebound effect of 20% and 100%, respectively, relating to increased comfort practices, such as maintaining higher temperatures, extended heating seasons, increased system heating coverage, as well as comfort cooling, where applicable (K. Gram-Hanssen et al., 2012). Evidence of rebound was also found in the EST trial, where both the heating area and operational hours were often extended in comparison to the previous heating system (Caird et al., 2012). Further qualitative data collection on a low-income segment of the EST population also indicated an increase in comfort and no energy savings in relation to the previous heating system (Owen, Mitchell, & Unsworth, 2013).

**Building thermal characteristics and ventilation patterns**

According to Staffell et al. (2012), ensuring a high thermal performance of the building envelope should be the first point of action when considering the installation of a HP. However, most EST
field trial HPs were installed in poorly insulated, retrofit properties (Dunbabin et al., 2013). High fabric heat losses, e.g., due to poor thermal properties or unnecessary window opening, may lead to excessive compressor cycling and higher flow temperature requirements, both of which lead to lower efficiency and increased energy consumption (Caird et al., 2012; Delta Energy & Environment, 2011; MCS & RECC, 2018; Stafford & Lilley, 2012)

**Technical characteristics: Design and installation quality**

Table 2-5 lists the strictly technical parameters identified in literature with efficiency optimisation in mind while the rest of the section expands on more generic socio-technical influencers identified through field trials. Technical issues, such as incorrect system sizing and setup, were recognised as being partly responsible for the poor HP performance of the EST field trial (Dunbabin et al., 2013). An insufficient understanding of the variable HP performance has been linked to remarkable under-sizing, which could be further enhanced through the use of standard rating conditions (MCS & RECC, 2018). The MCS Best Practice Guide (MCS & RECC, 2018) also raises concerns that installers tend to favour specific manufacturers due to familiarity with their specific design, installation and commissioning requirements, and this may be linked to significant under- or over-sizing of the HP. According to Caird et al. (2012), sizing and setup problems in the EST field trial often appeared to stem from the involvement of multiple installation contractors, many of whom probably lacked the experience required to design and size a HP system appropriately. The technical problems manifested themselves in the form of over- or under-heating, slow system responsiveness and increased energy bills. The influence of design and installation practices on HP performance was also acknowledged by Gleeson and Lowe (2013) through a meta-analysis of data from eight European trials, revealing a significant variation in performance across all trials and boundaries investigated. The Fraunhofer study also indicated that diligent planning and installation are essential factors for high performing HPs (Miara et al., 2014). Both the Fraunhofer and the Swiss FAWA field trials noted the tendency for improvement of HP efficiency with newer HP installations, which was attributed to technological advancements, as well as the increased knowledge and experience of installers through the years in the case of the Swiss field trial (Rognon, 2008). Overall, appropriate whole-system setup, including sizing, resistance heaters and temperature sink specification, is key to efficiency optimisation (Delta Energy & Environment, 2011). These aspects are discussed further below:

- **System sizing:** A higher installed capacity than the dwelling’s heat demand can trigger compressor cycling (Delta Energy & Environment, 2011). Oversized systems running at part load are still prone to suffering from frequent cycling. According to Staffell et al. (2012), inverter-driven HPs running at 40% below their rated power have been linked to dramatically
reduced COPs, which can be explained due to the limited turn-down capacity of the inverter technology that may not be able to prevent cycling in oversized systems (MCS & RECC, 2018). A lower installed than the dwelling’s heat demand can trigger excessive use of the HP’s resistance heater (Delta Energy & Environment, 2011; Staffell et al., 2012).

- **Resistance heater:** Auxiliary heating in the form of a HP-incorporated resistance heater is often an integral part of the system. It is meant to provide automatic supplementary or backup heating. According to Staffell et al., (2012) most HPs are sized below the calculated peak demand due to considerations relating to capital cost and practicality. Thus, backup heaters step in under extreme weather conditions and when the HP cannot raise the SH or DHW temperature to the desired level (Eurobserver, 2020; Fawcett, 2011; C. P. Gleeson & Lowe, 2013; MCS & RECC, 2018). According to MIS 3005 (MCS, 2017), such situations may arise when the HP is required to heat a building from a very cold state, the heating mode is intermittent, or large quantities of DHW are frequently drawn in cold weather. Another consideration relates to the fact that DHW should regularly be heated to a minimum of 60 °C for pasteurisation purposes, typically once a week (MCS & RECC, 2018). Depending on the output temperature of the HP, this may be achieved with or without supplementary heating (HPA, 2021c). Even though resistance heaters can be an attractive add-on to a HP system, both for their simplicity and low initial cost, their regular use can significantly reduce HP efficiency and lead to high running costs (Staffell et al., 2012). According to Zeller (2007) and Miara (2008) (as cited in Staffell, 2009), a well-sized system is expected to minimise the use of resistance heating, i.e., providing just 3-6% of the heat demand, thus reducing a HP’s COP of 4 by approximately 0.1-0.2 (Staffell, 2009). The second phase of the EST field trial (Dunbabin et al., 2013) and a number of smaller UK studies (Allison et al., 2017; Patterson et al., 2011) have raised concerns about the unnecessary energy consumed by HP-incorporated resistance heaters. Defrosting is another process in which supplementary heating may be utilised. Defrost cycles based on the reversal of the HP cycle are expected to have a small influence on the SPF (Klein, 2012). However, depending on the manufacturer’s specification, the system’s backup resistance heater can also kick in for defrost purposes, in which case there will be a much greater SPF reduction (Staffell et al., 2012). The frost that builds up on the evaporator is also likely to reduce the HP’s efficiency by reducing the amount of air that flows through the evaporator (Zhu et al., 2015). The identification of significant defrosting in specific case studies of the EST phase 2 work highlighted the need for monitoring and appropriately configuring the defrost function (Dunbabin et al., 2013).

- **Temperature ‘lift’:** Based on the Carnot cycle, maximising HP efficiency primarily depends on the temperature of the sink, i.e., the temperature of the flow to the heat emitter system and the DHW cylinder (if present). Based on manufacturer data for both ASHPs and
GSHPs, Staffell et al. identified a COP decrease of between 0.7 and 1.1 for every 10 °C increase (Staffell, 2009). In the EST field trial, most sites relied on conventional high-temperature radiators, however, better HP efficiencies can be achieved with systems requiring lower sink temperatures, such as UFH, oversized radiators or fan coils (Delta Energy & Environment, 2011). UFH may also reduce the need for higher temperatures as it reduces temperature stratification and can even save energy in rooms with high heat losses due to the resulting lower air temperatures (MCS & RECC, 2018). Overall, depending on the type of emitter system installed, flow temperatures should be set at the minimum comfortable temperature allowed and users should be informed about the consequences of raising it (Staffell et al., 2012). Fine tuning of flow temperature using closely optimised weather compensation in the EST field trial was also linked to higher efficiencies (Dunbabin & Wilkins, 2012).

Table 2-5: Individual technical features for optimisation of heat pump efficiency.

<table>
<thead>
<tr>
<th>System feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground loop or air fan</td>
<td>Appropriate sizing and installation of the ground loops/boreholes is critical for the operation of the HP. Closed loop circuits need to be fully filled, contain adequate antifreeze and be free of fouling and leaks. Adequate air flow needs to be allowed across the fan of external ASHP units.</td>
</tr>
<tr>
<td>Water flow temperature</td>
<td>Depending on the system’s individual characteristics, MCS requires that the lowest flow temperature possible should be utilised for SH. Where a HP provides both SH and DHW, the suggestion is that their flow temperatures should be completely separated, thus avoiding the use of blending valves (MCS &amp; RECC, 2018).</td>
</tr>
<tr>
<td>Compressor cycling</td>
<td>Of all HP components, the compressor is significantly more energy intensive, especially if accompanied by frequent on-off cycles, as large currents are drawn during start-up, and they are not able to modulate speed/outlet temperatures in response to higher source temperatures (Staffell et al., 2012). Laboratory tests by EA Technology have indicated that an effect of on-to-off times on HP efficiency is noticeable when they become shorter than 6 minutes (Green, 2012). Increased cycling may be linked to a particularly narrow SH temperature range between the start and the end of a cycle (hysteresis) or building fabric heat loss (Stafford &amp; Lilley, 2012). Interestingly, even though it is good practice to include thermostatic radiator valves (TRVs) in standard radiator systems, Green and Knowles, (2011) suggested they tend to increase cycling.</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>Appropriate water flow rates are important to ensure adequate heat is circulated around the system. Extremely low flow rates could lead to operation halt while too high rates can lead to higher noise levels and higher energy consumption by the circulation pump (MCS &amp; RECC, 2018).</td>
</tr>
<tr>
<td>Weather compensation</td>
<td>Weather compensation is recommended with a view to improving the HP efficiency during seasonal operation. Since weather conditions are a major influence of heat demand that fluctuates throughout the year, ‘heat curves’ account for external temperature changes (communicated through a shaded outdoor sensor) by proactively adjusting flow temperature (MCS &amp; RECC, 2018).</td>
</tr>
<tr>
<td>Thermal capacity</td>
<td>The presence of adequate heat storage capacity (e.g., in the form of buffer vessels), in</td>
</tr>
</tbody>
</table>

2 A higher hysteresis enables the HP to run more continuously, which has a positive influence on efficiency but if set too high, it can negatively affect comfort.
compliance with manufacturer requirements, will prevent frequent cycling. This is particularly important for ASHPs reversing their cycle for defrost purposes. However, inappropriate incorporation of buffer vessels can increase heat losses and parasitic loads through the inclusion of additional circulation pumps (MCS & RECC, 2018).

### Circulation pumps

The system’s number of circulation pumps should be carefully considered and controlled, as collectively they can lead a relatively high energy demand (MCS & RECC, 2018). High circulation pump energy use was identified in several sites of the EST trial (Dunbabin et al., 2013).

### Parasitic loads

Staffell et al., (2012) acknowledged the importance of operating the HP in a way that will minimise parasitic losses, including defrosting. Fahlen, (2008) concluded that the parasitic energy ratios of HP systems are usually significantly higher than optimal, with a significant amount of energy being consumed by the distribution and control components.

### Pipework

Attention should be paid to ensure appropriate pipework sizing/insulation and minimization of bends or changes of direction (MCS & RECC, 2018).

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**Technical problem resolution and control optimisation processes: System complexity and understanding**

HP systems are generally more complex than mainstream heating systems and the extent to which the user understands how they work was found to affect its efficiency (Roy et al., 2010). Installations with the simplest designs and controls were also linked to higher efficiencies. In the EST field trial, higher efficiencies were found to be correlated with a greater self-stated knowledge and understanding of the system and the way it operates by the occupants (Caird et al., 2012). There is wider evidence suggesting that perceived complexity may lead to suboptimal control of a HP and this is particular true in low-income housing of older occupants (Boait et al., 2011; Owen et al., 2013). In line with this, the social science analysis of the Customer-Led Network Revolution project (Durham Energy Institute & Element Energy, 2015) revealed that HPs may not have been operated in the best possible way due to the occupants’ limited understanding of the relevant technical and operational aspects, their unwillingness to interact with the HP’s controller, as well as the absence of incentives directing towards certain operational patterns. The MCS Best Practice Guide stresses the need to educate occupants who, for example, should be made aware that a dramatic change of the temperature set point will not result in a swift system response but will rather lead a gradual build-up of excessive room temperature (MCS & RECC, 2018).

**Ownership type**

Ownership forms a separate influencing category that is likely to be linked to several of the areas described above. In particular, the EST field trial identified a significant difference in efficiency between dwellings of social tenants and owner occupiers, with the latter presenting more efficient systems (Caird et al., 2012). Even though further investigation is needed to clearly identify the reasons behind this stark difference, the study identified likely causes relating
to building typology, efficiency and size, occupant behaviour and the type of installation, including HP type and whether it is a clean installation or a retrofit. Most owner occupiers resided in larger and more energy efficient dwellings, had newbuild HP systems coupled with UFH, and higher knowledge and understanding of the system, which was operated more continuously.

2.3.6 User satisfaction

Both the Scottish EST pilot (Clear Plan UK & Logan Project Management, 2008) and the EST field trial (Caird et al., 2012) participants were largely satisfied with the air- or ground-source HP (Caird et al., 2012). Users expressed satisfaction with the reliability, the continuous and whole-house warmth, DHW provision and the overall comfort provided by the HP. Uncertainty around the optimum system operation was the most common source of complaint, relating to a desire to optimise the efficiency and running cost of their system. This was followed by complaints on the complexity of system controls, the level of technical support provided, the inability to achieve the desired level of warmth and, less often, the slow system warm-up and noise levels (usually relating to social tenants and ASHP fans).

Social tenants were more likely to be dissatisfied with their HP, particularly when they compared it to their previous heating system. The high levels of satisfaction of owner occupiers, whose HPs were generally found to perform at higher efficiencies, are thought to be linked to the fact that they encountered less problems and were actively involved in the decision-making process for the installation of the HP.

2.4 Summary of Evidence from Literature and Knowledge gaps

Domestic HP installations in the UK have been increasing steadily in the past few years, with approximately 20,000 per year installed by 2018 and a sharp increase expected by 2028, when the government has committed to the annual installation of 600,000 HPs (HM Government, 2020; MCS & RECC, 2018). Clearly, there is huge HP market potential, however, there appears to be a performance gap between predicted and in-situ HP performance. A number of studies have highlighted several areas of potential improvement, and crucially the need for higher quality of installations and controls, including more continuous operation, lower flow temperatures and minimal use of supplementary heating (Delta Energy & Environment, 2011; C. P. Gleeson & Lowe, 2013; Roy et al., 2010).
Existing field trials and best practice guides have identified additional variables that are thought to influence HP performance in the UK. Figure 2-9 provides a representation of these influencing parameters and their interrelations, as identified through UK-based and international literature, in the form of a causal loop diagram (CLD). Further information on the application of CLD as a systems thinking tool and its application in this study can be found in section 3.4. The main performance influencing areas identified in literature are presented in Table 2-6, alongside the associated variables depicted in the CLD of Figure 2-9 (see Appendix K for an enlarged image of the variables highlighted in grey, as shown in Figure 7-1). In addition, Table 2-7 summarises the measures for the improvement of HP performance, as identified through several UK-based studies.

Figure 2-9: Causal loop diagram depicting the interrelationships between the variables influencing heat pump performance as identified through literature, focusing in the areas of space heating practices, bill affordability, building thermal characteristics and ventilation patterns, technical characteristics, and technical problem resolution and control optimisation.

Most UK HP field trials investigated HP performance through monitoring, focusing primarily on heating provision, energy consumption, carbon savings and/or running cost, often with the addition of user surveys or interviews (Caird et al., 2012; Clear Plan UK & Logan Project Management, 2008; Durham Energy Institute & Element Energy, 2015; Patterson et al., 2011; Singh et al., 2010). The collection of qualitative data was a useful tool, offering additional insights, on top of that elicited from the statistical analysis of the technical monitoring. They also examined performance from a wider perspective, i.e., also taking into consideration the building...
and its users. However, both the qualitative and quantitative data collection presented a limited capacity in terms of uncovering the reasons behind performance variation and identifying areas for improvement.

None of the existing studies have looked at the full range of influencing parameters and their detailed interactions and interrelations from a holistic point of view. This could only be achieved through in-depth investigations on an individual basis. In addition, there is limited evidence as to what needs to be done for the improvement of HP performance in the UK. The current study aims to address this literature gap and offer insights into the complex network of parameters influencing the performance of HPs in real life. This will be implemented through the socio-technical analysis of the detailed qualitative and quantitative data collected on 21 case studies as part of the RHPP project. The detailed methods and material utilised are described in the following chapter.
Table 2-6: Key influencing areas of heat pump efficiency and/or energy consumption, as identified in literature, and the associated causal loop diagram (CLD) variables.

<table>
<thead>
<tr>
<th>Key influencing areas</th>
<th>CLD variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH practices: Modes of operation</td>
<td><em>Continuity of HP operation, compressor cycling, electricity consumption, HP SH demand</em></td>
<td>More continuous operation is linked to higher SPF as a result of reduced cycling and higher energy consumption due to the increased heat demand.</td>
</tr>
<tr>
<td>Bill affordability: The rebound effect</td>
<td><em>Heated area to total area ration, room/radiator thermostat setpoint, schedule-based heating hours</em></td>
<td>Increased comfort taking in the form of spatial, temperature or temporal rebound.</td>
</tr>
<tr>
<td>Building thermal characteristics and ventilation patterns</td>
<td><em>Building fabric thermal resistance, building fabric air tightness, natural ventilation heat loss, SH flow temperature, HP operating hours, HP SH demand</em></td>
<td>Higher building heat loss increases heat demand through the need for higher sink temperatures and/or longer HP operating hours.</td>
</tr>
<tr>
<td>Technical characteristics: Design and installation quality</td>
<td><em>Technical issues, effective compared to design heat load ratio, compressor cycling, compressor speed modulation, hysteresis, heat storage capacity, building fabric thermal resistance, building fabric air tightness, window opening, heat generation by the HP incorporated resistance heater, number and power of auxiliary drives, pipework and buffer vessel/DHW cylinder heat losses, technological advancements, installer experience, temperature lift, emitter surface, design SH flow temperature</em></td>
<td>Several aspects of the installation have been found to affect SPF, often relating to improper sizing, increased compressor cycling (e.g., stemming from technical aspects of the installation, poor building thermal efficiency and occupant behaviour), the use of the HP-incorporated resistance heater, circulation pumps, and higher SH flow temperature settings (often encountered in retrofit installations).</td>
</tr>
<tr>
<td>Technical problem resolution and control optimisation</td>
<td><em>Design/control complexity, user understanding of the system</em></td>
<td>Higher SPF correlate with lower system complexity and greater user understanding.</td>
</tr>
<tr>
<td>Ownership type</td>
<td><em>Building fabric thermal efficiency, user understanding of the system, temperature lift, emitter surface, continuity of HP operation</em></td>
<td>It is suspected that lower SPF for social tenants in comparison to owner occupiers is related to the building/installation type and occupant behaviour.</td>
</tr>
</tbody>
</table>
Table 2-7: Areas for heat pump improvement as identified through literature.

<table>
<thead>
<tr>
<th>Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer practices</td>
<td>User-friendly instructions/interfaces and controls/displays reporting on operating efficiency/carbon savings/resistance heater (Caird et al., 2012; Durham Energy Institute &amp; Element Energy, 2015); careful consideration of defrosting, sterilization and supplementary heating processes, alongside the provision of relevant diagnostics and easy-to-understand controls for users (Dunbabin &amp; Wilkins, 2012)</td>
</tr>
<tr>
<td>Noise reduction</td>
<td>More prominent in small properties with ASHPs (Caird et al., 2012)</td>
</tr>
<tr>
<td>Installer training</td>
<td>Particular attention should be paid to installer education to ensure appropriate installation sizing, setup and controls (Caird et al., 2012; Roy et al., 2010); reconsider vocational education/training, including design, installation and controls, as well as monitoring practices and analytical protocols (C. P. Gleeson &amp; Lowe, 2013).</td>
</tr>
<tr>
<td>Centralised installation services</td>
<td>Installation responsibility to fall within one company, so there is no need for purchasers to coordinate several contractors and ultimately take responsibility for installation quality (Caird et al., 2012)</td>
</tr>
<tr>
<td>User education and support</td>
<td>Single point of contact for technical issues (Durham Energy Institute &amp; Element Energy, 2015); detailed handover advice, e.g., how to run HP efficiently and economically while paying particular attention to social tenants (Caird et al., 2012); provision of tailored information, suitably communicated according to individual needs; user engagement, e.g., by revisiting properties after the initial running period to enable user interaction and fine tuning according to individual needs (Parrish et al., 2021).</td>
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Chapter 3: Study Methodology

A pragmatic approach was taken for the development of a framework that facilitated a better understanding of the complex interactions between domestic HPs and their social and physical environments. The theory of pragmatism focuses primarily on the outcomes of methods, rather than “on the epistemology out of which they have emerged” (Patton, 1990, as cited in Datta, 1997). This is an inductive approach, seeking to generate theory on a complex phenomenon through a holistic analysis that can offer practical solutions (Salkind, 2010). Within this frame, the overall aim of this study was to support the improvement of HP performance in the field.

The study utilised a range of complementary quantitative and qualitative methods. Rather than adhering to an idealistic approach of fixed qualitative or quantitative theories, the research techniques and procedures were selected based on their suitability to the research problem. The research design was primarily based on a case study approach, utilising the quantitative data of the larger RHPP field trial population as the basis for the selection of 20 case studies. The rationale for using the multiple case study approach and the case study selection process is detailed in section 3.1. The mixed-methods approach, whereby both qualitative and quantitative data are extracted from the case study sample and then managed, analysed, and synthesised, is described in sections 3.2 and 3.3. The specific contribution of systems thinking is explained in section 3.4.

3.1 The Multiple-Case Study Approach

“Case study design can address a wide range of questions that ask why, what, and how of an issue and assist researchers to explore, explain, describe, evaluate, and theorise about complex issues in context” (Harrison, Birks, Franklin, & Mills, 2017). In this case, the aim of the case study approach was to investigate and achieve an in-depth understanding of the underlying causes responsible for the variation of HP performance in the field which were not possible to pin down through the use of quantitative data alone. Undoubtedly, the assessment of in-situ HP performance using monitored data (see subsections 3.2.1 and 4.1) is an important first step as it enables the calculation of a HP’s efficiency within real operational environments in comparison to the controlled testing chambers, where the assessments are time-limited and implemented under controlled environmental settings. However, the use of quantitative data alone can only provide a limited understanding of the in-situ HP performance, i.e., by summarising the
characteristics of large populations and groups within populations and by identifying any emerging patterns or relationships. This approach enables the generalisation of findings to a broader population through the use of statistics, however, it is limited in its ability to identify metering errors and in understanding new phenomena.

A qualitative inductive approach was thus deemed necessary for the collection of data, focusing more closely on the phenomena observed through the quantitative analysis to enable an insightful understanding. The case study approach was preferred over other methods because it allows the investigation of the various boundaries (e.g., at the user or building level) surrounding and interacting with HPs in real life. A variety of data collection procedures facilitated this holistic approach, e.g., direct observation of internal environment and equipment, site surveys and interviews with occupants (see subsection 3.2.2).

Employing multiple-case studies enabled the unique context of each case to be taken into consideration. The findings of multiple cases were grouped to examine the strength of the underlying relationships identified in the sample and explore contrasting perspectives. While time consuming, the evidence resulting from multiple-case studies tends to be more robust and reliable (Baxter & Jack, 2015). The use of semi-structured interviews, i.e., including both open-ended and fixed-response questions, ensured that it was possible to adapt the interview to the unique nature of each case and thus bring out any interesting stories and precedents that the pre-determined questions would not. Even though such an approach does not allow the generalisation of findings, it does allow a deeper understanding of the subject matter by providing evidence on the existence of complex mechanisms and unchartered phenomena. Thus, the resulting theory could be utilised to challenge established practices and inform future research.

In this study, the quantitative data were used as the basis for the selection of the case studies, and they also complemented the analysis and interpretation of the qualitative data collected. The mixed-methods approach enabled a more comprehensive understanding of each HP’s performance within its real-life environment. Since the complex reality in which HP technology is applied involves both social and technical aspects, their influence cannot be understood when examined in isolation. As explained in the previous paragraphs, both quantitative and qualitative approaches have strengths and weaknesses. This study utilised different but complementary methods in such a way that the resulting combination builds on the strengths and minimises the weaknesses of single approaches.

The significant amount of time and resources required in qualitative/case study research inevitably restricts the number of participants. In this case, the site investigations (see
subsection 3.2.2) were implemented as part of the RHPP project and thus the number of participating sites, i.e., 20, was decided jointly by BEIS (formerly known as DECC) and the research team undertaking the work, taking into consideration the time and budget restrictions present. An additional case study was used as a pilot, leading to material collected from 21 cases in total. The case study sample was not meant to be statistically representative of the overall RHPP sample but to allow investigation primarily of those cases that reside at the two ends of the performance spectrum (i.e., $2.0 > \text{SPF}_{H3} > 3.4$).

### 3.1.1 Participant recruitment and case study sampling

The primary metric for the selection of case studies was their SPF at boundary level H3 ($\text{SPF}_{H3}$), calculated for the same annual monitoring period (01/11/2013 – 31/10/2014) and using a dataset, consisting of 351 sites, named sample S1 for the purposes of this report. This dataset was the first of a series of datasets obtained from different phases of data analysis of the 699 RHPP sites resulting from the initial RHPP data analysis (Andrew Stone, Summerfield, Gleeson, Paterson, et al., 2015) and was the most current dataset, in terms of SPF calculation reliability, at the time of the case study sampling. The datasets utilised in the case study selection and analysis and the respective data cleaning and filtering processes are described in subsection 3.3.2. The recruitment approach was based on an opt-in basis, with the 351 RHPP site occupants in sample S1 being invited to take part in the study. The process involved three stages: (a) initial opt-in prompt via email or post, (b) case study sampling and follow up on selected participants, and (c) final arrangements with confirmed participants.

**Opt-in prompt**

The flow chart of Figure 3-1 depicts the invitation process, whereby all 351 possible participants were invited via email or post to register their interest in the study. All of them had previously taken part in BEIS’s RHPP monitoring scheme. A sample of the cover letter and invitation they were sent can be found in Appendix B. The invitation included a brief description of the interview and site investigation routine, as well as information on the RHPP HP analysis project and the relative performance of their HP within the trial. This was based on the prima facie results of the preliminary analysis, available at the time, that was later superseded by subsequent analysis and more robust datasets (see subsection 3.3.3 and Table 3-3). Owner occupiers were approached directly whereas social tenants were contacted through their Registered Social Landlord (RSL), who invited their tenants to participate at their discretion. Overall, contact was attempted with 117 owner occupiers and 31 RSLs (corresponding to 234 sites). Suitable

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3 Corresponds to what the RHPP Case Study Report refers to as the “preliminary and unpublished” dataset (Lowe et al., 2017a)
contacts were identified for two-thirds of the RSLs, of which only half established contact with tenants. Of the 69 social sites eventually contacted, a positive response was obtained from approximately one-fifth. Together with one-third of the owner occupiers who responded positively to the participation request, the number of potential participants reached 49, i.e., an overall positive response rate of 30%.

Case study sampling and piloting

Of the 49 householders who volunteered, 20 were finally selected based primarily on the relative SPF\(_{H3}\) distribution of their HP, as drawn from sample S1, and presented in Figure 3-2, with the addition of one pilot case. Secondary parameters, i.e., location, ownership, and HP and emitter type, were also taken into consideration to ensure a good divergence of variables in the sample, where possible. These parameters were selected with a view to developing an understanding of the variation in HP performance. The selection targeted those HPs at the two ends of the bell-shaped distribution, i.e., those with SPF\(_{H3}\) higher than 3.4 and lower than 2.0, as well as a few in the middle range (subsection 5.2.3 explains why final SPF\(_s\) were calculated at boundary level H4). These initial SPF estimations were eventually re-evaluated in four cases (CS07, SC09, CS15 and CS21), using an updated dataset that is thought to be more robust due to the additional data cleaning performed that removed significant data anomalies. This is explained further in section 4.4.
Figure 3-1: Flow chart of the process of invitation to participate in the case study investigation.

Figure 3-2: The distribution of heat pump efficiency for the 49 volunteer sites and the final selection of 21 case studies based on the weather adjusted SPF\textsubscript{H3} estimates for sample S1.
As shown in Figure 3-3, the final sample yielded a good geographical distribution in relation to the population that participated in the RHPP field trial, covering Wales, Scotland and the North and South of England. It also included private and social householders, ASHPs and GSHPs and a variety of heat emitters, *i.e.*, radiators, UFH or a combination of both, presented in Table 3-1. Overall, a higher number of owner occupiers volunteered in comparison to RSL owners, *i.e.*, at an approximate rate of three out of five. The final case study sample presents 14 owner-occupied and 7 social houses, the latter of which fall into two groups in terms of RSL ownership, location and building characteristics, *i.e.*, CS02-05 and CS06-08. The two groups of identical or very similar building structures and layouts were purposefully selected so that their comparison could provide insights into the effect of occupant behaviour on HP performance. Finally, similar numbers of ASHPs (n=10) and GSHPs (n=11) were selected, one-third of which had UFH and the remaining had radiators.

![Figure 3-3: Locations of the 49 volunteer sites on the map, where the final selection of 21 is marked with a black circle around a red dot for owner occupiers and a green dot for social tenants.](image)

One additional case was chosen to allow the site investigation procedure to be piloted. This included interviews with occupants, thermal imaging, building measurements and site investigation of the HP systems and their monitoring equipment. The qualitative data collection methods are described in detail subsections 3.2.2 and 3.3.3. The data collected for the pilot
case were used to test the boundaries, tools, and data collection instruments. The aim was to assist the refinement of data collection for the main sample of the 20 case studies. Eventually, the pilot case was included in the analysis since (a) the data collected were of sufficient quality, (b) only minor changes were made to the topic guide and the overall inspection process in comparison to what was followed in subsequent cases, and (c) as well as strengthening reoccurring patterns, it also provided some unique insights as to what might be affecting HP performance in the field. The main contributions of the pilot to the subsequent site investigation process relate to an increased awareness in the following areas:

- the limitations on the data collection, arising from time restrictions that can take place within a 2- or 3-hour visit;
- the difficulty or inability associated with assessing the technical quality of installations since many parts are hidden (e.g., ground loops/UFH), in hard-to-reach areas (e.g., loft installations) or researchers are not allowed to interfere with them (e.g., interfering with HP controls);
- the possibility of technical failure of the site investigation equipment/batteries;
- the likely weather condition interference with the quality of externally recorded thermal imaging (e.g., masking effects due to high winds, sun, or rain);
- the benefits associated with early in the day site visits due to the interviewers’ lower levels of physical and mental fatigue and the higher likelihood of obtaining better thermal and visual images.
Table 3-1: Summary of the 21 case study characteristics as observed during the site investigations – entries in brackets were either blank in the RHPP metering database or denoted as erroneous.

<table>
<thead>
<tr>
<th>ID</th>
<th>SPF</th>
<th>Ownership*</th>
<th>Occupants</th>
<th>HP type</th>
<th>Emitter type</th>
<th>Previous fuel</th>
<th>Dwelling type</th>
<th>Age</th>
<th>Area (m²)</th>
<th>Bedrooms</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS01</td>
<td>2.4</td>
<td>P</td>
<td>[2-3]</td>
<td>ASHP</td>
<td>UFH</td>
<td>[N/A]</td>
<td>[Detached]</td>
<td>[2011-12]</td>
<td>[210]</td>
<td>4</td>
</tr>
<tr>
<td>CS02</td>
<td>2.6</td>
<td>S</td>
<td>[1]</td>
<td>ASHP</td>
<td>Rads</td>
<td>[Gas]</td>
<td>[Mid-terrace]</td>
<td>[1954-64]</td>
<td>[50]</td>
<td>[1]</td>
</tr>
<tr>
<td>CS03</td>
<td>2.5</td>
<td>S</td>
<td>[1]</td>
<td>GSHP</td>
<td>Rads</td>
<td>[Gas]</td>
<td>[End-terrace]</td>
<td>[1954-64]</td>
<td>[50]</td>
<td>[1]</td>
</tr>
<tr>
<td>CS04</td>
<td>3.1</td>
<td>S</td>
<td>[1]</td>
<td>GSHP</td>
<td>Rads</td>
<td>[Gas]</td>
<td>[End-terrace]</td>
<td>[1954-64]</td>
<td>[52]</td>
<td>[1]</td>
</tr>
<tr>
<td>CS05</td>
<td>2.6</td>
<td>S</td>
<td>[2]</td>
<td>GSHP</td>
<td>Rads</td>
<td>[Gas]</td>
<td>[Mid-terrace]</td>
<td>[1954-64]</td>
<td>[52]</td>
<td>[1]</td>
</tr>
<tr>
<td>CS06</td>
<td>2.9</td>
<td>S</td>
<td>[1]</td>
<td>ASHP</td>
<td>Rads+[HFC]</td>
<td>[Electr.]</td>
<td>[Semi]</td>
<td>[1930s-50s]</td>
<td>[34]</td>
<td>[1]</td>
</tr>
<tr>
<td>CS07</td>
<td>1.5</td>
<td>S</td>
<td>[2]</td>
<td>ASHP</td>
<td>Rads+[HFC]</td>
<td>[Electr.]</td>
<td>[Mid-terrace]</td>
<td>[1930s-50s]</td>
<td>[41]</td>
<td>[1]</td>
</tr>
<tr>
<td>CS08</td>
<td>2.6</td>
<td>S</td>
<td>[1]</td>
<td>ASHP</td>
<td>Rads+[HFC]</td>
<td>[Electr.]</td>
<td>[Mid-terrace]</td>
<td>[1930s-50s]</td>
<td>[34]</td>
<td>[1]</td>
</tr>
<tr>
<td>CS09</td>
<td>1.0</td>
<td>P</td>
<td>[2]</td>
<td>ASHP</td>
<td>Rads</td>
<td>Oil</td>
<td>[Detached]</td>
<td>1973</td>
<td>[164]</td>
<td>[4**]</td>
</tr>
<tr>
<td>CS12</td>
<td>0.7</td>
<td>P</td>
<td>[1]</td>
<td>GSHP</td>
<td>UFH+Rads</td>
<td>[N/A]</td>
<td>[Detached]</td>
<td>2008-09</td>
<td>[106]</td>
<td>2</td>
</tr>
<tr>
<td>CS14</td>
<td>3.9</td>
<td>P</td>
<td>[2]</td>
<td>GSHP</td>
<td>UFH</td>
<td>[N/A]</td>
<td>Detached</td>
<td>2012</td>
<td>[293]</td>
<td>[4**+]</td>
</tr>
<tr>
<td>CS15</td>
<td>0.8</td>
<td>P</td>
<td>[2]</td>
<td>GSHP</td>
<td>UFH+Rads</td>
<td>[N/A]</td>
<td>[Detached]</td>
<td>2011</td>
<td>[162]</td>
<td>4</td>
</tr>
</tbody>
</table>

* P stands for private and S for social housing. ** Including one bedroom added following the conversion taking place during the monitoring period. *** Including non-commercial guest room in a separate building. N/A: Not applicable
Final arrangements

The householders of the selected sites were contacted via emails or phone calls to arrange the final dates and times for the site investigation to take place. These were arranged within the project’s timescale, based on the concurrent availability of occupants and the research team. Following ethical approval from the UCL Research Ethics Committee (Approval ID: 6268/002), all participants were provided with an information sheet and consent form prior to the site investigation. These can be found in Appendix B. The former outlined the research and its aims and what their participation entailed. The latter highlighted the voluntary nature of the participation, the steps taken to protect their privacy, the right to withdraw from the project at any stage and potential risks and benefits.

3.1.2 Brief overview and data availability on the selected case studies

The 21-strong case study sample included 14 owner-occupied and 7 social households. The interviews and site investigations took place within 2 months, starting in late November 2015 and ending in late January 2016. The case studies were identified using the initials CS (Case Study) followed by a two-digit number denoting the order in which the case studies were visited. The time the researchers spent at each case varied between 2 and 3 hours, including the interview and site investigation routine. All installations were found to have benefited from the RHPP fund but only two-thirds of the occupants received the Domestic RHI fund (described in subsection 2.2.2). Excluding newbuilds, the fuel that the HP replaced was predominantly oil, followed by equal numbers of cases of electricity and gas.

Table 3-1 provides a breakdown of the main characteristics per case study (corrected where required based on the data collected on-site), where the entries in brackets denote a mismatch between the data collected during the site investigations and the metadata available in the RHPP metering database. The latter was handed to the research team at the onset of the RHPP project. Further detailed information on the household, dwelling and technical characteristics of the HP installation, as well as the control and usage of heating systems, overall energy costs and occupant perception on comfort and satisfaction can be found in section 5.1 and Appendix C. Comparison between the data collected during site investigations and the data collected by subcontractors as part of the original RHPP project revealed a great deal of discrepancy, either missing or incorrect entries. The ownership and HP type information were found to be consistent, but this was not always the case with emitter types. In one-third of the cases, a single heat distribution system was recorded, i.e., radiators or UFH, whereas in reality a combination of both or radiators and hydronic fan convectors4 (HFC) was present.

4 Wall-mounted fan convector connected like a radiator to the central heating system.
The RHPP metering database included no information on household or dwelling size for the case study sample. Total floor area (TFA) was extracted from EPCs, obtained from the government’s publicly available repository (DCLG, 2021), and corroborated with site survey measurements and/or architectural plans obtained during the site visit. The household size was also obtained through observation and the occupants’ narratives (elicited from interviews, described in subsection 3.2.2), as in some cases there were changes in the occupancy numbers taking place during the monitoring period. An accurate dwelling type and age entry in the RHPP metering database was available in one-fourth and two-thirds of the cases, respectively. The entries on the number of bedrooms were accurate or available approximately half the time and in two cases this was due to internal layout conversions that took place post HP installation. The entries recording previous heating fuel were accurate in one-third of the cases. The remaining were either missing or incorrect, in equal numbers.
3.2 The Mixed-methodology Framework

The mixed-methods approach involves the collection, analysis, and integration of both quantitative and qualitative data, as these combined provide greater insights to the thesis research questions. The comparison of qualitative and quantitative results ensure multiple angles of the same scene are recorded, providing more evidence and thus a richer perspective. In addition, the overall strengths compensate the inherent weaknesses of each method. For example, quantitative research is weak in understanding the context in which people behave, which can be counterbalanced by qualitative research, whereas qualitative research weaknesses lie in the possible interpretation bias induced by the researcher and the difficulty associated with the generalisation of findings.

Prior to each site visit, the monitored data and metadata provided as part of the RHPP project were utilized to establish as much information as possible on the profile of each installation and the environment it was installed in. The metadata information available included location, ownership, HP type/size and installation date, emitter system type, and annual heat-generation estimations for all case study installations. Information that was available only in part included dwelling age and size, previous fuel type, HP configuration, DHW sources, renewable energy systems (RES), monitoring equipment, metering schematic types and other data included in installer’s reports. As explained in subsection 3.1.2 and later in subsection 3.2.3 on triangulation, only after the site visit investigation did further discrepancies between the metadata available and real conditions become clear.

In terms of the monitored data, the RHPP project data analysis team provided information on the energy consumed/produced for SH and DHW and daily usage patterns, and pinpointed any unusual aspects of the installation, efficiency, or metering. These were then complemented and corroborated with the interview and site survey data collected from case study visits. The quantitative and qualitative data collection methods utilized in this study are detailed in subsections 3.2.1 and 3.2.2 respectively. Subsection 3.2.3 elaborates on the triangulation method and the discrepancies identified.

3.2.1 Quantitative data and metadata from monitoring

The monitored data that supported the wider analysis in this study were sourced through the government’s RHPP scheme. The scheme was available to both owner occupiers and social landlords and necessitated the agreement to the installation of metering equipment alongside the HP installation to assess their performance. Of the 14,000 HPs installed through the scheme, more than 700 were metered for a period of between 1 and 3 years, i.e., between the
start of November 2011 and end of March 2015, with mostly mild winters. The methodology utilised for the collection of high-frequency data that would enable the SPF calculation for the sites involved is described in detail by Wickins’ preliminary results report (2014). Wickins also comments on the methodological complexity that inevitably arises with large-scale monitoring, *i.e.*, necessitating the adaptation of the monitoring strategy to differing installation configurations and identifies possible sources of uncertainty and measurement error.

Monitored data from 699 sites was provided to RAPID-HPC in the form of Matlab files, one for each monitored day of each site. These included electricity, heat, temperature, and water flow measurements recorded at various parts of the system every 2 minutes. The significance of important variables missing from the monitored data is discussed in Table 7-2. Table 3-2 presents all the monitored variables provided by BEIS. The energy consumption of the system’s resistance heaters was measured separately, albeit not consistently, but that of auxiliaries, such as circulation pumps and fans, the supply air fan or the ground loop pump power consumption was not. Descriptions and explanations of the technical features of HPs are included in section 2.1, subsection 2.3.5 and

Table 2-5. Since a wide range of HP configurations was monitored, different variable combinations were monitored at different sites. For this purpose, a list of monitoring installation schematics grouped into 20 main categories, with sub-categories, also accompanied the monitored data. The main groups are categorised based on DHW vessel location (*i.e.*, integral or non-integral), SH and DHW pipework configuration (*i.e.*, two-pipe or four-pipe), and the presence of a separate or non-separate electricity supply to the SH and/or DHW booster heater.

Those schematics that could be confidently assigned to the case study sample following the site visit and the inspection of the installation are listed in Appendix D. They also detail the intended location of the monitoring sensors utilised for any given HP installation configuration. The visual inspection of the installations revealed several inconsistencies and, thus, the sites for which accurate schematics were identified following the site investigations are listed in Appendix D. Except for the two-HP systems of CS14 and the SH-only HP of CS20, no matching schematics of those accompanying the monitored data were identified for CS11, CS13, CS14, CS17, CS18 and CS19. Based on this final revision of the case study sample schematics identified during the RHPP project, the information collected from site investigations and from manufacturers’ data sheets, a unique *tailored schematic* was put together for each HP installation. These are presented in Appendix E, alongside the detailed architectural drawings of the case study dwellings.
Table 3-2: The complete set of the RHPP-monitored variables.

<table>
<thead>
<tr>
<th>ID</th>
<th>Monitored Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eboost</td>
<td>Electricity used by the whole system in-line heater</td>
<td>Wh</td>
</tr>
<tr>
<td>Edhw</td>
<td>Electricity used by the immersion heater on the DHW tank</td>
<td>Wh</td>
</tr>
<tr>
<td>Ehp</td>
<td>Electricity used by the HP (may include in-line heater and circulation pump)</td>
<td>Wh</td>
</tr>
<tr>
<td>Esp</td>
<td>Electricity used by the SH in-line heater</td>
<td>Wh</td>
</tr>
<tr>
<td>Fhp</td>
<td>Water flow rate to SH and DHW system (if the HP provides both)</td>
<td>L/2 min</td>
</tr>
<tr>
<td>Fhw</td>
<td>Water flow to the DHW system</td>
<td>L/2 min</td>
</tr>
<tr>
<td>Hhp</td>
<td>Heat leaving the HP as measured on circulation system</td>
<td>Wh</td>
</tr>
<tr>
<td>Hhw</td>
<td>Heat entering the DHW system from the HP</td>
<td>Wh</td>
</tr>
<tr>
<td>Tco</td>
<td>Temperature of water flow after the condenser</td>
<td>°C</td>
</tr>
<tr>
<td>Tin</td>
<td>Temperature of refrigerant leaving the evaporator (for ASHP) or of the fluid</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>returning from the ground loop (for GSHP)</td>
<td></td>
</tr>
<tr>
<td>Tsf</td>
<td>Temperature of water flow to the SH system</td>
<td>°C</td>
</tr>
<tr>
<td>Twf</td>
<td>Temperature of water flow to the DHW system</td>
<td>°C</td>
</tr>
</tbody>
</table>

As well as the schematics, the metadata included MCS certificates, RHPP monitoring installation checklists/photos for each site, an incident log file and a ‘metering database’. The latter summarised the MCS certificates and RHPP monitoring installation checklists and provided additional but very limited information on the building (i.e., type, age and number of bedrooms), the HP components (e.g., heat emitters, circulation pumps, DHW cylinder and ground loops), previous heating fuel (if applicable), supplementary heating sources (if applicable) and any incidents recorded in relation to the monitoring equipment. By limited, it is meant that no detailed information was provided, for example, on the emitter system configuration and sizing other than the type of emitters present. Even then, this information was not made consistently available for all sites and the same was true for the installers’ monitoring installation photos and the incident log files. Very few sites presented information on circulation pump settings/power, supplementary heating, type of ground loop and the size of DHW vessels.

Of those variables not recorded (see subsection 3.2.1), perhaps the single most important was the indoor air temperature, as this could provide valuable insights into the HP’s operational conditions, the validity of the monitored data, the use of supplementary heating and occupant satisfaction. External weather conditions, such as temperature, are also important as they affect the HP’s operation as well as the occupants’ need for heating. BEIS did not include indoor/outdoor temperature measurements due to budget constraints. Other information that
could have facilitated an in-depth understanding of a HP’s technical performance include the total amount of household energy delivered to each case (electricity and any other fuel utilised for supplementary heating and cooking, e.g., gas, wood burners), as well as that produced by any RES technologies present, the DHW tank temperature and detailed information on the ground loop and UFH design.

3.2.2 Qualitative data collection methods – the interview and site investigation routine

The qualitative data collected during the site investigations stem from the interviews with occupants, the site surveys and the direct observation of internal environment and equipment installed by the researchers (see section 3.3 for further information). Detailed information on the roles and responsibilities of the RHPP project team are included in section 1.1. The semi-structured interview guide and site investigation routine were jointly designed by the RHPP project team and BEIS. The former was based on BEIS's briefing and the post-occupancy evaluation guide developed as part of the Facilitation, Learning and Sharing programme (FLASH) project (Chiu, Lowe, Raslan, Altamirano-Medina, & Wingfield, 2014). It was also informed by the initial findings of the RHPP monitoring campaign (Stone, Summerfield, Gleeson, Paterson, et al., 2015). The interview guide, included in Appendix B, was aimed at encouraging conversation with participants in order to bring out the unique nature and content of each case. Piloting resulted in only a few minor changes being made to the original plan. The structure of the final topic guide was divided into four distinct parts:

A. Briefing session

- Researcher introductions, explanation of the study aims and objectives and description of the site investigation routine.
- Participants were handed an information sheet and consent form.
- Initiation of audio and image recording (both regular and thermal), providing that participants consented.

B. Confirmation of details

- Participants confirmed their personal details and provided general information about their household’s characteristics and the decision-making process in relation to their HP installation.

C. Walk-through
- Context-specific information gathering on house configuration, structure type, internal conditions and equipment installed.
- Information collection on a room-by-room basis through observation, image recording and discussion with participants.

D. Sit-down session

- Elicitation of information on occupant experiences with the current and previous heating system, their habits, energy use, lifestyle, and perception of thermal comfort.

Except for CS12, all households permitted extensive photography and audio recording of the discussions. In CS12, photography was limited to the HP installation only and, at the occupant’s request, audio recording was not undertaken. Instead, detailed notes were taken by the researchers both during and after the site investigation.

### 3.2.3 Data accuracy and triangulation

A wealth of qualitative information was made available in addition to the monitored data and metadata after the site investigations. The data availability through different sources, such as monitoring and the associated metadata, the interviews with occupants and the site surveys enabled triangulation. Utilising a variety of methods to collect data on the same topic increases the validity of results and reduces bias by identifying aspects of complex phenomena more accurately since they are approached from different perspectives (Denzin, 2017).

Triangulation was applied both on the wider RHPP dataset (by the RAPID-HPC statistical analysis team) and the case studies material. The former concerns cross-checks performed between different metadata sources, between metadata and monitored parameters, and between monitored parameters. These are described in subsection 3.3.2. The qualitative case study data collection provided the opportunity for a deeper and more extensive understanding of the complexity underlying HP performance. Section 5.1 provides an overview of the case study characteristics, following triangulation between the range of qualitative sources available (e.g., occupants’ narratives, researchers’ direct observations, and the technical paperwork available). Results from the triangulation of qualitative and quantitative data sources are included in section 5.2, discussing the profile of the monitored data considering the qualitative data available.

Throughout the data cleaning, organisation and analytical process, the four basic triangulation types proposed by Denzin, (2017) were exploited, i.e., triangulation between data, investigators, theories and methods. *Data triangulation* includes data comparison on a temporal (e.g.,
reflecting on the dynamic changes of monitoring profiles or the occupant experiences over time) and spatial level (e.g., considering different locations) and in between stakeholder perceptions, i.e., obtaining views of multiple occupants or researchers on the same topic etc. When it comes to investigator triangulation, a diverse interdisciplinary team (known as RAPID-HPC), including the author, was involved in the analysis and interpretation of both quantitative and qualitative data to produce the RHPP project reports. The active involvement of researchers from different disciplines (e.g., architecture, engineering, and social sciences) as part of the RHPP project enabled multiple perspectives on the interpretation of a single set of data, also known as theory triangulation. Finally, methods triangulation utilised data gathering from the range of qualitative and quantitative data collection methods described in subsections 3.2.1 and 3.2.2.

The case study data triangulation process revealed a great deal of inconsistency/inaccuracy relating to various data sources, including the programme specification, the monitored data and the metadata accompanying the monitored variables, examples of which are provided below.

- **Programme specification** - Even though the RHPP programme was only intended to support the installation of HPs in houses that were off the gas grid, gas cookers were present in four social houses, according to their tenants.

- **Metering database** – This included some miscategorised HP types and missing or erroneous information, such as those recorded in installers’ checklists and MCS certificates. Conflicts were also identified between the metering schematics and the data recorded in the metering database, such as the incorrect MCS certificate number listed for CS02. Only radiators and/or UFH were listed, however, social houses CS06-08 also included hydronic fan convectors and combinations of both radiators and UFH had been erroneously recorded in the UFH-only systems of CS10, CS15 and CS19. Fields containing irrelevant or ambiguous information were also identified, e.g., manufacturer names, models or a range of pumping power being reported instead of the circulation pump power.

- **MCS certificates** – MCS certificate inconsistencies were spotted in relation to the overall declared net capacity that was between 5 and 16 kW instead of the 6 to 14 kW range recorded, the number of HPs installed, i.e., two were observed in CS10 (14 and 8.5 kW) but in CS03, only one 22.5 kW HP was recorded, and even the type of technology installed, i.e., a solar panel model, was erroneously listed in the MCS certificate instead of the HP.

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5 A two HP configuration was one of the options suggested in the specific HP range technical documentation.
• **EPC documentation** – Several inaccuracies were identified, such as incorrect HP type recording, thermostatic control ignored (CS08) and, crucially, insulation level underestimation (CS07, CS09, CS12, CS19, CS20).

• **Metering schematics** – As mentioned earlier in subsections 3.2.1 and 3.3.2, the RHPP data analysis team, upon cross-checking the information included in the metering schematics and the monitored data, identified that many had been inaccurately applied. The validity of these schematics was tested against the combination of monitored variables available in each case and a revised list of schematics was produced. Even then, the site investigations revealed that seven of the reviewed schematics did not match the installation configuration identified on site and the schematic numbers were revisited once again. The final list of schematics can be found in Appendix D. As an example, the schematic for CS21 did not match the installation configuration identified during the site investigation and none of the schematics available present an ASHP with a thermal store.

• **Monitored data** – The two HPs present in CS10 were recorded as one in the metadata, and their combined peak power was listed. Of the 11 immersion heaters identified through the site investigations and manufacturer data as being in the DHW vessels (CS01-02, CS06-11, CS18), buffer vessels (CS19-20) and thermal store (CS21) of the case study sample, monitored data were available for only four (CS01-02 and CS09-10) and in CS06, CS07 and CS08 they were possibly misrecorded as in-line heaters. For the rest, it is not clear if the variable was not recorded or if the output was always null. Any additional systems providing hot water (e.g., standalone DHW immersion heater in CS20) or generating energy [e.g., solar thermal or photovoltaic (PV)] were not metered. A detailed presentation of the case-study monitoring profiles alongside the data inconsistencies/anomalies observed is included in section 5.2.

In addition to discrepancies between the different data sources utilised in the case study analysis, the site investigations also revealed details of the HP installations that were either not included or were ambiguously represented in the metadata. For example, even though the presence of immersion heaters in DHW vessels was explicit in the schematics (although not always accurate), this was not the case for in-line heaters placed in the external casing of Monobloc ASHP units, which were always marked with the phrase “if fitted”. The HP system investigations enabled the identification of in-line immersion heaters to some extent, but this was not always possible as many HP components were installed in enclosures or hard-to-reach-areas. Eventually, the presence of in-line heaters in approximately half the cases (CS03-CS05, CS09 and CS12-CS18) was confirmed through the manufacturers’ technical specification manuals. In terms of immersion heaters, nine were identified in CS01, CS02, CS06-CS11 and
CS18, in one of the following locations: DHW vessel, buffer vessel or thermal store. Of these, the immersion heaters in CS11 and CS20 were not metered. In addition, the heat exchangers present in CS10 and CS11 and the multiple circulation pumps present in several case studies were also not noted in the schematics or elsewhere in the metadata.

3.3 Data Management and Analysis

A large amount of data was eventually generated in relation to the 21 case studies using the data collection methods described in section 3.2. This comprises monitored data, audio recordings of interviews with occupants, visual and thermal imaging, field notes and output from other direct observational methods, such as measurements of the building and the visible parts of the heat-emitter systems. In some cases, the occupants were able to provide bill paperwork, HP documentation and/or architectural drawings. Before the site visit investigations took place, a crude profile was established for each case study, based on the monitored data and metadata, as well as the EPC available. The initial case study profile was refined through detailed comparison and corroboration with the post-visit data, after the methodical synthesis of the latter. The following sections describe the data storage, synthesis, and analytical process. The data storage and protection mechanisms in place and the ethical practices followed are described in subsection 3.3.1. Subsection 3.3.2 describes the monitored data analysis and discusses SPF calculation considerations and subsection 3.3.3, the qualitative data processing and analytical methods.

3.3.1 Data protection and ethical practice

Both the pre- and post-visit material were stored on ‘Bartshare’, a physically and electronically secure server suitable for the storage of confidential data in accordance with the UCL Information Security Policy. This service is fully compliant with the Data Protection Act 1998. The monitored sites were anonymised with the use of unique IDs, which were also used to link monitored and site survey data. On rare occasions, when data containing confidential information had to be transferred outside the secure server for processing and analysis, it was stored on encrypted and password-protected laptops or desktops.

Eventually, all case study data were fully anonymised to minimise risks relating to personal data disclosure. All direct identifiers (e.g., names, addresses, postcodes and phone numbers of all stakeholders) were removed from the transcripts, photographs and any relevant documents provided (MCS certificates, EPC etc.). The transcription work was carried out largely by the author and outsourced only in part. The names and addresses were removed from recordings before outsourcing. The final proof listening/reading and anonymisation was implemented in all
cases by the author. In the transcripts, the occupants’ names have been replaced by pseudonyms. Any other names mentioned (e.g., manufacturers, installers, energy providers, members of the occupants’ family/social circle and interviewers) were typified using a tag that signifies their general role. A unique two-digit identification code was included in the case of individuals and companies relating to the HP installation (e.g., company 43, installer 22) to retain as much meaningful content as possible, since some of them appeared multiple times in the case study sample. The HP manufacturer codes were the only unique three-digit codes for each case study to ensure manufacturer anonymity. Demographic information, such as gender, occupation and location were only presented in aggregate format (see Table 3 of Appendix C).

Under the RHPP contract terms, all non-anonymised technical and social case study data collected were erased on the 12th of December 2017. The anonymisation techniques described in this section were applied rigorously across all transcripts, photographs and other documents that were retained after the identifiable data deletion deadline. The present thesis and any associated datasets are fully anonymised. All data collected as part of the site investigations were approved by BEIS and the UCL Ethics Committee. The HPs and their monitoring equipment had been previously installed by other institutions (BRE and EST), which had their own ethics approval procedures in place.

### 3.3.2 Monitored data analysis and Seasonal Performance Factor considerations

BEIS assigned RAPID-HPC with the analysis of the RHPP-monitored data and metadata to assess the efficiency of the 699 HPs installed as part of the RHPP scheme and provide insights into their performance. The work that started in December 2014 was completed within approximately 28 months. Stone et al. describe the initial data cleaning and analysis performed in the Data Quality (Stone et al., 2015) and Initial Findings (Stone, Summerfield, Gleeson, Paterson, et al., 2015) internal BEIS reports. Further information on the processing applied to the large RHPP dataset can be found in Appendix F.

The preliminary data cleaning and analysis performed by RAPID-HPC was based on 351 sites, known as the sample S1. Table 3-3 summarises the site selection criteria and the SPF calculation method applied. The SPF calculation at boundaries H4, H3 and H2 is detailed below:

- **SPF at boundary H4** - SPF\textsubscript{H4} calculations derive directly from measurements, i.e., by dividing the total heat output by the total electricity consumption. The total heat output calculations add up the total heat produced by the HP (Hhp) and any heat provided by backup resistance heaters (Eb, Esp and Edhw), assuming they operate at 100% efficiency. The total electricity output calculations add up the electricity used by the HP (Ehp) and any backup resistance heaters present (Eb, Esp and Edhw). In most cases,
the circulation pump is also integrated into the HP unit and thus its electricity consumption and heat production are included in Ehp and Hhp, respectively. The calculations were adjusted for sites not falling in this category. Should there be a HP integrated in-line heater, then Hhp and Ehp also include the energy associated with this in-line heater.

- **SPF at boundary H3** - The calculation of SPF\textsubscript{H3} requires the subtraction of the circulation pump power from the total electricity and heat output at level H4, however, the associated energy was not metered directly in the RHPP trial. Since the number of circulation pumps, their power and speed settings in the metadata were highly ambiguous and the electricity meter resolution of 1 Wh per 2 minutes (equivalent to 30 W) was too low to pick up some of the pump power demand, some assumptions were made\textsuperscript{6}. The reasoning, robustness and likely impacts on the SPF calculation for these simplified assumptions are explained in detail elsewhere (Summerfield et al., 2017). The resulting electricity consumption of the circulator pump is assumed to be equal to the heat contribution and thus an equal amount is subtracted from the electricity and heat output at boundary level H4.

- **SPF at boundary H2** – SPF\textsubscript{H2} calculations require the subtraction of the energy associated with any backup resistance heater from the electricity and heat outputs at boundary level H3. Unfortunately, this was not always straightforward as many in-line resistance heaters were built into the HP unit and thus not metered separately. As explained by (Summerfield et al., 2017), the frequent offsets between the sensors measuring the temperature of the water flow flowing out of the condenser (Tco) to the SH (Tsf) and DHW system (Twf) do not facilitate the heat input estimation of an unmetered backup heater. In addition, a reliable algorithm that would pick up such events automatically was not developed at the time of the study.

\textsuperscript{6} The calculation was based on the fraction of the rated pump power to the design flow rate being 280 W/kg/s, the denominator of which is the 95\textsuperscript{th} percentile of the monitored flow rate (Fhp) in each site. The circulation pump power is calculated by multiplying the rated power with the flow rate (Fhp) for each time step and by dividing the product by the estimated design flow rate, i.e., linearly scaling down the rated power consumption with the use of the measured flow rate.
Table 3-3: Characteristics of the RHPP raw dataset and the sub-samples S1, S2 and S3 utilised in SPF calculations of the wider RHPP project (where SPF\textsubscript{H4} was utilised for comparison with traditional central heating systems, SPF\textsubscript{H3} was utilised in the case study selection, and SPF\textsubscript{H2} enabled the calculation of HP efficiency based on HP total energy measurements), while the PhD case study work is largely relevant to sub-sample S1 and SPF\textsubscript{H4}.

<table>
<thead>
<tr>
<th>Raw dataset</th>
<th>Number of sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw dataset</td>
<td>699</td>
</tr>
</tbody>
</table>

**Sample S1**

- **Number of sites**: 351 (253 ASHP and 98 GSHP)
- **Selection criteria**:
  - Metadata availability: no strap-on sensors\(^7\) present (raising temperature recording quality concerns); data for at least one of the important monitored variables utilised in the analysis; no physically implausible data recordings; no continuous missing data period of ≥14 days and/or ≥250 days of missing data.
- **SPF calculation method**:
  - Based on a fixed 12-month period starting 01/11/2013; no weather correction applied; refers to the weighted average of both SH and DHW.

**Sample S2**

- **Number of sites**: 418 (319 ASHP and 99 GSHP)
- **Selection criteria**:
  - No strap-on sensors present; 13 consecutive months with at least five days per month of concurrent heat and electricity readings, in which the water flow rate difference between the 1st and the 13th month was minimal; schematic identified matching the monitored variables present.
- **SPF calculation method**:
  - Based on the most recent 1-year period of the 13-month period selected per site; no weather correction applied; refers to the weighted average of both SH and DHW.

**Sample S3**

- **Number of sites**: 385 (293 ASHPs and 92 GSHPs)
- **Selection criteria**:
  - Cropping all sites with 1.5>SPF>4.5 in addition to the selection criteria for sample S2 above.
- **SPF calculation method**:
  - Same as for sample S2 above.

The calculation of SPFs at boundary levels H4, H3 and H2 for the sample S1 during a fixed 12-month period and without the use of weather correction led to the identification of many atypical SPFs. At that stage, a few sites with implausibly high or low SPFs (i.e., close to zero or higher than 9) were removed from the analysis, as well as those with obvious errors. The inclusion of sites and data points was investigated further in subsequent analysis.

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\(^7\) 99 RHPP sites with known strap-on sensors were removed, however strap-on sensors may still remain elsewhere in the sample.
The final and most complete statistical analysis of SPFs was undertaken as part of the RHPP Performance Variations Report (Love et al., 2017), aiming at the provision of insights into the variations in performance observed in the RHPP dataset. This process necessitated the formulation of additional subsets, details on the most relevant of which can be found in and Appendix C. Sample S3 is the most robust of all RHPP sub-samples and the most stable for statistical analysis purposes. Figure 3-4 depicts SPF distributions for sample S3 and Table 3-4 presents the main statistical metrics of the sample. These show that GSHPs perform consistently better than ASHPs by approximately 0.3 and that the difference between SPF_{H2} and SPF_{H4} is only 0.2. Both differences are small compared to the interquartile range. The authors (Love et al., 2017) acknowledged that sample S3 may still incorporate data/sites with metering errors and the statistical analysis performed revealed a significant number of new issues. However, it was not possible to identify these issues through the data analysis of the large RHPP dataset due to time and resource limitations, as well as the need for additional data and background information that could only be collected through an in-depth site investigation.
Table 3-4: Mean and median efficiencies for ASHPs and GSHPs within sample S3.

<table>
<thead>
<tr>
<th>Efficiency level</th>
<th>HP type</th>
<th>N</th>
<th>Mean (95% confidence interval)</th>
<th>Median (interquartile range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPF2</td>
<td>ASHP</td>
<td>292</td>
<td>2.64 (2.60 - 2.70)</td>
<td>2.65 (2.33 - 2.95)</td>
</tr>
<tr>
<td>SPF2</td>
<td>GSHP</td>
<td>92</td>
<td>2.93 (2.80 - 3.06)</td>
<td>2.81 (2.63 - 3.14)</td>
</tr>
<tr>
<td>SPF4</td>
<td>ASHP</td>
<td>293</td>
<td>2.41 (2.37 - 2.46)</td>
<td>2.44 (2.15 - 2.67)</td>
</tr>
<tr>
<td>SPF4</td>
<td>GSHP</td>
<td>92</td>
<td>2.77 (2.66, 2.89)</td>
<td>2.71 (2.48 – 3.02)</td>
</tr>
</tbody>
</table>

3.3.3 Qualitative data processing and analytical methods

The site investigations yielded a wide range of qualitative data, falling into four main categories: (a) the material deriving from interviews with occupants; (b) the visual and thermal photographic evidence; (c) the researchers’ direct observations, including detailed measurements and sketches of the building and heating system; and (d) the data provided by householders, e.g., bills, HP documentation and architectural drawings. Bill paperwork and technical documentation were provided either fully or in part in approximately half of the cases. Shortly after their collection, the raw data were organised, filtered, and corroborated with the pre-visit material (monitored data, metadata, and EPC) to create a structured database or master matrix facilitating the data analysis required as part of the RHPP project. Due to the tight project timescales, the audio recordings were initially transcribed in the form of summary notes for each case. Only after the end of the RHPP project were the audio recordings fully transcribed and analysed in detail. Similarly, the remaining data collected on-site were scanned through and methodically organised and analysed only after the end of the RHPP project. Since the author was the main interviewer in all cases, the data familiarisation started from the time of the site visit and was further enhanced during the summary note production, detailed transcription, and thematic analysis later. Memos of any emerging thoughts and ideas were kept throughout the whole process.

Other data sources, such as the researchers’ field notes and images were also utilised in the thematic analysis. Much of the information contained in images, sketches, and field notes, including radiator sizing and HP configuration, was incorporated in detailed building floor plans, facades and sections that can be found in Appendix E. These were based on the architectural drawings provided by householders and/or on the measurements and photographs taken during the site visits. The themes identified were eventually fed into a complex systems thinking diagram that facilitated the understanding of various variable interactions in relation to the research questions of this study.
The master matrix

The structure of the database was based on questions and topics deriving from the interview guide. The data extraction was manual and resulted in a master matrix with data grouped under six main areas:

- Social information and decision making,
- Dwelling information
- Technical information
- Control and usage of heating systems
- Overall energy cost
- Occupant perception on comfort and satisfaction

The aim was to obtain a preliminary understanding of the data under each area for every case study, as well as the case study sample as a whole. This process served the analytical purposes of the RHPP project, which was limited in time and scope. The matrix created as part of the RHPP project was based on summary notes and was revisited after the recordings were fully transcribed to ensure data reliability. The main parameters captured in the matrix are discussed in section 5.1 and presented in the detailed tables of Appendix C.

The transcription process

Each of the 2- to 3-hour occupant interviews were transcribed in an abridged ‘intelligent’ verbatim format, where filler words and any content not relevant to the analysis was removed. The first part of each interview, i.e., briefing session, was also omitted to reduce transcription time and avoid unnecessary repetition. Where it was not possible to obtain an audio recording, detailed field notes were taken. This was the case in CS12, at the occupant’s request, and only in part for CS16, where the last section of the interview was conducted over the telephone. As explained in subsection 3.3.1, all personal details were removed from the transcripts for data protection and confidentiality purposes. The full set of transcripts and the field notes accompanying CS12 and CS16, alongside a case study summary sheet containing dwelling and heating system technical information, have been uploaded on the UK Data Service (DECC, 2016, 2017b, 2017a). A sample transcript can be found in Appendix G.

Thematic analysis

The six main areas identified in the master matrix were utilised in the thematic analysis that followed the initial matrix-based analysis. The thematic analysis aimed at describing and summarising the occupants’ narrative alongside content from field notes and images to interpret its meaning and identify themes that categorise and summarise it in relation to the research
question. The coding framework was generated based only on these pre-determined codes. For the main analysis, the coding approach was bottom-up. The coding was done line-by-line using the NVivo qualitative data analysis software. Finally, 16 main themes were identified:

- Household profile
- Building profile
- Decision making
- HP system characteristics
- Satisfaction with training
- Control methods and ease of control
- Thermal comfort & indoor environment
- Occupant habits and lifestyle
- HP technical issues
- Economic profile and RES
- Satisfaction with HP
- Comparison with neighbouring properties
- Supplementary SH and DHW
- Experience with previous heating systems
- Preferred heating system
- Memorable quotes in relation to occupant experiences with the HP

The themes identified contained several descriptive and analytical sub-codes, up to three levels deep, and facilitated the transition from people’s descriptive experiences to the analytical/inductive interpretation of these experiences. These were influenced by grounded theory and served the formulation of a systems thinking integrating framework that is detailed in the following section.

3.4 Systems Thinking as an Integrating Framework

The application of systems thinking in the form of causal loop diagrams (CLD), implemented in the Vensim software (Ventana Systems, 2015), concern the qualitative representation of both qualitative and quantitative data. This was the final step in the analysis and the method that brings together the qualitative and quantitative material. This method facilitated a better understanding of the complex interrelationships between the HPs and the wider environment they interact within. This project utilised systems thinking to:

- identify the complex qualitative models that depict the heat pump systems’ interactions;
- hypothesize/theorise about the causes of HP system dynamics;
- identify important feedback structures that are thought to be responsible for the poor performance of HPs in the UK.

The use of CLD as a systems thinking tool necessitates a good understanding of the underlying principles and conventions, which are described in detail by (Sterman, 2000, 2018a, 2018b). In brief, a CLD is a simple diagrammatic representation of interacting elements, depicting the variables and their causal relationships in the form of arrow links. The arrows always point from a causal to an influenced variable. When two variables influence each other, either directly or
indirectly, then these variables are part of a ‘closed’ or ‘feedback’ loop, that is valid only if all arrows point in the same direction when moving around the loop. The ‘plus’ or ‘minus’ signs assigned to links indicate that changes, i.e., an increase or decrease, depending on whether the influencing and influenced variable move towards the same (+) or opposite (-) directions. A feedback loop can be balancing (negative) or reinforcing (positive) depending on the result of the multiplication of its positive and/or negative links. In a balancing feedback loop, the resulting multiplication is negative, indicating that the system regulates itself by opposing the original change, whereas a reinforcing feedback loop, enhances the original change, thus leading to growth or decay. Contrary to reinforcing loops, balancing loops are assigned with specific goals, i.e., reaching the system’s desired state by comparing to the actual state, such as a room thermostat that controls heat production to maintain the desired/set room temperature.

The thematic analysis described in the previous section, identified 16 main themes and several sub-codes. This study adopted an inductive coding approach, which is similar to systems thinking in terms of linking and drawing relationships between factors to build theory (Luna-Reyes & Andersen, 2003). Thus, the coding elicited within the themes also served the generation of CLDs. The main steps in the generation of CLDs through the incorporation of grounded theory were similar to those described by Kim and Andersen (2012) and Eker and Zimmermann (2016):

(a) open coding – the qualitative data were broken down in smaller entities, ranging from single words to whole paragraphs. These were compared and grouped into more abstract categories and a label was assigned to each phenomenon identified. As the coding progressed, these were often revisited and regrouped. Through open coding, the key variables were identified, and the boundaries of the system were set. These were limited to the insights provided in relation to the actual and perceived HP performance through interviews with occupants, the researchers’ direct and indirect observations and the technical data collected, all of which were mapped in Nvivo. Following the system boundary definition, the data segments were further filtered, and the analysis centred around the area of research interest.

(b) axial coding/conceptualisation – the fragmented data were reassembled, and causal relationships were identified between codes. The relationships identified were transformed into word-and-arrow diagrams. Multiple structures were then combined to form composite maps. This was first applied to the information drawn from literature, forming a literature-based CLD, which was then expanded to include the evidence obtained through individual case studies, thus forming 21 preliminary CLDs. This process incorporated the mental models of different stakeholders, i.e., as described by HP users and perceived by the author and through the author’s observations and technical data examination.
selective coding/integration – this final stage utilised selective coding in the sense that it connected and integrated all identified categories to generate theory. This required all preliminary CLDs to be merged, utilising implicit structures (i.e., structures that decompose causal relationships further) where required. The resulting case-study based CLD was the basis of a final cumulative CLD serving the identification of the most prevalent parameters and relationships. This was formed through an iterative process, where the strength of each theme was addressed by counting the instances of this topic in the case study sample and through their corroboration with literature. The comparison between the literature-based and case study-based CLDs facilitated the identification of potential knowledge gaps. The CLD development is described in detail in Chapter 6.

Overall, the causal maps distinguished between objective and subjective realities, such as between the actual SH availability and the SH availability as perceived by the case study occupants. According to Kim and Andersen (2012), the gap between the objective and subjective reality can be a source of ineffective decisions, as actors act to change their perceived reality. The aforementioned CLDs make these mental models explicit to improve decision making. Chapter 6 elaborates on the parameters affecting HP performance and their interrelations, as identified through the systems thinking approach.

3.5 Methodological and Design Constraints

Study limitations occur as a result of methodology and design choices and are thus largely beyond the control of the researcher (Simon & Goes, 2013). This thesis utilises case studies as the main methodology to approach the research question, as they are excellent for theory building. However, the observed causal relationships cannot be generalised as they may or may not be representative of similar entities and this would need to be confirmed through further research. Another limitation relates to the occupant recollections of events that may involve misconceptions relating to the timing and interpretation, particularly as many of those discussed occurred several years before. The general lack of occupant ability to understand and express themselves in precise technical terms may also have been a source of misconception or misinterpretation on the researchers’ side (Lowe et al., 2017a). The case study sample was also found to be biased, since the volunteers were primarily people spending most of their time at home, it being easier for them to accommodate the interview and site investigation. It was not possible to interview installers and RSLs as part of this study and thus their view of the challenges faced could not be factored in the analysis. Both occupant and researcher bias can skew the research findings, and this was counteracted to some extent through the triangulation between different data sources and data collection methods, where possible. Despite the
application of triangulation, there were areas where it was still unclear how conflicts arising in the interpretation of findings could be resolved. Limitations also lie in the decision-making relating to the coding and systems thinking application, e.g., in terms of content interpretation, treating conflicting causal statements and merging multiple mental models. The system modellers inevitably influences the nature of what is represented in CLDs as their subjective influence cannot be completely eliminated (H. Kim & Andersen, 2012).

Evidence from instruments, such as the monitoring data indirectly acquired as part of this study, should be treated with caution as their accuracy could not be ascertained, particularly due to the very limited and often erroneous accompanying metadata. Similarly, caution should be exercised with the thermal imaging and utility bills obtained. Thermal imaging output can be influenced by weather conditions and time of day, however it was not always possible to avoid such influences as the site visit timings were based on occupant availability. Utility bill uncertainty relates to them being based partly on occupant assumption and partly on paperwork involving different coverage periods, tariffs etc. On some occasions, equipment/battery failure, occupant privacy concerns or hard-to-reach installations (e.g., in small cupboards or lofts) prevented the researchers from obtaining the relevant photographic evidence. Overall, site visit time constraints had a limiting effect on the amount of social and technical data that could be collected, which in turn posed limitations on understanding complex HP installations and the environment they interacted with.
Chapter 4: RHPP Heat Pump Field Trial Project Results

This chapter presents a summary of the main findings from the published reports of the RHPP HP field trial project, in which the author had a key role, being responsible for the management and coordination of the whole project work. The author also co-authored the majority of published and unpublished internal RHPP reports and was heavily involved in the RHPP Case Study Report. She was a lead member of the case study research team that planned and executed the 21 site visit investigations and was the researcher responsible for the high-level analysis of the case study data. The following sections elaborate on the results from the RHPP published reports. In particular, section 4.1 focuses on the exploratory analysis of the variations in HP performance (Love et al., 2017), section 4.2 focuses on the savings relative to alternative heating technologies (Lowe et al., 2017c), section 4.3 focuses on the investigation of compliance with MCS standards (Gleeson et al., 2017) and section 4.4 briefly summarises the results of the case study analysis undertaken as part of the RHPP project (Lowe et al., 2017a). The overall conclusions and implications of results from the RHPP project as a whole are presented in section 4.5 (Lowe et al., 2017c).

4.1 Exploratory Analysis of the Variations in Heat Pump Performance

The main aim of the Performance Variations Report (Love et al., 2017) was to investigate the causes of the large variation in HP performance in the RHPP sample. As explained in section 3.3.2, sample S3 was developed with this purpose in mind. The exploratory statistical analysis investigated the differences between distinct categories of the HP systems, such as HP types, heat-emitter types and tenure, and the effect of specific technical features on the HP efficiency. This includes compressor cycling, backup resistance heating, load factor and flow temperature.

Figure 3-4 shows a varied distribution of SPFs within sample S3. The statistical analysis of this dataset revealed SPFs to be linked to variations in operational settings and controls, including the utilisation of backup resistance heaters, as well as a significant level of systematic error. The investigation between different HP types, emitters and tenure provided little clarity as to what might be contributing to higher or lower efficiencies and suggested a wide range of confounding factors being present. GSHPs had higher efficiencies, and ASHPs performed better with UFH. As expected, UFH was generally coupled with lower flow temperatures, except for two sites...
which were over 55 °C. Average flow temperatures for SH were generally lower than 45 °C, with only a few sites presenting average flow temperatures higher than 50 °C.

In terms of backup resistance heaters, *i.e.*, immersion or in-line, these were not physically present at all sites and in some cases, they were not measured even if present. The data for those sites where measurements were available revealed limited use of the system's in-line heaters. However, several cases with excessive backup DHW immersion activity were identified, which on average accounted for 12% of the overall HP electricity consumption. At over half of the sites with an SPF$_{H4}$ lower than 2, the DHW immersion heater was found to be responsible for more than 20% of the system's overall electricity consumption. As shown in Table 12 of Appendix C, 10-minute on-to-on cycles were common for a significant number of ASHPs, whereas for GSHPs on-to-on cycling tended to be longer, with a median of 18 minutes. The data analysis did not identify any relationship between median on-to-on cycling and monthly COP, however this may have been significantly influenced by the data-quality issues encountered. Overall, the SPFs at the two ends of the performance range could not be attributed to a specific type of installation nor a technical characteristic.

### 4.2 Savings Relative to Alternative Heating Technologies

For the calculation of the minimum SPF$_{H4}$ required for a HP system to yield savings when compared to alternative heating fuels, in terms of both CO2 and energy bills, Lowe *et al.* (2017c) used the CO2 emissions and energy costs for typical UK dwelling typologies, *i.e.*, terraced, semi-detached and detached, as a reference point. The alternative fuels tested were electricity, coal, oil, liquefied petroleum gas (LPG) and gas, with an assumed system efficiency of 100% for electricity, 60% for coal and approximately 85% for the others. Fuel carbon intensities and costs were sourced from publicly available data sources (DECC, 2015a; EST, 2016). Further information on the fuel cost and carbon intensity assumptions can be found in Appendix H. For the calculation purposes of this exercise, a simplistic approach was taken, where heat demand was assumed to remain constant for all fuel scenarios. This was based on the median gas consumption per dwelling type.

Table 4-1 shows that all sample S3 (described in subsection 3.3.2 and Table 3-3) HPs performed above the CO2 thresholds for savings in relation to all alternative fuels examined, since the highest SPF$_{H4}$ equivalent for alternative fuels coincides with the lowest cut-off point for sample S3. CO2 savings were generally found to range between 1 and 5.6 tonnes per annum per dwelling, with savings being lowest when comparing with gas and highest when comparing with coal. Overall, GSHPs presented higher CO2 savings than ASHPs by approximately 1 tonne per annum per dwelling.
In terms of fuel cost savings, the comparison with alternative heating fuels is even more complicated since highly varied energy tariffs can significantly influence energy costs. The calculations here involved two electricity tariffs, namely standard and economy 7. Of all scenarios, the replacement of resistance heating at a standard tariff seems to be by far the most cost-effective, leading to savings of just under £1,000 per year, with all HPs in sample S3 exceeding the minimum SPF$_{H4}$ threshold for cost savings. Most HPs in the sample also exceeded this threshold when considering coal, LPG or electricity at an economy 7 tariff, however, significantly lower savings were achieved, i.e., of between £100 and £300 per year. Only a few HPs presented an SPF$_{H4}$ high enough to yield cost savings when replacing oil and gas. Thus, such a replacement is likely to lead to higher running costs. Under all scenarios, GSHPs appear consistent in achieving slightly lower running costs in comparison to ASHPs, by approximately £65 per year, however, they are generally associated with significantly higher capital costs.

Table 4-1: SPF$_{H4}$s required for a heat pump (HP) to outperform alternative fuels in terms of CO$_2$ and cost savings, percentage of sites achieving this in sample S3, and the mean annual CO$_2$ and median annual cost savings per dwelling in comparison to alternative fuels (Lowe et al., 2017c).

<table>
<thead>
<tr>
<th>Alternative fuel</th>
<th>SPF$_{H4}$ threshold for CO$_2$ emissions reduction</th>
<th>SPF$_{H4}$ threshold for fuel cost reduction</th>
<th>HP sites above CO$_2$ threshold (%)</th>
<th>Mean median annual CO$_2$ savings (tonnes per dwelling)</th>
<th>HP sites above fuel cost threshold (%)</th>
<th>Mean median annual fuel cost savings (£ per dwelling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (standard)</td>
<td>1.00</td>
<td>1.00</td>
<td>100 / 100</td>
<td>2.2 / 2.3</td>
<td>100 / 100</td>
<td>933 / 997</td>
</tr>
<tr>
<td>Electricity (economy 7)</td>
<td>1.00</td>
<td>1.92</td>
<td>100 / 100</td>
<td>2.2 / 2.3</td>
<td>89 / 95</td>
<td>175 / 239</td>
</tr>
<tr>
<td>Coal</td>
<td>0.53</td>
<td>2.11</td>
<td>100 / 100</td>
<td>5.5 / 5.6</td>
<td>78 / 90</td>
<td>101 / 166</td>
</tr>
<tr>
<td>Oil</td>
<td>1.02</td>
<td>3.25</td>
<td>100 / 100</td>
<td>2.1 / 2.3</td>
<td>2 / 17</td>
<td>-162 / -97</td>
</tr>
<tr>
<td>LPG</td>
<td>1.30</td>
<td>1.77</td>
<td>100 / 100</td>
<td>1.4 / 1.5</td>
<td>95 / 99</td>
<td>246 / 310</td>
</tr>
<tr>
<td>Gas</td>
<td>1.50</td>
<td>2.82</td>
<td>100 / 100</td>
<td>1.0 / 1.1</td>
<td>13 / 35</td>
<td>-87 / -22</td>
</tr>
</tbody>
</table>

### 4.3 Investigation of Compliance with MCS Standards

Assessing the level of agreement of the HP installations in the RHPP field trial with the MCS MIS 3005 was the main focus of the MCS Compliance Report (Gleeson et al., 2017). MCS MIS 3005 sets out the technical requirements to be followed by contractors on several aspects of HP installation, however, different versions of the scheme were in force throughout the HP design
and installation process of the RHPP sample. Since installers’ quotation dates are provided only for owner-occupied sites and MCS certificate installation and commissioning dates provide only a general idea of the design and installation period, it is uncertain which version was applied at each site and how many HPs were installed after MIS 3005 became mandatory in 2012. Without the relevant metadata, a statistical analysis of the compliance level was not possible. The following aspects of the MIS 3005 were considered instead:

- **Building heat loss** – The building heat loss calculations are a fundamental component in the HP and radiator sizing process. Since building design (area, volume, U-values etc.) and ventilation information were not part of the metadata provided, it was not possible to comment on the accuracy of the installer’s heat loss estimates in the RHPP sample. Instead, Gleeson et al. (2017) focused on a single RHPP site (CS20) to explore the sensitivity of building heat loss calculations to the U-value and ventilation rate assumptions. The calculations showed a 24% increase in estimated ventilation heat loss by assuming different natural ventilation rates, i.e., representing a newer (post-2006) and an older (pre 2000) building (BSI, 2003). A great deal of uncertainty was also recognised in relation to the U-value assessment, stemming from a range of sources, including installers often not having access to the required technical specification and the variable quality of insulation installation. The results showed that the subjective assessment of a building’s thermal properties and ventilation rates can significantly affect building heat loss estimations, and thus HP and radiator sizing.

- **Annual heat demand** – A HP’s annual heat load is influenced by complex socio-technical parameters, including its technical characteristics and control, the environmental conditions and the occupants’ behaviour and preferences. The MIS 3005 method for the calculation of a HP’s heat load involves assumptions predominantly in relation to the weather conditions, building heat loss, the likely SPF at the selected SH and DHW flow temperature, and the SH to DHW ratio. The comparison between the monitored and the estimated heat demand as recorded in EPC and MCS certificates indicated limited correlation and a consistent overestimation of the heat load by both EPC assessors and installers. The discrepancy is likely to stem from a number of areas, including complex and possibly poorly understood calculation procedures, the differences between assumed and actual conditions, such as the milder than projected winters of the monitoring period, the questionable quality of data included in the EPC (DECC, 2014) and the systematic error in monitored data.

- **Radiator sizing** – The launch of the Heat Emitter Guide in 2011 aimed at the simplification of the radiator sizing process for installers. It is an essential part of the process that the designer understands the impact that flow temperature, room heat loss, heat emitter type and their interrelationship have on HP performance. Gleeson et al. (2017) used case study
20 (CS20) as the basis for the calculation of radiator star ratings under different heat loss and heating mode scenarios, e.g., continuous or intermittent heating. Based on the radiator characteristics observed on-site, star ratings appeared to vary significantly both between different scenarios and between rooms within the same scenario. The analysis also indicated that in reality, the selection of radiators is likely to be influenced by a wide range of factors stemming from aesthetic and practical considerations, such as cost and space restrictions.

- **Heat pump sizing** – In order to assess HP sizing adequacy of the RHPP sample, a comparison between the peak heat load, as inferred from the monitored data, and the *declared net capacity* (design heat load representing the maximum capacity at which the system can operate for a sustained period without damage) was attempted. The metadata available revealed inaccurate entries for the declared net capacity on the MCS certificates, with most installers listing the manufacturer’s *nominal capacity* instead, *i.e.*, the amount of heat that can be generated at optimal outdoor conditions. In the absence of reliable metadata, the declared net capacity was deduced by applying make- and model-specific corrections to the nominal capacity for a range of HPs. For the estimation of peak heat load, a simplified approach was taken, in which the RHPP monitored heat output was extrapolated using regression calculations to a daily average external temperature of 0 °C to obtain an approximation of the peak heat load at the MCS design temperature. The comparison of the two extrapolated estimates suggests that most HPs in the sample were adequately sized, however, the implications relating to the great amount of uncertainty involved is acknowledged by the authors of the RHPP MCS Compliance Report (Gleeson et al., 2017).

- **Design flow temperature** – As with peak heat output, the assessment of maximum flow temperature close to design conditions also required the extrapolation of the monitored flow temperatures to an average daily external temperature of 0 °C. The resulting design flow temperature was on average 40-45 °C for all heat emitter systems, *i.e.*, equivalent to a HEG star rating of 4-5, which is good practice. However, the distribution was wide and varied, with more than 15% of the data on the 50-60 °C range (star rating of 1-3) and approximately 35% being less than 40 °C (star rating of 5-6).

- **Weather compensation** – Results from the same extrapolation process and the comparison of measured flow temperatures with outdoor temperatures indicated the presence of weather compensation at approximately 65% of the sites. Gleeson *et al.* (2017) noted that even though weather compensation is generally linked to higher system efficiencies, it may not be ideal under certain circumstances, such as when intermittent heating is utilised.

- **DHW sterilisation** – Any system installed after MIS 3005 v3.1a came into force was required to employ measures for protection against Legionella, however, there was uncertainty
around this matter in the RHPP sample. If a HP maintains a DHW cylinder temperature of at least 60 °C then there is no need for sterilisation through the use of resistance heating (Lévesque, Lavoie, & Joly, 2004). Where this is not the case, then DHW sterilisation is required at regular intervals. DHW cylinder temperatures were not metered in the RHPP sample, however, the data from the 220 sensors monitoring the use of immersion heaters revealed approximately 25 - 35% of the profiles were compatible with sterilisation processing, i.e., heating up the water at regular intervals, usually weekly or daily.

- **Likely Heat Emitter Guide efficiency for SH** – The HEG’s likely SPF (equivalent to SPF_{H2}), as derived from the design flow temperatures that were calculated for each site, was not found to be related to the measured SPF_{H2} for SH. However, the latter was found to be consistently lower than the former.

### 4.4 RHPP Project – Stage Analysis of the Case Study Data

The RHPP Case Study Report (Lowe et al., 2017a) presented the initial results from the analysis of the data collected during the site visit investigations. Due to the limited time and resources available, the raw data were scanned through, compared to the pre-visit material, and swiftly organised into a master matrix that formed the basis of all case study analysis. As explained earlier in subsection 3.3.3, for the purposes of this RHPP report, the transcription work was limited to the production of summary notes. The first part of the report provided an overview of the main characteristics of the 21 case studies. The second part focused on the in-depth cross-case comparison of a sub-sample, i.e., the five best and worst performing HPs. As shown in Figure 4-1, a significant change in the case study performance ranking, as originally selected (being part of sample S1), and as part of a final SPF estimate\(^8\) at boundary level H4, was noted in only three cases, i.e., moving CS07, CS09 and CS15 from the worst performing sites to the middle range of those that volunteered. This difference resulted from the exclusion of monitoring periods involving anomalies that were identified at a later stage and is explained further in section C1 of Appendix C. A cross-case comparison of the social cases (CS02-08) in the sample was also included in the RHPP Case Study Report.

\(^8\) Corresponds to what the RHPP Case Study Report refers to as the "representative SPF" (Lowe et al., 2017a).
The main findings of the case study report are summarised below:

- **Heat pump installation quality** – The quality assessment of the HP installation, in terms of pipework insulation and overall planning, was based on 10 case studies, of which six were judged to be of good quality, one of intermediate and three of either poor layout and/or planning.

- **User satisfaction** – With a few exceptions, occupants were generally satisfied with their HP system and preferred it to the heating systems they had previously experienced. Only in one case (CS07) were the occupants deeply dissatisfied with their HP, an outcome that seemingly contrasted the good SPF of their HP (see Table 1 of Appendix C). The qualitative data analysis revealed that satisfaction with the HPs is a highly complex matter, relating to a wide range of parameters that vary between cases studies, including thermal comfort, bills, ease of control, environmental friendliness, technical integrity, and noise level.

- **User control strategies** – A range of HP heating control strategies for SH and DHW were encountered across case studies, including single- or multiple-zone thermostats, TRVs and programmers. Open fires, wood burners and standalone resistance heaters were also often utilised. Thermostat setpoints ranged between 12 and 23 °C, except for one social tenant who set it as high as 30 °C. Contrary to owner occupiers, many of whom experimented with different controls, social tenants were instructed by RSLs/installers to interact with their HP through the thermostat only.
- **Technical faults** – Significant disruptions to HP operation emerged in approximately half of the case studies. The problems reported included faulty HP or components, problematic installation setup, antifreeze issues, dripping of the external ASHP unit, radiator blockages and unintended use of the backup resistance heater. Lowe et al. (2017a) suggested that post-installation follow-up visits by competent technicians may be crucial in resolving HP performance issues that may otherwise be dragged out over a long period of time. The social tenants' narrative highlights that RSLs need to work with a more competent workforce that can resolve technical issues (Lowe et al., 2017a).

- **Comparison between the case studies and overall field trial data** – Metadata inconsistencies, which were not detected from the statistical analysis of the RHPP dataset alone, were revealed upon the site investigations. These concerned the data included in the metering database and the MCS/EPC certificates and highlight the importance of sufficiently resourced teams when visiting sites to collect metadata for field trials. On some occasions, the occupants provided valuable information that led to a better understanding of the monitoring profiles. In one case a social tenant (CS08) described an unintended/accidental backup resistance heating period, alongside plausible explanations as to why this may have happened. Similarly, an owner occupier (CS15) expressed his great surprise at the low SPF reported by the statistical analysis team and recalled an incorrect sensor placement that was revisited at a later stage of the monitoring period. This led to the close examination of the heat and electricity data, whose sensors had been interchanged, revealing a dramatic underestimation of the SPF. This highlights the challenge in collecting good-quality quantitative data for a complex technology, such as a HP, installed in a complex socio-technical system, a home.

- **Factors emerging as influencing performance** – Lowe et al. (2017a) identified three main areas that are likely to influence HP performance, *i.e.*, backup resistance heating, heat load and pipework heat losses, including long distances between the HP and the heated dwelling. The influence of heat load emerged from the comparison of monthly COP and load factors for three similar types and sizes of dwellings and GSHP systems (CS14, CS16 and CS18).

### 4.5 Overall Conclusions from the RHPP Project

The RHPP Final Report (Lowe et al., 2017c) brings together the findings and the overall lessons learnt from the RHPP project. It stresses that (a) the reader should tread carefully through the RHPP reports as the monitored data and metadata provided were imperfect, and (b) the degree to which the HP units involved were representative of domestic HPs in
the UK was not assessed. Despite the limitations, the RHPP study as a whole made a significant contribution towards a better understanding of domestic HPs in the UK. The main project findings are summarised below:

- Approximately 65% of the ASHPs and 80% of the GSHPs in sample S3 can be classified as RES under the EU Renewable Energy Directive (European Commission, 2013), i.e., have a SPF$_{\text{H2}}$ of 2.5 or greater. The use of alternative samples/filters was found to marginally influence this result.

- The detailed monitoring error assessment identified a limited number of sites with errors leading to both higher and lower SPFs. Of all errors, two types were expected to significantly affect median SPF values: (a) the presence of electricity but no heat data and (b) the lack of glycol calibration in heat meters, likely to apply to most HPs in the sample. The analysis showed that the lack of heat data is likely to lead an underestimation of the median SPF$_{\text{H2}}$ by less than 4% and the lack of calibration to a 4-7% overestimation.

- Based on the assumptions utilised in the RHPP study, cost calculations indicated that the majority of ASHPs and GSHPs in sample S3 are expected to present savings when compared to the running costs of electric storage heaters and LPG, and the converse when compared to oil and natural gas. However, cost estimations are highly dependent on fuel prices and tariffs, with oil and gas prices being on a descending trend in the past few years. Note that in the UK gas is currently subsidised whereas electricity is bearing the full cost of decarbonisation of the energy system (CPLC, 2020).

- Both HP performance and occupants’ satisfaction were found to be highly complex, as they depend on a wide range of parameters. The former was found to be sensitive to its environment, at the building, technical installation, and occupant levels. Occupant satisfaction was linked to thermal comfort, running costs, ease of control, environmental friendliness, technical integrity, and noise level. It was suggested that controls are optimised to avoid unnecessary use of resistance heating.

The RHPP project has contributed to a more advanced and holistic understanding of UK domestic HP performance. It has highlighted the importance of combining technical field trials with detailed socio-technical site visit investigations to achieve a better and deeper understanding of HP operation and the ways in which HP performance can be improved. Overall, it has been demonstrated that a socio-technical, mixed methods case study approach can be a valuable addition to field trials of technologies such as HP.
Chapter 5: Results of High-level Analysis – The Case Study Sample and Variables

The purpose of the high-level analysis was to provide an overview of the case study characteristics, as they derive from the qualitative and quantitative collection methods and discover the common themes that form the building blocks of the systems thinking-driven socio-technical analysis that is presented in Chapter 6. Where multiple views/data sources were available on the same aspect, the data were filtered through the triangulation process described in subsection 3.2.3. Section 5.1 presents an overview of the main case study characteristics, section 5.2 focuses on the monitoring profiles in the light of the occupants’ narrative and the quality of the monitoring equipment installed, and section 5.3 summarises the previous two and draws conclusions from the high-level analysis.

5.1 An Overview of the Qualitative Characteristics of the Case Studies

This section aims to provide an overview of the wide range of data as they were perceived through the synthesis of qualitative data sources relating to the 21 case studies, including aspects that are likely to influence or be influenced by the HP's performance. The following paragraphs deal briefly with the household and dwelling characteristics, occupants’ control and usage of the ventilation and heating systems available, the technical features of the HP installation, the overall household running costs and the occupants’ quality of experience with the HP, including ease of control and overall satisfaction. The accompanying Appendix C encapsulates these aspects in Tables 2 to 21.

5.1.1 Household characteristics

The case study sample was made up of one-third social and two-thirds owner-occupied households. Except for a few private dwellings accommodating families with up to two children, most households in the sample were of single or double occupancy. All but one household had at least one member occupying the house throughout the day, either due to working from home, caring for young children, an illness or being a pensioner. CS18 appeared to be the only house with half-day occupancy. Absences throughout the year seemed to be rare in half the cases and up to 8 weeks per year for the remainder.
At the time visited, case study occupants had been living in the properties anywhere between 3 and 39 years, with only one-quarter living in the same house for more than 10 years. Based on the occupants’ description and MCS documentation available, the overall amount of time they had been living with their HP was much shorter, spanning between 2 and 5 years in all but in one case which appeared to have been installed 7 years prior to the site visit. The occupants in approximately one out of three cases claimed they had some sort of technical expertise, even though it was not directly linked to the HP. No information was collected on the income and age of household members; however, all social tenants were retired.

5.1.2 Dwelling and ventilation characteristics

Building types and thermal characteristics

The case study sample includes a variety of dwelling types, sizes, and age bands, with distinct differences between the social and owner-occupied houses. Overall, more than half the dwellings in the sample were built before 1976, when the Building Regulations set an insulation minimum for the first time (see Table 5 of Appendix C). In particular, social houses were one-bedroomed, ground-floor, mid-terraced or semi-detached bungalows built in the 1930-60s that lie on the smaller side of the spectrum in terms of floor area, i.e., between 34 and 52 m². Owner-occupied houses were mostly detached, usually spanning over two or three floors, encompassing up to five bedrooms and being up to seven times larger than their social counterparts, with a TFA of between 95 and 346 m². Their age bands spanned from the Victorian and Georgian periods (CS10, CS13 and CS19), four built around the same period as social housing (CS11 and CS20) or within the following decade (CS09 and CS21), and the remaining post 1992. Except for CS12 built in 2007 and CS17 in 1992, the remaining were newbuilds post the 2010 Building Regulations update.

Since their build year, most dwellings had undergone building fabric improvements and extensions had been added in four cases (dated in the 1950-60s in CS19 and more recently, 2004-05, in CS11, CS13 and CS21). As a result, all walls and roofs were insulated to some extent, except for the thick stone walls in CS10 and CS19. All insulated walls were filled cavities, with an additional layer of external wall insulation in CS02-05. The roofs were pitched for the whole sample and their insulation level also varied, from moderate (e.g., 150 mm flawed joist insulation due to technical difficulties in CS10) to highly insulated (e.g., 100 mm glass-fibre insulation between and 250 mm over joists in CS01). Although the occupants were usually aware of the floor insulation only when there was underfloor heating present, it is expected that all floors in houses built after 2002 and 2010 should be insulated to achieve a minimum U-value of 0.51 and 0.22, respectively. All windows were double glazed, except for triple-glazed
windows in three cases (CS09, CS14 and CS16). Improvements to the original building fabric both before and after the installation of HP are expected to influence its energy performance. Draught-proofing and insulation improvements post the HP installation were reported in one-third of the cases.

**Ventilation patterns and the presence of draughts**

The presence of draughts was reported in approximately half the cases. The occupants named three different sources, *i.e.*, draughty mechanical ventilation with heat recovery (MVHR) systems (CS02, CS04 and CS05), convective currents due to large, glazed areas (CS01); and air leakage through structural defects and/or open flues and vents (CS07, CS10, CS12-14 and CS18). The latter appeared to be particularly bothersome in four cases, two of which were older houses with leaky windows/doors (CS07 and CS10) and the other two were new builds (CS18) or had extensions (CS13) with major but localised technical imperfections. Issues with mould and/or condensation were reported in one-third of the cases. These appeared in the form of mould around door/window frames (CS04, CS06 and CS08) and in bathrooms (CS05), and rising damp and/or condensation on walls (CS19 and CS20).

Of all case studies in the sample, only four social houses were provided with MVHR (CS02-CS05). The remaining homes relied on natural ventilation, to the extent that their window opening level would allow them to do so, as well as individual bathroom and/or kitchen extractor fans. One extreme example is CS03, where windows were locked and the social occupant was only able to operate the living room patio door, however, full use of the MVHR system was made throughout the year. In fact, CS03 and CS04 were the only two cases that would operate their MVHR system extensively. The remaining two would only turn it on occasionally due to the draughts and/or noise attributed to this system. Most occupants stated their ventilation patterns changed between winter and summer. With the exception of CS08, whose occupant was the only one with an extensive winter ventilation routine, the remaining reported they either never ventilated, or they did so in a very limited way during the wintertime. In the summertime, the pattern would change, with most occupants reporting frequent use of natural ventilation via windows and doors, one-third limiting their ventilation to a particular room only or when very warm outside, and one case (CS10) reporting they did not feel the need to open windows at any time during the year due to their Georgian dwelling’s high air leakage.

**Weaknesses identified through thermal imaging**

All 17 case studies for which thermal images were obtained presented some thermal weaknesses that are typically found in the UK domestic stock (Weeks, Ward, & King, 2013), relating to areas of reduced insulation (thermal bridging around window/door edges, joints and
intersections of the building fabric etc.) to which it is technically difficult but not impossible to apply insulation. Despite their double-skinned walls, presenting both cavity and internal wall insulation, all four neighbouring social cases CS02-CS05) presented another area of thermal weakness due to gaps in their external wall insulation. Figure 5-1 illustrates the heat loss paths on the façade of CS02, i.e., through the door and window frames, the wall/roof junction, the location of the previously used gas meter and at the ground level, where the original bricks were visible. Two examples of heat loss through improperly insulated wall junctions are those of Figure 5-2 and Figure 5-3, where heat appeared to escape through the junction between the cavity and the 550 mm stone wall (on the left hand side) in CS19 and between the two timber frame walls in CS18.

Figure 5-1: Visual and thermal image of the CS02 façade showing heat loss paths through windows, doors, and junctions.

Figure 5-2: Visual and thermal image of the CS18 interior showing heat loss paths through the timber frame wall and roof junctions.
Figure 5-3: Visual and thermal image of the CS19 exterior highlighting a primary heat loss path through the cavity wall and stone wall junction.

Figure 5-3 and Figure 5-4 show large temperature variations in the gable wall of CS19 and CS20. This is often found in subsequently filled cavity walls for several reasons, such as drilling fewer holes than needed for the cavity to be filled properly and debris blocking the cavity, which may lead to condensation issues (Davies, 2013; Stephen, 2018). This may have contributed to wall condensation appearing in CS20, alongside the possibility of broken render/cracks on the wall and bricks/insulation saturated with moisture. A similar pattern is observed on the cavity wall of CS06, illustrated in the thermal image of Figure 5-5, where the evaporation of moisture was the likely cause of the cooler patches. Another type of thermal inconsistency of cavity walls is illustrated in Figure 5-6, where heat appeared to escape through the window lintel of CS21. Other wall features that can compromise the thermal resistance of building fabric is the way insulation is fixed onto the wall (an example of thermal bridging via the use of fixings on external wall insulation is illustrated in Figure 5-7), the number and type of extractor fans (note the heat escaping through the extractor fan of CS19 in Figure 5-3) and the thermal qualities of the materials and glazing used in doors and windows. It was not possible to investigate the latter through thermal imaging due to the glass reflecting infrared radiation.

Figure 5-4: Visual and thermal image of the CS20 gable wall showing large temperature variations, possibly due to the subsequently filled cavity wall.
In terms of the roof thermal performance in the case studies, the thermal imaging and on-site visual inspection revealed several areas of uneven insulation thickness. The thermal images of Figure 5-8, Figure 5-9 and Figure 5-10 show areas of significant heat losses from the roofs of CS17 and CS18, in the form of uninsulated patches, thermal bridges at junctions and the timber structure holding up the roof. The loft-hatch, also shown in Figure 5-9, appeared to be a weak
point of the thermal envelope in at least another three cases (CS04, CS06 and CS18) and similarly the perimeter of the loft platform built in CS04 for storage purposes. The cold patches in Figure 5-11 correspond to this platform base. The lack of insulation underneath the HP installation, as shown in Figure 5-12, represents another weak area in terms of thermal transmittance.

Figure 5-8: Visual and thermal image of the CS17 interior, highlighting heat loss paths through the roof.

Figure 5-9: Visual and thermal image of the CS17 interior, highlighting heat loss paths through the loft hatch junctions and the uninsulated surrounding patches.

Figure 5-10: Visual and thermal image of the CS18 interior, highlighting heat loss paths through the timber structure holding up the roof.
Figure 5-11: Visual and thermal image of the CS04 interior, highlighting heat loss paths through the perimeter of the loft platform.

Figure 5-12: View of the CS07 loft space, highlighting the lack of insulation underneath the heat pump installation (Source: Lowe et al., 2017a).

5.1.3 Technical characteristics of the heat pump installations

An overview of the main heat pump features

There were approximately equal numbers of ASHPs and GSHPs in the sample, all providing SH and DHW, except for CS20, where the HP provided only SH. GSHPs utilised either boreholes or horizontal collectors. All HPs were Monobloc except CS09, which was a split system. The declared net capacity of all HPs ranged between 5 and 15 kW. The system sizing increased with higher floor areas, i.e., 5-6 kW, 7-11 kW and 11-16 kW were installed in dwellings with floor areas of 35-50, 95-100 and 150-345 m², respectively, except for the 293 m² CS10 dwelling, having two HPs installed and totalling a capacity of 22.5 kW.
From the cross-examination of metered data, schematics, on-site observations, and technical specifications, it appears that at least one type of backup resistance heater was present in all case studies in the sample, either in the form of an immersion heater or an in-line electric flow boiler. In particular, the manufacturer’s technical specification confirmed the presence of an in-line heater in the hydrobox of the only split-system HP in the sample (CS09) and in the casing of all but one GSHP (CS19). Immersion heaters were present primarily in DHW stores (CS01, CS02 and CS06-CS11), buffer vessels (CS19 and CS20) and the thermal store of CS20. While immersion heaters were used solely for DHW provision, it is not certain whether in-line heaters in the sample were used for SH, DHW or both.

As shown earlier in Table 3-1, radiators were the predominant emitter type in the case study sample. These took the form of single and double panels/convectors, hospital-type cast iron radiators, hydronic fan convectors and towel radiators. UFH appeared in nine cases and was present throughout the house in only five. The remaining utilised a combination of both radiators and UFH. With the exception of newbuilds and those cases that previously used a non-centralised heating system, i.e., storage heaters and coal, the occupants of at least eight cases reported that their HP system utilised the radiators connected to the previous gas or oil heating system, fully or in part (see Table 9 of Appendix C).

**Heat pump complexity and system heat loss**

During the case study site visits, it was not possible for the site investigation team to establish the full characteristics of the installations. Doing so would have required the removal of covers, cases and insulation applied to the HP installation and its parts, and interaction with the system’s interface, which was not appropriate or permissible for this study. Overall, the observed HP configuration and components installed varied significantly between cases.

The main parameters that were identified as increasing complexity include the incorporation of multiple HPs in one installation (e.g., 2 in CS10), the presence of long running pipework, such as those shown in Figure 5-13, and the presence of pipework heat exchangers and multiple circulation pumps. In CS10 and CS11, for example, heat exchangers were placed after each HP condenser. Both installations, depicted in Figure 5-14a and Figure 5-14b were designed by the same installer and although the installer’s intention is not known, it is hypothesised that the plate heat exchangers were used as a precautionary measure, i.e., to avoid dirt going into the in-house installation elements, and to avoid the extensive use of antifreeze for cost-reduction purposes. In addition, several installations (e.g., CS10, CS11, CS12, CS15 and CS19) were found to incorporate a greater number of circulation pumps than was originally assumed by the RHPP research team. As an example, 5 circulation pumps can be traced in Figure 5-14a.
may lead to higher parasitic energy consumption. Some of the parameters increasing complexity, may also lead to higher system heat losses.

Figure 5-13: Long pipework in CS20 (a) running through the outdoor water closet, (b) running between the outdoor water closet and the first of the two garden sheds and (c) reaching the second garden shed, where the buffer vessel can be seen located inside a DIY insulation box (box lid shown uncovered) (Source: Lowe et al., 2017a).

Figure 5-14: (a) Heat pump installation in the heated plant room of CS10, where the heat exchangers can be seen in grey insulated enclosures and (b) heat pump installation in the unheated roof space of the garage of CS11, where the heat exchanger can be seen in black insulation enclosures (Source: Lowe et al., 2017a).
The main areas, where unnecessary system heat losses may be incurred are listed below:

- **Pipework insulation** – With a few exceptions, the HP installations in the sample were largely imperfectly insulated, e.g., presenting foam insulated pipework with uninsulated connection points, as well as pumps and valves. A few example of the different levels of insulation encountered in the case study sample is offered below.
  - Thoroughly-insulated pipework: The tubular rubber insulation work of CS15, depicted in Figure 5-15a, was of high quality, since it provided a continuous seal. The joints, termination points and valves were all covered with insulating material or enclosures. Similarly, CS19 used foam to cover the pipework, as well as circulation pumps and manifold enclosures, as shown in Figure 5-15b and Figure 5-15c, although with minor gaps in the elbows and joints.
  - Moderately-insulated pipework: Figure 5-16 shows that the installations of CS14 and CS13 also used tubular foam. In these cases, aluminum foil/tape was used to cover the elbow gaps and parts of the exposed pipework. As shown in Figure 5-17, instead of enclosures for the insulation of circulation pumps and valves in CS14, the installer had used duct tape and foam, leaving the equipment partly exposed.
  - Inadequately-insulated pipework: The insulation application of CS01 was one of the few installations located in weather-exposed locations, where extensive areas of the pipework had been left unprotected, as well as having improper application of insulation in areas such as those depicted in Figure 5-18a.
  - Completely uninsulated pipework within the insulated perimeter of the house: While most of the installation parts placed inside the building’s insulated envelope presented foam insulation on most pipework, except for pumps and valves, the visible pipework in CS12 and CS19 was completely uninsulated.

- **Cylinder insulation** – in the case study sample, it was generally not possible to visually confirm the DHW and/or buffer vessel level of insulation. However, it was confirmed that those cylinder models that could be identified through images incorporated factory-applied insulation. The DHW vessel of CS10 was the only one with visible foam insulation lagging (see Figure 5-14a) whereas insulation with additional bubble wrap was placed inside the box surrounding the buffer vessel in the garden shed of CS20, as shown in Figure 5-13c.

- **Installation location** – The HP installations were often located, either fully (CS01, CS06-CS08 and CS20) or in part (CS02-CS05, CS15 and CS19), in unheated spaces outside the insulated perimeter of the house, i.e., ‘cold roofs’, unheated garages and garden sheds. For example, in social cases CS02-CS05, the external ASHP unit or borehole was connected through the loft space to the internal part of the installation, including the DHW cylinder and/or buffer vessel.
• **Long pipework** – in approximately one-quarter of the cases, the ASHP external units were placed far away (≤ 10 m) from the house perimeter, however, it was impossible to inspect the level of insulation of the connecting pipework as it was buried underground.

• **Pipework heat exchangers** – the presence of heat exchangers is expected to incur some heat losses through hot water circulation.

![Figure 5-15: (a) High-quality pipework insulation in the unheated/uninsulated garage of CS15, (b) good-quality pipework insulation in the unheated/uninsulated shed of CS19 and (c) ditto with images of pump and manifold insulation covers removed (Source: Lowe et al., 2017a).](image1)

![Figure 5-16: (a) Imperfect pipework insulation in the unheated garage of CS14 and (b) in the unheated utility of CS13 (Source: Lowe et al., 2017a).](image2)
Figure 5-17: Imperfect circulation pump insulation details in the installation of CS14 (Source: Lowe et al., 2017a).

Figure 5-18: (a) Strap-on temperature sensor fitted on improperly insulated pipework in CS01 and (b) exposed valves in CS06 (Source: Lowe et al., 2017a).

**Metering installation quality**

A detailed examination of the monitoring equipment was not possible, as many HP components and sensors were hidden from sight, *i.e.*, placed in narrow or hard-to-reach cupboards/lofts, were obstructed by items stored in the same area and/or covered by insulation. In addition, the specifications of the metering equipment were not known, *e.g.*, length of probes etc. However, on some occasions there was clear indication of either improperly fitted sensors or possible inconsistency between meter readings due to the different types of sensors installed. Some relevant examples are described below.

- At least two strap-on temperature sensors were fitted in CS01, such as that depicted in Figure 5-18a, in contrast to the majority of sensors in the case study sample that involved a
temperature probe, leading to a possible under-reading of the temperatures obtained from the former.

- As shown in Figure 5-19a, an improperly fitted temperature probe sensor was noted in CS12 due to the deformed jubilee clip. Figure 5-19b presents a seemingly properly positioned temperature probe sensor.

![Figure 5-19: Temperature sensors fitted on CS12 pipework presenting (a) proper and (b) inconsistent positioning due to deformed jubilee clip (Source: Lowe et al., 2017a).](image)

### 5.1.4 Control and usage of the heating systems available

**Heat pump space-heating controls**

The HP control adjustments, as described by the occupants of the case study sample varied from simple thermostatic- to flow temperature- and weather-compensation control. The occupants’ ability to operate these controls and their ability to alter the installer’s original setup depended on their level of technical competence, the instructions provided and the extent to which they were physically accessible and self-explanatory. There appeared to be a distinct difference in control accessibility between social-housing and owner-occupier groups. The former were ‘locked out’, *i.e.*, verbally advised by the RSL not to interfere with the physically hard-to-reach controller, with access to room/radiator thermostats and/or programmer settings only. Owner occupiers had full access to the controller, including flow temperature, heat-curve adjustment, and other advanced interface features, should they want to. Excluding two case study occupants stating they ran their HP intermittently, the remaining reported continuous and daytime-only operation in almost equal numbers, as shown in Table 5-1.

- **Room thermostats**: A single, wall-mounted thermostat was available in the living rooms of all social houses and maintained room thermostat comfort temperatures anywhere between 18 and 23 °C, except for one case (CS06) whose occupant claimed he had to set it higher, at 30 °C, for health reasons. The comfort temperature settings in owner-occupied houses,
controlled by either single- or multiple- zone thermostats (fixed and less often portable), were kept between 16 and 21.5 °C. More than half of the owner-occupied houses were equipped with multiple thermostats and many occupants took advantage of the ability to set lower temperatures in bedrooms and unoccupied rooms.

- **Programmer**: The self-reported setback temperature ranged between 14.5 and 17 °C. With the exception of one occupant (CS03) who stated he turned down the temperature manually every night, the setback temperature periods described relied on the programmer settings. Of all social-housing tenants, only two had access to the programmer.

- **Thermostatic radiator valves**: As most radiators in the sample were fitted with TRVs, some of the occupants in single-zoned houses, including those without room thermostats, also stated they had permanently altered the TRV settings for similar reasons and to avoid overheating in rooms with high heat gains (e.g., kitchens). In CS07 the TRV proved to be particularly confusing as it was impossible to read, due to the label’s placement towards the back of the valve. Even with clear and legible labelling, some occupants appeared to be dubious as to what they had set their TRV at or what the best TRV control strategy was. As an example, the occupants of CS07 and CS17 expressed some contradicting views on the matter.

  Never touched it [the TRV] […] Well, Greg keeps telling to turn those things down. Are we meant to have them turned down or turned up? […] If they’re on full, are we using more energy? […] I don’t even know where it [the TRV] is [set at], I have no idea whether it’s on… (Gabi, CS07)

  Our understanding from reading the book was that you left them open, and you let the… y’know, the sensor to control the temperature, the thermostat. There’s a [room] thermostat in the hall. […] We just leave them open because when we first got the heat pump and we read the book, it kind of suggested that if you started mucking around with them, the heat pump had to work harder (Quianna, CS17)

Overall, the majority of occupants in the sample stated they would very rarely interact with the TRV settings, if at all, and many tended to ignore their existence. Such was the case of Clive (CS03), Dawn (CS04), Francis (CS06), Gabi (CS07) and Jennifer (CS10), who explained they had never touched their TRV.

- **Flow temperature control**: There were only three cases with occupants having no access to room thermostat controls, namely CS19, CS21 and CS09 – the latter for a specific but extended period of time only. The only indoor temperature control methods in these cases were adjusting the system’s flow temperature and altering TRV settings (where available). The alteration of the controller settings, including flow temperature, was generally limited in
the sample. Excluding the flow temperature adjustments in CS09, access to the controller by the occupants for indoor temperature control purposes was limited and reserved as a response to technical problems/perceived setup shortfalls (usually undertaken by the more technically competent occupants) and extreme weather conditions. One of the more advanced settings showcased by occupants to the research team was the adjustment of the weather compensation curves in CS17.

Table 5-1: The main space-heating (SH) operating patterns based on occupant description.

<table>
<thead>
<tr>
<th>Operational schedule</th>
<th>Description</th>
<th>Case studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>Depending on the control method, the SH flow temperature is kept constant, or the HP thermostat(s) are set at a specific temperature (or narrow temperature range) at all times, at least during the heating season.</td>
<td>CS02, CS05, CS08, CS12, CS13, CS14, CS15, CS18, CS19, CS21</td>
</tr>
<tr>
<td>Daytime-only</td>
<td>The programmer(s), or the occupants in some cases, either switch off the HP completely during the night or set a night setback temperature that is usually significantly lower than the daytime temperature, with the occupants assuming no HP operation during the night.</td>
<td>CS01, CS03, CS04, CS06, CS07, CS09, CS10, CS11, CS17</td>
</tr>
<tr>
<td>Intermittent</td>
<td>This is the most variant pattern, similar to the way a gas boiler is operated, where programmer(s) are utilised to set comfort and setback temperatures throughout the day and/or night.</td>
<td>CS16, CS20</td>
</tr>
</tbody>
</table>

**Supplementary space-heating methods**

With regards to SH, at least one source of supplementary heating was present in each case study, in the form of fixed or portable resistance heaters and wood/solid fuel burners. The latter was present in approximately half the case studies and was utilised by most of them to some extent for aesthetic or practical reasons. An equal number of cases were equipped with fixed resistance heaters, *i.e.*, wall-mounted fan heaters in the CS02-CS05 wet rooms, two-bar fires in the CS06-CS08 living rooms and electric-only towel radiators/UFH in CS09 and CS18. The supplementary electric heaters in social housing cases and CS18 were complementary to the HP-connected radiators or UFH that were also present in these rooms. Electric UFH also complemented the HP-connected towel radiator in the bathroom of CS09, whereas the UFH and towel radiator of its ensuite bathroom were both electric only. Since they were the only heating means available, these resistance heaters were more likely to be utilised often. With the exception of these two cases and the hybrid towel radiators of CS16, fixed resistance heating was rarely utilised, *i.e.*, in emergency situations relating to ill health and extreme weather conditions. The same was true for portable resistance heaters, where regular use was reported in just one case. CS10, due to insufficient heating provided by the HP in the attic. The range
cooker in CS16 was also frequently utilised in the occupants’ search for an alternative heating strategy that would reduce their energy bills.

**Domestic hot water provision and controls**

Overall, both the social-housing and owner-occupier groups thought they had a fairly accurate idea of what their SH controls were, contrary to DHW controls, since most occupants were unaware of the relevant schedule. In only one-third of the cases were the occupants able to suggest when their DHW was heated, *i.e.*, in hourly or bihourly slots, around one or two times a day for CS01, CS07, CS08, CS09 and CS11, and instantly in CS13, CS18 and CS21. All but one HP installation provided DHW, however, the site investigations revealed electric showers installed in several bathrooms, despite the presence of a DHW-providing HP. This was an initiative taken by the RSL in CS02-CS05 for unknown reasons and a decision based on familiarity and personal preference for the owner occupiers of CS16. For the SH-only-providing HP of CS20, DHW was produced by solar thermal panels, complemented by an electric boiler (primarily for winter use). Both systems had been present long before the HP installation and since the occupants were familiar and satisfied with them, they decided not to switch over to HP-generated DHW. Surprisingly, in CS07, a kettle was frequently utilised to produce of hot water for washing up. Except for the HP, the electric showers and the kettle, the only other possible DHW sources appearing in the sample were the gas-fired condensing boiler of CS19 and the 5- and 10-kW wood stoves of CS13. Both could serve as a SH/DHW backup system during a HP breakdown.

**5.1.5 Overall energy costs and cost-alleviation mechanisms**

As part of the interview, the occupants were asked to provide energy-bill paperwork or, if bills were not available, a rough estimate of their energy costs per month or quarter. The occupants of all except one case study (CS06) were able to provide this information, however, a comparison between these estimates should be treated with caution. These are based partly on paperwork provided by occupants, involving different coverage periods, and partly on occupant assumptions. The electricity bills, as provided by energy suppliers, are not necessarily proportionate to the household electricity consumed. They can be a function of the chosen electricity tariff, the electricity produced by renewables\(^9\), the energy proportion provided by electricity versus other fuels present (*e.g.*, gas hobs in CS02-CS05) and any benefits paid directly to the electricity supplier. However, there is some benefit in examining the energy costs quoted by occupants as they influenced their perception of efficiency and satisfaction with the heating system.

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\(^9\) The energy produced by PVs and solar thermal panels was not metered as part of the RHPP study.
Table 17 of Appendix C summarises the data available on energy use and bills using HP and previous heating systems. Any bill estimates provided by occupants, based on individual payment arrangements (e.g., quarterly, monthly), were multiplied and averaged accordingly to obtain an annual cost estimation for each case. Where both high and low estimates were provided, these were averaged out, except for cases such as CS08, where the unintentional operation of the HP’s backup heater resulted in excessively high bills. In this case, the bill estimate was not taken into consideration in the calculation of the average but noted separately. These cost estimations do not incorporate the RHI, feed-in-tariffs and any other grants/benefits that do not offset bills directly. Taking into consideration the above, a crude comparison between case studies was attempted.

Overall, energy cost per square meter was found to be lower with higher TFA. The annual energy cost for the small social bungalows ranged between £400 and £700. The bills of the smallest owner-occupied houses, which were approximately double the size of social houses in the sample, i.e., around 100 m², fall within the £650-1150 range per annum. The highest bills in the sample, i.e., between £1000 and £2150 per annum, were associated with larger owner-occupied houses, with a TFA from 165 m² and up to 350 m². Considering the whole sample, the houses with the lowest energy cost per unit area fall within the higher end of this last group.

Of all social housing cases and excluding the temporary increase in electricity usage due to the unplanned immersion heater use in CS08, two cases seemed to have the highest bills. These were CS05 and CS07, totaling approximately £700 per year or higher (excluding any benefits provided and the gas oven-associated costs in CS05), with the remaining ranging between approximately £440 and £540. It is noted that CS05 and CS07 were the only two social-housing cases with two occupants, implying a higher usage of DHW. Comparing CS16 with other newbuilds (CS13-CS15 and CS18), of similar size (252-346 m²) and taking into consideration the electricity production by PVs, CS16 also stands at the higher end of the spectrum in terms of electricity costs. This spectrum ranged between £1000 and £2150 per year and the cost variation did not appear to be linked to occupancy numbers of these houses, which was between two and four occupants.

In terms of RES systems, PVs were installed in approximately half the cases (CS09 and CS13-CS21), which were also in receipt of the feed-in-tariff, and two cases presented solar thermal panels installed on their roof. Of these two, CS20, the only case with a non-DHW-providing HP, utilised the solar system, whereas the occupant of CS21 stated it was disconnected at the time of the HP installation due to a solar thermal panel fault. No RES systems were installed in the
social housing cases, other than a Trombe wall\textsuperscript{10} in the south facing facade of CS04. This did not appear to be utilised as intended due its external shutters remaining closed most of the time. Moreover, none of the social-housing tenants were receiving any governmental economic incentives for the installation of the HP. In their cases, the recipient of these incentives was the RSL (who paid the installation). Contrary to social-housing cases, all except one owner occupier (who bought the house with the HP pre-installed) were in receipt of the RHI payments. Other benefits and entitlements assisting the alleviation of energy costs that were recorded in the sample include winter fuel payments (CS02), the warm house grant (CS04) and a farming group scheme (CS16).

5.1.6 **Occupant experience with the installation and operation of the heat pump**

The quality of experience with the HP, as described by occupants, concerns different stages of the occupants’ contact with the system, from decision making, installation and commissioning (including any building fabric energy efficiency measures implemented and the training provided) through to day-to-day experience. These are set out in the following three paragraphs.

**Decision making around the heat pump installation**

As per the occupants’ narrative, all owner occupiers except CS01 made an informed decision about the HP installation. They all considered some of its benefits and drawbacks in comparison to other heating systems, as well between HP types. For some, installing an ASHP was preferred to a GSHP due to the higher cost and the disrupting/time-consuming ground works required for the latter. For others, a GSHP was preferred due to its higher efficiency, as stated by the manufacturer, installer or through word of mouth. On a few occasions, the occupants mentioned that they had some influence on the type of emitters utilised, e.g., by installing a visually pleasing or practical radiator, such as a towel radiator. However, in CS01, the HP was already in place when the owners Andrew and Amanda bought the property, and they had to accept the presence of UFH coupled with a carpeted floor, which they were uncertain as to how it may affect the performance of their HP.

Unlike owner occupiers, the social-housing tenants were never the ones initiating the installation of a HP or receiving the RHI fund and they had minimal or no control over their system’s installation. Unfortunately, the exact decision-making process for RSL around both the selection of tenants/dwellings and the heating system is not known. The tenant of CS05 thought that the RSL wanted to take advantage of the funding incentives available. From the tenants’ point of

\textsuperscript{10}A passive solar heating system that utilises glazing and thermal mass to capture and store solar heat during the day and then gradually release it to adjacent spaces that need to be heated (Hu, He, Ji, & Zhang, 2017).
view, in all but one case (CS02), the RSL merely informed the social tenants of the change that was going to take place and did not give them the option to refuse its installation. This was usually accompanied by an invitation to a formal briefing, explaining how HP technology works and the benefits of embracing this over other heating solutions. In CS07, the occupants were subsequently extremely dissatisfied with this process; they felt that not only was a poorly performing heating system forced on them but that they were also unnecessarily deprived of having access to a well-performing gas central-heating system, like that many of their neighbours had:

They wouldn’t give us gas. We had storage heaters when we first came, and the council refused to give us gas. They said it wasn’t near our front door. So, it’s on either side, it’s across the road but it wasn’t near here! So, we had to have these [the heat pump]. (Gabi, CS07)

Overall, the parameters mentioned as influencing the installation of HPs over other options, no matter whether a ground or air source, fall into six main categories:

- **Environmental friendliness** relating to the perceived low energy consumption and carbon footprint of HPs;
- **Financial motivations** due to its proclaimed lower running and overall costs, government incentives such as the RHI payments and its compatibility with PVs and feed-in-tariffs;
- **Practicalities**, such as the low maintenance required, the lack of need for refuelling and its long-life cycle;
- **Comfort considerations**, *i.e.*, favouring constant heat provision;
- **Technical practicalities**, *e.g.*, no need for natural gas pipeline network availability or installation restrictions as is the case with oil tanks;
- **Expert or social recommendations** in the form of renewable energy systems (RES) awareness days and suggestions provided by installers or existing HP owners.

**The heat pump installation process and handover**

Even though the occupants were not explicitly asked to rate their satisfaction with the overall HP installation process, many shared their experiences and commented on the aspects of the process that they thought were significant for a smooth and effective handover. Emphasis was placed on issues relating to the installers’ technical capabilities and the disruption associated with the HP installation, including any associated building fabric measures implemented. In some instances, certain aspects of the installation process extended over a significant period of time, resulting from either an incorrect system setup or the implementation of belated building fabric improvements. Another aspect of the handover process concerns the instructions and...
training made available to the occupants, which they were specifically asked to rate and comment on. These are discussed in the following three paragraphs.

The occupants’ view of the installers’ technical capabilities

One of the first considerations, shortly after the decision for the installation of a HP is taken, is the identification of knowledgeable and trusted installers. While social-housing tenants were not involved in the HP installation process, a significant number of owner occupiers in the sample mentioned this was often a very important and difficult task. While some owner occupiers were happy with their initial selection, others had to employ multiple installers to get their HP to work properly. There were some cases where both social-housing tenants and owner occupiers felt the technicians involved were not capable enough, leaving some social tenants feeling very insecure about whether they would be able to reach a knowledgeable person to resolve any problem arising.

Overall, a great number of technical problems was reported for the sample, with many likely to have been present since the HP installation, implying an imperfect handover to the occupants. In CS07 and CS16, the occupants thought that their excessively high energy bills resulted from an unresolved technical issue. At the time of the CS16 site visit, this was still being investigated/monitored by a privately hired technician. However, this was not the case in CS07, where the social-housing tenants, Greg and Gabi, had been left hopeless. Multiple technical teams and RSL representatives had previously visited CS07, but no one had been able to identify and resolve the problem nor alleviate the retired couple’s negative feelings. As a result, they strongly felt that this was the result of the technicians’ limited technical capabilities, alongside their poor building fabric thermal performance, even though it had been retrofitted to some extent. A detailed list of the technical issues encountered is included in Table 21 of Appendix C.

Disruption associated with the heat pump installation

A certain amount of disruption is expected with every HP installed in an already inhabited dwelling. This is usually greater with GSHP installations and in cases where the building fabric efficiency needs to be improved to boost HP efficiency. In the case study sample, two out of the three social housing cases located in close proximity and being managed by the same RSL (CS06-CS08) expressed dissatisfaction with the disruption caused as part of the energy-efficiency upgrade implemented approximately 1 year after the installation of the HP. This involved the addition of loft and cavity-wall insulation. The latter was implemented by removing the external brick layer, adding insulation and reinstating external brickwork. The third case (CS08) also went through this same process, but the occupant did not report any dissatisfaction.
in relation to this matter, the reason being that she had temporarily relocated to her daughter’s home. In addition, the tenant of CS08 described a highly disruptive process concerning the drilling of boreholes in her small backyard during wintertime.

Occupant training and operational instructions

The final step in the handover of a HP is to ensure that users are adequately trained and provided with sufficient documentation that will enable them to run the HP smoothly and efficiently. The occupants’ training in the sample varied between cases, including being provided with booklets, pamphlets, flashcards, installer/RSL demonstrations, verbal advice and, on a few occasions, technical group briefings. Out of 21 case-study occupants 17 stated they were either satisfied or very satisfied with the training provided, however, almost everybody agreed that the instructions were too lengthy and complex.

*Giving somebody a manual that thick and telling them a whole lot of stuff they didn’t understand, and it was never going to make any sense to anybody.* (Gabi, CS07)

Despite the detailed information sources provided, most social-housing tenants explained that the RSL had advised them not to interfere with the HP. The general recommendation was to control the HP through the room thermostat only and ideally maintain a stable, set temperature. Many owner occupiers were also advised by the installer to run the HP continuously at a constant temperature.

Overall, the occupants stated they were satisfied with the training provided. Of the few that stated they went through the manual, they largely perceived it as a complex information source. Those clearly dissatisfied stated that they would have liked more tailored information as to how they could improve the performance of their HP, *e.g.*, how to optimise its operational conditions and fine tune it. Some occupants also highlighted the importance of post-installation visits by experts that could help them answer specific questions once they had tried themselves and suggested the creation of a “central resource of knowledge” exhibiting typical installations, problems encountered and solutions/links to relevant sources.

**Ease of control and comfort on a day-to-day basis**

Once a HP is set up and running, it is expected to provide sufficient SH and DHW to the occupants, who should be adequately educated on how to control it to satisfy their needs. Despite most occupants acknowledging a HP as being an extremely complicated system, all but the occupants of CS07 agreed that a HP is very easy to use. This is mainly because they do not need to make frequent adjustments, most of which are implemented through the thermostat, or access the HP controller interface. Gabi and Greg of CS07 felt that the question was not
relevant to a system that was not functioning properly and which they felt they knew how to control but was not responding accordingly.

In terms of the occupants’ perception of ambient warmth, it seems that their desired and perceived comfort with the HP concurred with only a few exceptions. For most occupants, their stated comfort was within the ‘comfortable’, ‘quite warm’ or ‘warm’ range and thus they rarely needed to employ any warming-up measures on top of their usual HP routine. If needed, the warming-up measures mentioned included various HP control adjustments to HP control, the use of wood stoves/resistance heaters and an increase in clothing layers. Gabi and Greg of CS07 were the only occupants that were deeply dissatisfied with the warmth provided by the HP, as they felt they were not getting sufficient SH for the cost paid and could not afford to raise the thermostat temperature to sufficiently warm up their small bungalow.

*It feels cool, we want it warm […] we sit here freezing. And we can’t get the washing dry and just isn’t the heat we would have expected (Gabi, CS07)*

A similar situation was described in CS16, a large farmhouse, where at the time of the site visit, Patricia explained that up to the previous winter season, the HP had kept the whole house as warm as they would like but at a greater cost than they would have liked. Thus, they subsequently decided to compromise by not allowing whole-house heating, implemented through the HP’s frost protection settings and alternative/localised heating methods. The occupants of CS01 stated they also compromised with slightly less ambient warmth than what they would have liked by keeping room thermostat settings at a lower level, with Amanda preferring a warmer environment in comparison to her partner. A similar gender-based difference in ambient warmth preferences was noted in at least another three cases (CS09, CS13 and CS14), whose occupants declared they were generally happy with the level of warmth provided. The occupants of CS10 and CS18 also stated they were content with the overall warmth but acknowledged a lower level of comfort in certain areas of their houses due to perceived structural inefficiencies and/or heat-emitter inadequacies.

### 5.2 Case Study Monitoring Profiles in the Light of the Site Visit Field Data

Following the data cleaning, filtering and statistical analysis performed by the RHPP team on the 21 case studies, their monitoring profiles were visually inspected as part of this work. The visual observation of the time-series data complemented the existing data analysis and enabled the identification of site-specific data patterns and arbitrary structures that it was not possible to identify through statistical analysis alone. The aim of this section is to provide a better understanding of the HP monitoring profiles in the case study sample through the integration of
qualitative data sources, understand the uncertainties associated with the monitored data and explore their potential impact on the SPF calculation. An approximate magnitude of the temperature, flow rate, heat and electricity statistics, based on the visual inspection of the data series, alongside a summary of selected aspects of the metering data are provided in Appendix I.

5.2.1 Metering uncertainty

The case-study monitoring data span between 01/01/2012 and 31/03/2015 and were collected for different periods in each case, as shown in Table 9 of Appendix C, with a minimum of 18 and a maximum of 36 monitored months. The range of variables monitored in the RHPP field trials, alongside their definition, are presented in Table 3-2. The sensor configuration is depicted in the monitoring installation schematics provided by BEIS at the start of the RHPP project, however, as explained in subsection 3.2.3, these were not always correct. As shown in Table 5-2, the monitored variables available in each case generally matched the configuration identified on site and/or the technical specifications provided by manufacturers, with some exceptions and uncertainties. These include unmetered variables, monitored data present but no corresponding variables in the tailored schematics, and uncertainty around which HP system was being monitored when two were installations identified during the site investigation of CS10. In CS06, CS07 and CS08, in particular, the resistance heater monitored was erroneously logged as a whole-system boost (Eboost) instead of the DHW tank immersion heater (Edhw), and in CS20, the temperature of the water to the DHW system (Twf) seemed to be recorded, even though no DHW was provided by the SH-only HP (explained further in subsection 5.2.2). A description of the monitored variables can be found under the Monitored Variables Nomenclature (p. 17).
Table 5-2: Monitored variables available in the case study sample.

<table>
<thead>
<tr>
<th>ID</th>
<th>Tco</th>
<th>Tsf</th>
<th>Twf</th>
<th>Fhp</th>
<th>Fhw</th>
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<td>-</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td>CS14</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
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<td>-</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td>CS15</td>
<td>√</td>
<td>√</td>
<td>√</td>
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<td>√</td>
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<td>√</td>
<td>-</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td>CS16</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td>CS17</td>
<td>√</td>
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<td>-</td>
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<td>N/A</td>
<td>N/A</td>
<td>√</td>
</tr>
<tr>
<td>CS18</td>
<td>√</td>
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<td>√</td>
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<td>N/A</td>
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<tr>
<td>CS19</td>
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<td>√</td>
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<td>-</td>
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<td>-</td>
<td>√</td>
<td>N/A</td>
<td>N/A</td>
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<td>-</td>
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</tr>
<tr>
<td>CS20</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>√</td>
<td>-</td>
<td>√</td>
<td>-</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>-</td>
<td>√</td>
</tr>
<tr>
<td>CS21</td>
<td>√</td>
<td>√</td>
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<td>-</td>
<td>√</td>
<td>-</td>
<td>√</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>√</td>
</tr>
</tbody>
</table>

✓ Variable measured.  ¡ Very limited non-zero entries or insufficient data present.
? Data present but no corresponding variable.  * Uncertain which of the two HPs present the data correspond to.

Except for the uncertainty relating to the presence of specific variables, the monitored data available were often insufficiently comprehensive and subject to errors. Subsection 3.3.2 describes the data-cleaning process and acknowledges a significant amount of implausible data remained, including large numbers of data spikes and periods of invalid or missing data. However, it is generally accepted that the monitored data will be imperfect to some extent, leading to measurement errors that are usually categorised as random or systematic (JCGM, 2008). Systematic errors shift the measured data in the same direction and thus affect accuracy rather than reliability. The Systematic Errors Report (Lowe et al., 2017b) identified three possible sources of systematic bias. All three affect the heat-meter output and concern:

(a) inappropriate calibration, since heat meters were calibrated for water, but the majority utilised an antifreeze mixture of water and glycol-based additives;
(b) a temperature offset of the meter output (not thought to be widespread in the sample);
(c) a declining output, with a very clear effect in Sample S2, where the median decay over a year is approximately 1.5%.

All three types of systematic error were thought to be related to the use of glycol-based additives. While the first two are likely to cause SPF overestimation, the latter is expected to cause underestimation. Mechanism (a) appears to have had the largest effect of the three but there is generally no clear evidence of the magnitude of the bias. Lowe et al. (2017b) concluded that a detailed estimation of all three possible sources of bias is only possible through an on-site investigation of a sample of installations.

Unlike systematic errors, random errors reduce the reliability of the measured data but may not affect the overall accuracy of the results from the statistical analysis of large samples since they tend to average out. Thus, they are not thought to have significantly influenced averages resulting from the statistical analysis of the large RHPP sample, particularly following the detailed filtering process that aimed to increase detection accuracy of the factors influencing performance variation (see section 3.3.2). A detailed description of the range of metering errors that may have not been completely eliminated in the latest and most robust of all subsets (i.e., sample S3), alongside their expected impact on individual SPF calculations, where possible, is included in the RHPP Performance Variations report (Love et al., 2017). Most of these metering errors were also identified in the case study monitoring data. Table 5-3 presents a non-exclusive list of these fault types, also appearing in the case study sample, alongside plausible causal explanations.
Table 5-3: Metering faults in the case study sample and plausible explanations and effects.

<table>
<thead>
<tr>
<th>Suspected fault type</th>
<th>Possible cause</th>
<th>Effect on SPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat output spikes of extreme values (isolated or closely together).</td>
<td>May be a metering issue, a wireless transmission error or a real dynamic effect when changing mode.</td>
<td>SPF overestimation unless real effect</td>
</tr>
<tr>
<td>Systematic heat meter under-reading.</td>
<td>Metering installation issues, e.g., strap-on sensor or poor installation of pocket sensors.</td>
<td>SPF underestimation</td>
</tr>
<tr>
<td>Heat meter output limited to 18 kW.</td>
<td>Heat meter pulse frequency(^{11}) limitations.</td>
<td>Expected to impact SPF slightly in cold weather.</td>
</tr>
<tr>
<td>Heat output but no electricity input.</td>
<td>Heat meter temperature sensor offset, exacerbated by circulation pump over-run.</td>
<td>SPF overestimation</td>
</tr>
<tr>
<td>Electricity input but no heat output (zero or unusually low heat data were not filtered out during the data-cleaning process).</td>
<td>Heat meter fault; a not fully powered-down HP continuing to consume electricity due to parasitic loads.</td>
<td>SPF underestimation</td>
</tr>
<tr>
<td>Transposition of heat or energy sensors, such as between SH and DHW heat sensors and between in-line and immersion resistance heaters.</td>
<td>Planning or processing error.</td>
<td>Overall SPF unaffected; depending on the sensors involved, other boundaries may be affected or SH/DHW SPF.</td>
</tr>
<tr>
<td>Concurrent missing electricity and heat data.</td>
<td>Unknown</td>
<td>Depends on the time of year</td>
</tr>
<tr>
<td>Limited periods of invalid heat or energy meter data</td>
<td>Faults subsequently identified and corrected</td>
<td>Depends on type of invalid data</td>
</tr>
<tr>
<td>Accumulated records of energy consumption that should have probably been distributed over a previous period of several null time stamps</td>
<td>Energy meter anomaly</td>
<td>None</td>
</tr>
<tr>
<td>Flow temperature sensors influenced by one another, i.e., SH and DHW flow temperature sensors.</td>
<td>Sensors too close to other pipes.</td>
<td>Overall SPF unaffected, unlike SH and DHW SPF.</td>
</tr>
<tr>
<td>Suspected unmetered variables (e.g., missing Eboost, Edhw or Esp)</td>
<td>Planning or processing error.</td>
<td>SPF overestimation</td>
</tr>
</tbody>
</table>

The visual inspection of the case study monitoring data confirmed the presence of the suspected metering faults listed in Table 5-3 and revealed additional uncertainties often encountered in relation to: (a) the temperature of the water flow after the condenser (Tco) being recorded as higher than that of the water flow to the SH (Tsf) and DHW (Twf) system, (b) the maximum measured heat produced by the HP being higher than the system’s declared net capacity, and (c) heat leaving the HP as measured on the circulation system (Hhp) not including

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\(^{11}\) Pulse frequency refers to the number of pulses of a repeating signal in a specific time unit.
any heat produced for DHW, raising concerns about heat sensor placement (additional information included in Appendix I). Among other reasons, all these might have been related to the use of the backup resistance heater, however, it was not always possible to confirm this due to the extensive lack of relevant metering data. The extent of resistance heater use in the sample is explored in subsection 5.2.2, alongside other insights stemming from the cross-examination of the monitored data and the qualitative information collected during the site visits.

5.2.2 Insights in line with observations from site investigations

In addition to the technical monitoring data and metadata, the in-depth site investigations were intended to collect information on the wider environment a HP interacts with. They also provided further insights, as well as more clarity, on the existing monitoring profiles and to an extent enabled the assessment of the HP installation and monitoring equipment. On some occasions, the data revealed that the observed data ‘anomalies’ related to unexpected features of the system, for example, or shed light on aspects of HP operation that the users were completely unaware of, and on others they confirmed the users’ narrative.

Critical information missing from metadata

The lack of crucial information in the metadata for the understanding of the HP installation configuration initially led to the false belief that a single SH- and DHW-providing HP was installed in two cases. Much to the surprise of the visiting researchers, the site investigations revealed that the installation of CS20 concerned a SH-only HP and CS10 comprised of two HP units. Further information on the monitoring profiles of these sites are provided below:
• In CS20, the Tco and Tsf readings were almost identical, while Twf recordings were consistently approximately 10 °C lower than the former, as shown in Figure 5-20, indicating the erroneous application of the Twf sensor and its likely transposition with Tsf.

![Figure 5-20: CS20 monitoring profile.](image)

• In CS10, Twf was found to be consistently higher than Tco, with little or no correlation between the two. Since there were two HPs but only one Tco sensor present, it is very likely that only one of them was related to DHW, and the other, whose Tco and Tsf readings correlated perfectly, produced hot water for SH only, an idea that was first suggested by the occupant. As shown in Figure 5-21, the fact that there was also no corresponding Hhp, Ehp, Fhp or Tin when DHW was heated confirms the hypothesis of a SH-only and a DHW-only HP, where all the monitored parameters, except for Twf relate to the HP supplying heat to the SH system only.
Plummeting monitored data compatible with heat pump or sensor battery failure

On some occasions, the reasons behind periods of missing or plummeting monitored data became clear following the interviews with occupants and in particular:

- In CS06, CS08 and CS17, the occupants’ narratives revealed that the monitored periods were lacking energy input (Ehp) and output (Hhp) data while dropped temperature sensor readings were linked to the reported HP breakdowns that took one or several weeks to restore.
- In CS09 the drop in Hhp/Fhp readings plummet between April 2013 and September 2014 appears to be consistent with the flat battery incident reported by the occupants.
Extensive resistance heater use

The backup resistance heater of HPs appeared to make a substantial contribution to the heat production in several case studies, primarily for DHW heating purposes. However, none of the occupants thought that their HP was utilising resistance heating on a regular basis or that it was present, unless they encountered unusually high electricity bills caused by its unexpected use. The cases where high resistance heater use was identified or suspected are listed below, alongside the relevant context:

- The monitored data of CS02 show that DHW was provided exclusively by the immersion heater (Edhw), which appeared to come on approximately seven times a day at approximately 2-2.7 kW, throughout the whole monitoring period. While the occupant appeared to be completely unaware of the DHW immersion button being switched on, the visiting researchers were able to confirm this on site.

- In CS03, where the occupant stated the system was expensive to run, the data indicate that this may be, in part, have been due to use of the internal electric flow boiler (Eboost), as well as the presence of an electric shower, increasing overall electricity bills. Even though Eboost was not metered directly, the winter COP of between 1 and 1.5, the consistently higher Twf than Tco by approximately 3 °C and the Hhw winter max of up to 6 kWh higher than the system’s declared net capacity indicate that Eboost was utilised for pasteurisation purposes every 2-3 days (see Figure 5-22)\textsuperscript{12}.

- In CS08, the occupant stated that the accidental initiation of the DHW booster resulted in an extended period of excessively high bills. Although it was not possible to confirm this through the monitored data, Edhw which may have been misrecorded as Eboost, was found to contribute regularly to the production of DHW by approximately half of the time or more throughout the monitoring period, at a maximum of 5 kW. A similar Edhw pattern (also likely to be misrecorded as Eboost) was noted in CS06 and CS07\textsuperscript{13}.

\textsuperscript{12} The possible contribution of Eboost to the SH production is less likely, i.e., Tsf is consistently higher than Tco by approximately 1.5 °C, albeit at a much higher winter COP of around 3 and a maximum heat output higher than the system’s Declared Net Capacity by just under 1 kW, pointing to a likely metering error.

\textsuperscript{13} The periods of accidental actuation of the DHW booster in CS12 and the resistance heater actuation following the HP’s breakdown in CS17, both noted by the occupants, could not be confirmed through the monitored data.
Occasional Eboost use, although not metered, was also suspected in CS14, whose occupants were expecting their system to provide them with more savings. This is also based on the presence of higher Twf than Tco readings. These appeared to follow an initial DHW heat up by the HP, where Twf and Tco lay closely together. Figure 5-23 shows that the subsequent DHW cycle seemed to be powered by Eboost and this is supported by an accompanying COP of 1. The maximum heat produced by the HP for SH varied significantly but was often up to 3 kW higher than the system’s declared net capacity, possibly suggesting the use of some Eboost heat for SH as well.

In CS09, the occupants stated that the DHW boost was rarely needed, however, the data show that the system suffered from excessive use of Edhw. DHW was usually heated twice or three times a day, with maximum DHW flow temperature from the HP at around 50 °C, which was then always topped up by the immersion heater, providing approximately 3 kW of heat. This might be linked to legionella control or to settings for the maximisation of cylinder storage capacity. In some parts of the monitoring data, the immersion heater came on up to 10 times over a 24-hour period, indicating that the householder may have changed the settings during the year so that the immersion timer switch was set to continuous mode.
Eboost was likely involved every time DHW was heated to pasteurisation temperature in CS16, since Twf was always higher than Tco, as shown in Figure 5-24. This occurred extremely often (2-3 times a day) until early March and was occasionally true with DHW heated at lower temperature, as well as with SH, since the heat produced often exceeded the system’s declared net capacity by up to 4.5 kW. However, this was accompanied by a corresponding Ehp of only 4.5 kW, which could point to a heat meter issue instead.

A significantly reduced load factor

From early March 2014 onwards, a significant reduction in the SH load of CS16 was noted. Even though the occupants explained in detail the changes they implemented to the way they controlled the system beyond the monitoring period\textsuperscript{14}, in an attempt to reduce its running cost, the monitored data revealed that experimentation with controls may have been initiated long before that. A reduced heat load may lead to a lower SPF, particularly since a fixed speed compressor was present, and this is supported by the RHPP case study

\textsuperscript{14} The occupant reported an initial intermittent SH regime at a comfort temperature of 20-21 °C, resulting in a very comfortable environment but at a very high running cost. Thus, they decided to experiment by using their HP as a background heating system, with the addition of standalone supplementary heating. Most room thermostats were set at 16 °C, while bringing the bathroom and hallways occasionally up to 20-22 °C.
report (Lowe et al., 2017a) finding from the comparison between monthly COP and load factors of three similar cases studies (CS14, CSC16 and CS18).

Figure 5-24: CS16 monitoring profile.

Heat pump and metering installation quality

It was not always possible to establish installation quality and validity of the monitored data definitively for reasons explained earlier on p. 121. The following points highlight possible links between the monitored data and the observed quality of the HP installation and its monitoring equipment, where this was feasible.

- In CS01, the installer’s photos revealed the presence of at least two strap-on sensors present, one of which is depicted in Figure 5-18a. Strap-on sensors might lead to systematic heat meter under-reading. However, even with pocket sensors, it is still not possible to comment on the quality of their installation as there is no way to know the length of the probe inside the pipe.

- In CS12, the Twf temperature readings were consistently higher than Tco by approximately 5 °C, which may be related to the improperly fitted sensor depicted in Figure 5-19b, although it is not certain whether this had been fitted on the DHW
pipework or not. Another temperature sensor at the same site appeared to be properly positioned.

- Assuming Tsf was erroneously being reported as Twf in the SH-only-providing HP of CS20, the high temperature difference between the Tsf and Tco readings might stem from the placement of the pipework and sensors in the uninsulated garden shed shown in Figure 5-13c.

**Investigating the excessive electricity consumption reported**

Among all case studies, two stand out due to their occupants clearly expressing their concerns with regards to the high electricity consumed by their HP system. Their monitoring data were examined to identify any emerging contributing issues.

- As shown in Figure 5-25, the monitoring data of CS07 indicate unusually high Tin and Tsf readings. Tin was much higher than the external temperature (Tex) and did not follow seasonal variation while Tsf was regularly recorded at highs of 60°C in SH mode and 65-70 °C shortly after DHW was heated. It is very unlikely that the system was running at such high temperatures, especially as the occupants noted that their radiators never felt warm. It is more likely this is an issue related to faulty or improperly calibrated temperature sensors. Even though maximum Twf readings were within reasonable limits, *i.e.*, reaching 65 °C once a day in the winter, they are also likely to be erroneous. When not heated, the DHW flow usually maintained temperatures of around 55 °C, which is too high considering there was no heat input. Thus, it is not clear from the monitored data what the source of the reported electricity consumption could be, other than the likely regular use of Eboost for DHW purposes (explained earlier on p. 139).

- In CS16, the occupants felt they were paying too much for the heat provided by their HP system. The monitoring data indicate this may have been related to an unanticipated DHW heating pattern, since the occupant thought DHW was heated once every morning. The Twf series of Figure 5-24 shows that DHW was heated in long 90-minute cycles, 2-3 times a day and always at a high temperature (65 °C) until early March 2014, when a drastic change in DHW settings was noted. The new setting concerned DHW being heated multiple times a day (12-20 or more), in significantly shorter cycles (varying from 15 minutes to nearly instantaneous) and at a lower temperature of 55 °C, reaching 65 °C just once per week. Both settings are likely to lead to high energy consumption, especially if Eboost is involved, which was present but not monitored. March 2014 also signifies the start of a low SH load period that manifested earlier than the 2015-16 period reported by the occupants, resulting from the occupants’ financial concerns. This is also expected to have reduced the HP’s SPF further.
5.2.3  **Emerging seasonal performance factors**

As noted earlier in subsection 3.1.1, the case study selection was based on SPF's at boundary level H3. However, the calculation of SPF H3 requires the subtraction of the electricity used by auxiliary drives, such as circulation pumps, as well as the heat added to the circulating water. Since none of them were measured directly and their energy consumption and heat addition can only be assumed, it would be more appropriate to consider the relative efficiency of HP in the case study sample at boundary level H4 (see subsection 3.3.2 for SPF calculation at different boundaries). The calculation of SPF H4 is based on measurements alone and thus eliminates the uncertainties associated with the influence of circulation pumps on the system’s efficiency.

Subsections 3.3.2 and 4.4 explain why and how the originally calculated SPF's, based on sample S1, were recalculated utilising varying inclusion criteria and data periods as part of the RHPP project work. The process resulted in an updated list of SPF estimates at level H4, which are referred to as final SPF estimates. These were re-evaluated as part of this work, based on the visual observation of the monitoring data. Table 1 of Appendix C lists the SPF's calculated for each case study as part of the RHPP project. The visual inspection of the monitoring data revealed that some of the final SPF estimates were unreliable since they were based on periods...
containing metering errors or untrustworthy data. All case studies identified with extensive periods of seemingly unreliable or missing data are included in Table 27 of Appendix I, alongside plausible explanations, where possible.

The final SPF estimates that are thought to be influenced by such data are marked in Figure 5-26. An up or down arrow indicates an SPF that was likely to be under- or overestimated, respectively, and a question mark denotes an SPF that was likely to change either way. In particular, the final SPF estimation period in cases CS03, CS15, CS16 and CS21 includes approximately 15 or 30 consecutive days of HP energy input (Ehp) but no heat output (Hhp), regular incidents of Ehp without Hhp throughout the whole SPF calculation period or approximately 3-month long abnormally high Ehp readings. The converse applies to cases CS07, CS08 and CS18, showing Hhp output but no Ehp or abnormally high Hhp signal for a period of 2 or 4 months or regular incidents of 1-1.5 kW Hhp output but no corresponding Ehp signal throughout the whole SPF calculation period. Similar concerns on the accuracy of the heat meter data also apply to CS13, with regular incidents of 1 kW Hhp but no Ehp expected to lead to an overestimated SPF, while the 18-kW heat sensor cap is likely to lead to an underestimated SPF. In the case of CS12, the collected data are problematic because of the implausible heat meter readings throughout the whole monitoring period (see section I2 of Appendix I). Hence the calculated SPF is considered invalid. In the remaining cases listed in Table 27 of Appendix I, the data in question do not appear to have an impact on the SPF_{H4}, as calculated during the final SPF calculation period due to any of the following reasons: (a) even if disregarded they would have minimal impact on the SPF, (b) they do not fall into the final SPF calculation period, and (c) they do not concern the parameters required for the SPF calculation.

Figure 5-26 also compares monitored SPFs to manufacturers published COP. Even though SPF_{H4} and COP are not technically comparable\textsuperscript{15}, it is still interesting to see how their advertised efficiency relates to the efficiency resulting from the monitoring data, which is closer to what the occupants experienced, providing that the monitoring data are valid. Based on this limited number of case studies, the laboratory test performance (COP) of a HP does not seem to be a good indicator of actual performance. However, an exact match between measurements of real performance and that of test laboratories, under controlled conditions, is not to be expected (Chesser et al., 2021). It might be expected that in general HPs with a higher COP would result in a higher SPF, however, this is not the case with this case study sample. Unlike real-life installations involving anomalies (e.g., metering errors, operation issues, and missing data),

\textsuperscript{15} The manufacturer’s COP and SPF_{H4} cannot be compared for a number of reasons: (a) different data periods are utilised for their calculation, i.e., instantaneous for COP and annual for SPF, (b) different operating conditions are involved, i.e., predefined nominal working conditions for the manufacturer’s COP and real highly variable working conditions for SPF, (c) they concern different boundary levels, i.e., H1 or H2 for COP and H4 for the final SPF estimates, as part of the RHPP project.
Laboratories are capable of addressing any issues arising on the spot, both in terms of metering and operation. In addition, real-life installations interact with a much wider range of parameters.

Figure 5-26: Final SPF estimates in relation to manufacturers’ declared COP for the 21 case studies.

5.3 Summary and conclusion of the results section

This chapter provided an overview of the qualitative and quantitative data collected for the 21 case studies, corroborating between the two where appropriate. Overall, the monitoring data involved a great deal of inconsistent or implausible readings and the metadata presented limited and often unreliable information about the HP system. This included inconsistent or implausible schematics, no mention of multiple circulation pumps, pipework heat exchangers and the presence of long or imperfectly insulated pipework. Surprisingly, they sometimes lacked information as critical as the presence of two HPs operating in tandem. Unmetered variables or data recordings of features not present in the system were also noted, e.g., DHW recordings for a SH-only HP. This was sometimes linked to the improper installation of the metering sensors, revealing a variation in installation quality both within and across case studies. The detailed visual inspection of the monitoring data identified case studies whose SPF is likely to be higher or lower than their statistical estimation (as part of the RHPP project) and which was completely invalid in one case.

The qualitative data revealed distinct differences between social-housing cases and owner occupiers, primarily in terms of decision making around the HP installation and access to the
controller. Unlike most owner occupiers who made an informed decision to install the HP, social tenants were not those initiating the process and they had no or very limited influence over the decisions surrounding the installation, which was under the full control of the RSL. All social-housing cases involved retrofit installations to which the occupants had very limited access in terms of controls, on the contrary to the privately owned dwellings, involving both newbuild and retrofit installations, whose occupants had full access to the controller. Many of the larger owner-occupied houses had multiple thermostats with varied settings, contrary to the smaller, single-thermostat social housing cases, whose TRVs were minimally utilised and/or understood. Besides accessibility, ease of understanding and user knowledge were key to the extent controls were utilised. It was generally acknowledged that whilst a HP system is very complicated, it is easy to operate on a day-to-day basis unless technical problems arise.

However, technical issues were extensively encountered in the sample, fuelling a general lack of trust of installer capabilities. Many of these issues appeared to be present from the HP handover and took a long time and/or several technicians to be resolved. Even though the monitoring data indicate that use of the HP backup resistance heaters in the sample was quite prominent, users were generally not aware of this. What was likely to make them aware of it were the associated high electricity bills that usually required a technically skilled individual to be able to identify the source of the problem.

The cross-examination between the EPC and data collected on site raised concerns about EPC reliability that may have had HP sizing implications, as did the building fabric thermal improvements that took place after the HP installation in several cases. Uncertainties in relation to the building fabric efficiency were also raised due to the existence of technical imperfections relating to leaky windows/doors and the improper application of insulation. The frequent use of standalone supplementary heating, particularly in the form of wood-burning fires and stoves, may also be linked to sizing implications.

Overall, the site investigations enabled a holistic assessment of the HP installations by portraying a significantly broader context than that provided by the monitoring data and metadata alone. This included looking at the HP systems from different perspectives, i.e., the technical installation, the building it is installed within and user interactions. The high-level analysis of the qualitative and quantitate data collected on the 21 case studies indicated that monitoring data and metadata cannot be well understood in isolation, particularly due to the uncertainty associated with the quality of the measured parameters and their associated metadata (Lowe et al., 2017a).
Chapter 6: Socio-technical Factors Affecting Heat Pump Performance in the Case Study Sample

This section elaborates on the parameters affecting the performance of HPs and their interrelations, using a systems thinking approach. As explained in section 2.4, the first step in relation to systems thinking was the creation of a literature-based causal loop diagram (CLD), which is expanded here to include the evidence obtained through the analysis of the qualitative and quantitative data collected on the 21 case studies. Each of the following sections present sequential CLDs linked to a final aggregate CLD, including seven interconnected focal areas. Each focal area is marked with a different colour that helps navigation through the diagram and also links the sequential CLDs to the final aggregate CLD. The focal area each sequential CLD belongs to is marked with the respective colour of the label within the arrow, denoting the type of the loop, i.e., balancing (B) or reinforcing (R), accompanied by an ID number or letter. Where the ID is accompanied by a letter, it denotes balancing or reinforcing loops that represent more generic areas, i.e., those that formed the underlying structure of the detailed CLDs. A loop can be clockwise or anticlockwise due to stylistic reasons.

With Vensim software, the total number of feedback loops passing through a specific variable can be calculated, providing they are up to 32 variables long (Ventana Systems, 2015). This provided useful information on the centrality of variables and enabled the identification of high-influencers. A variable surrounded by ankle brackets (< >) indicates a duplicate and is used to simplify complex CLDs by refraining from adding additional arrows. Within the text, variable names are in italics and feedback loops in brackets to facilitate easy identification. Where new CLD structures are described, variable names are highlighted in bold. A list of all feedback loops utilised in the aggregate CLD, alongside a short description for each, can be found under the Feedback Loop Names section (p. 18). Appendix J includes additional information on selected topics and occupant quotes that are referred to in the following sections.

Section 6.1 introduces the relationship between subjective and objective perspectives of HP performance and then expands on the seven focal areas influencing performance in sections 6.2, 6.3 and 6.4. Section 6.2, in particular, focuses on the ability of the HP to fulfil occupant needs, section 6.3 on the influence of overall heat loss and indoor humidity level and section 6.4 on the technical parameters influencing HP performance. Section 6.5 brings everything together in an aggregate CLD that highlights the prevailing influencing paths and addresses system
complexity. These sections also discuss, where applicable, the confounding factors that might influence the occupants’ opinion about their HP's energy consumption, and thus their perspective of the HP’s perceived performance.

6.1 The Relationship Between Subjective and Objective Perspectives of Heat Pump Performance

This section describes the relationship between the actual HP performance and its performance as is perceived by the occupants. The actual performance is an objective estimation of HP performance. The perceived performance of a HP is a subjective measure of the occupant’s indirect evaluation of HP performance based on factors such as costs and the provision of heat. In this study, it is used to denote the HP’s ability to meet needs as described by the occupants of the 21 case studies.

The actual HP performance is expected to influence the occupants’ perception of the HP’s ability to fulfil needs indirectly. However, being a subjective perspective, the perceived performance relies heavily on occupants’ experiences, views and conceptions. Whilst the actual performance is expressed as the ratio of the heat produced to the total energy consumed by the HP for a given period of time and within a specific boundary, the occupants’ perceived performance relates to a different set of variables. These act within a larger boundary, which is primarily the dwelling’s envelope. They intervene between the HP installation and the occupants, and together with the occupants’ personal circumstances, experiences and beliefs and the actual HP performance, they form their perception of the system’s performance. Thus, there appears to be a gap between what is considered efficient in technical terms and what the occupants experience.

In terms of perceived performance, as shown in Figure 6-1, the main needs that the occupants of all 21 case studies were expecting their HP to satisfy were having sufficient and uninterrupted SH/DHW availability at an ‘affordable’ energy cost. These were also found to be primary drivers of occupant satisfaction (among other secondary drivers listed in Table 28 of Appendix J). Note that affordability is highly subjective, as it depends on the individual circumstances of each household, the occupants’ experiences and any bill-offsetting revenue or renewable energy systems (RES). In addition, a high actual efficiency cannot guarantee a low running cost, e.g., depending on the size of the house, DHW use etc. Overall, the levels of SH and DHW required, as well as the desired bill threshold, varied between case studies, as did the parameters influencing them. Whenever one of these requirements was not satisfied, the occupants proceeded to make system adjustments (e.g., through the HP settings or their lifestyle), where
possible, to correct the perceived SH/DHW insufficiency or lower the perceived high electricity bills.

Figure 6-1: Causal loop diagram focusing on the effects of employing corrective measures based on the perceived heat pump performance.

The corrective measures employed by occupants were as simple as adjusting the thermostat temperature or as sophisticated as fixing a complicated technical issue. Most of the HP technical issues acknowledged by the occupants, as well as the time required to resolve these issues, had a negative influence on the HP’s ability to fulfil needs. As well as the apparent inconvenience caused, the technical problems encountered often affected HP efficiency and the problem-resolving process was not always successful or straightforward. In any case, the occupants’ goal was to reduce the gap between the perceived performance and the desired performance, with the latter reflecting the expectations of users that may change over time, e.g., due to the changing affordability. For the purposes of the CLD of Figure 6-1, the measures leading to the desired outcome, i.e., the elimination of the gap, are named appropriate corrective measures and their balancing effect is depicted by loops [Ba] [Appropriate corrective measures improving heating availability] and [Bb] [Appropriate corrective measures improving energy consumption].
However, not all adjustments have the expected outcomes. Small changes can, unknowingly in some cases, cause imbalance in other parts of the system leading to a lowered system efficiency, increased energy consumption or a reinforced initial problem. Figure 6-1 shows how the perceived performance shortfall can be exacerbated due to corrective measures inducing unintended consequences that may reduce SH/DHW availability, represented by reinforcing loop [Ra], and increase the energy consumption directly [Rb] or indirectly by lowering the HP’s actual performance [Rc]. As an example of the latter, occupants employing intermittent over continuous HP operation to reduce running costs may unwittingly lower the HP’s efficiency, thus offsetting any perceived savings due to increased HP cycling. The main mechanisms triggering a reduction of HP efficiency are discussed in detail in section 6.4 and listed below:

- reducing the continuity of HP operation,
- increasing the temperature lift, and
- utilising the HP’s incorporated resistance heater (usually unintentionally).

Undoubtedly, the relationship between the actual and perceived HP performance is a complex one. A high HP efficiency does not necessarily guarantee a high perceived performance by the occupants and a poor perceived performance might not be an accurate reflection of the actual performance. In addition, a poor perceived performance is likely to lead to a chain of reactions that under certain conditions can be detrimental to actual HP efficiency and/or energy consumption. The following sections discuss the mechanisms influencing these areas in detail.

### 6.2 The Ability of a Heat Pump to Fulfil Needs as an Actual Performance Driver

Occupants expect HPs to provide sufficient heating, at a cost they can afford. In many cases, the occupants deliberately altered their HP controls to improve the system’s performance. However, as previously mentioned social-housing tenants are often ‘locked out’ of the main controller, with access only to a single-zone thermostat (and occasionally a programmer), as well as TRVs, the latter utilised to some extent by CS02 and CS05 only. On the contrary, owner occupiers had full access to the system should they have wanted to. Setting HP controls aside, there are also other measures that the occupants employed to satisfy their needs, such as dressing in warm clothing and using supplementary heating methods. These are described in the following subsections: 6.2.1 - The occupants’ responses to the perceived shortfall in space-heating performance, 6.2.2 - The occupants’ responses to a perceived domestic hot water availability gap, 6.2.3 - Direct, indirect and secondary rebound effects and electricity consumption considerations, 6.2.4 - Overall effects of heat pump settings and user adjustments. Subsections 6.2.1, 6.2.2, 6.2.3 focus primarily on the intuitive effects of the
occupant actions and 6.2.4 discusses the less anticipated effects that stem from the complex nature of the HP technology.

6.2.1 The occupants’ responses to the perceived shortfall in space-heating performance

The most common control methods used with traditional central heating systems are thermostats, programmers and TRVs. All of them feature in the case study sample but not all were present (or utilised) in individual case studies. For example, in cases CS09, CS19 and CS21, there was no usable or no physically present thermostat, other than the occasionally adjusted TRVs on radiators, where present, and occupants controlled their HP by direct-flow temperature adjustment\(^\text{16}\). Depending on the manufacturer’s specifications, the HP controls are originally set by the installer, sometimes after discussion with the occupants, and they can subsequently be altered to different extents. As explained in section 5.3, the level of control alteration in the case study sample was found to depend on both the accessibility to controls and on user understanding of the system. The synergy between the HP control mechanisms available as originally set and subsequently modified by users can significantly affect actual performance and energy consumption of the HP.

The following sections elaborate on the occupants’ perceptions of control settings and the adjustments made based on their perceived SH availability gap, which is a function of the actual SH availability and the desired SH availability, as shown in Figure 6-2. The latter can be affected by air movement and the occupant metabolic rate, health issues, the time spent at home and the preference for cooler night-time temperature, further information on which can be found in Table 27 of Appendix J. The most common actions taken by occupants to meet their heating needs when there was a gap between actual and desired SH availability differed between case studies. These are described in the following paragraphs and represented by balancing feedback loops [B1] to [B8] of Figure 6-2. They relate to HP SH control adjustment increasing heat demand [B1 - B4], window opening [B5], supplementary heating [B6 - B7] and clothing insulation [B8]. The main HP SH controls described concern programmer, flow temperature and room and radiator thermostat settings and adjustments.

\(^{16}\) Note that the new ‘boiler plus’ regulations that came into force in April 2018 require the installation of timers and room thermostats for all gas and oil systems (BEIS, 2018b).
Programmer settings and adjustments

All programmer settings were initially set by the installer, either with or without occupant consultation. Since owner occupiers had full access to every aspect of the system, when they wanted to alter it, some of them intervened. Andrew (physicist, CS01) reprogrammed the HP as he thought it was not working properly; James (engineer, CS10) and Quianna (physicist, CS17) changed the programmed settings and the controller’s heating curves, respectively, to meet their households’ needs in the long term; and Ian (teacher, CS09), Patricia (farmer, CS16) and Samuel (physicist, CS19) experimented with different settings in search of a more efficient way to run their HP. All the changes mentioned above were driven by a desire to increase the HP’s perceived efficiency in the long run, i.e., identifying the optimum balance between the perceived SH availability and the size of their electricity bills.
Figure 6-3: Causal loop diagram focusing on the area of ‘space heating availability’ and ‘electricity bill size’ in relation to programmer adjustments to meet heating needs and balance energy consumption. Other ways to adjust space heating relate to flow temperature (see Figure 6-4) and thermostat adjustments (see Figure 6-5).

Figure 6-3 depicts the two interlinked balancing loops [B1] [Programmer adjustment to meet heating needs] and [B9] [Temporal rebound], examined in subsection 6.2.3, that most occupants (except perhaps a few with technical expertise) had in mind when setting or adjusting their programmer settings. The CLD shows that an increase in the schedule-based heating hours due to a perceived SH availability gap will increase the HP SH generation that is linked to higher electricity consumption. Although this may have been the case with traditional heating systems, such as gas-fired boilers, the situation is more complex with HPs, due to the often-unanticipated link between the scheduled-based heating hours and the system’s efficiency, which is discussed in detail in subsection 6.2.4.

From the occupants’ perspective, the parameters affecting their choice of settings in terms of timing (continuous, semi-continuous or intermittent, as described in Table 5-1) related to their perceived SH availability gap, their perceived bill threshold gap (defined as the difference between the actual electricity bills and the desired bill threshold), their perceived HP noise level and their intermittent operation efficiency beliefs. The latter reflects the occupants’ intuition to operate heating systems intermittently, stemming from their experience with traditional heating systems.
The experts’ advice also seems to have played a role in the occupants’ decisions. The social-housing tenants of CS03-CS06 and CS19 were aware of the installer’s or RSL’s advice to set the thermostat ‘at a comfortable temperature’ and ‘leave it alone’. However, their suggestions were not always followed strictly or without questioning, such as in CS19, where Samuel was advised to run the HP continuously, but he wanted to test for himself what would be the best way to run his HP.

*I tried both ways, running in the same sort of way that I was running the oil boiler, off at night […] Oh yes, never take anybody’s word for anything, why not experiment […] [Eventually] it was less expensive to run it continuously (Samuel, CS19).*

Ian of CS09 reached a similar conclusion by experimenting with different settings, including varying flow temperatures.

…I quickly realised that it was more efficient to run it all the time, at a lower temperature (Ian, CS09)

In these two cases, *experimenting with programmer settings while monitoring energy consumption* led to the deconstruction of the occupants’ *intermittent operation efficiency beliefs*. The occupants’ perception of flow temperature adjustments and their effects are discussed in detail in the following paragraphs.

**Flow temperature settings and adjustments**

The type of heat emitters coupled with the HP system is one of the parameters determining the flow temperature of the water circulation. The larger the surface area of the heat emitter, the lower the water flow temperature required. Irrespective of the surface area of the heat emitter, some owner occupiers (CS09, CS17, CS19 and CS21) explained that they altered the flow temperature settings as a way of controlling their HP, either alone or in conjunction with other control methods. In CS19, Samuel stated that ‘the controller for the HP is the return flow’. Indeed, there were no room thermostats present and although TRVs were installed on the first-floor radiators, there were no controls linked to the ground-floor UFH system. It was also not clear what the exact flow temperature settings were as there was no visible temperature gauge indicator.

*In this case, the only control that matters is the [return] heat setting and it isn’t in degrees, it’s in blobs (Samuel, CS19).*

As explained in the previous paragraph, both Ian (CS09) and Samuel (CS19) started off by experimenting with their control settings and they soon perceived that it was more efficient to run the HP continuously, at a lower temperature (Quote 1, Appendix J2). Even though TRVs
and/or room thermostats were present in CS09, CS17 and CS21, flow temperature settings were utilised to different extents. The occupants of CS17 and CS21 stated they altered the flow temperature settings during particular periods only, such as during a cold spell, more so in CS17 than in CS21 (Quotes 3 and 4, Appendix J2). In CS09, it was the thermostat’s location that deemed it unusable, i.e., initially close to the fireplace and subsequently in the unheated entry space/utility, and forced the occupants to alter the flow temperature settings (Quote 2, Appendix J2).

The balancing loop [B2] [Flow temperature adjustment to meet heating needs] of Figure 6-4 shows that an increased SH flow temperature leads to a higher HP SH generation, thus minimising the perceived SH availability gap while also increasing electricity consumption. The interaction between flow temperature and electricity bills, as perceived by most occupants, is represented by balancing loop [B10] [Flow temperature rebound], examined in subsection 6.2.3. The additional, often unanticipated mechanisms affecting the relationship between SH flow temperature and electricity consumption are described in subsection 6.2.4.

![Causal loop diagram focusing on the area of ‘space heating availability’ and ‘electricity bill size’ in relation to flow temperature adjustments to meet heating needs and balance energy consumption.](image-url)
Room and radiator thermostat settings and adjustments

Room thermostats were present in most case studies in the sample. Overall, occupants reported that room thermostat temperatures, whether pre-programmed or not, would rarely be altered or overridden (if at all) and the same was true for TRV settings. The situations involving occasional adjustments of either the room or radiator thermostats are presented in Table 6-1. A very different approach for adjusting the indoor temperature was observed in CS11, where the occupants were changing the thermostat’s location instead of its settings (Quote 5, Appendix J2). Likewise, at the time of the site visit, Ian and Irena (CS09) had just started experimenting with their new thermostat in a similar way (Quote 6, Appendix J2). Of all case studies, the lowest comfort temperatures were encountered in CS16, where the occupants attempted to alleviate their perceived high HP electricity consumption with dramatically lowered thermostat settings and a restricted heated area, as noted in Quote 7 of Appendix J2 (also see subsection 5.2.2, Figure 5-24).

Table 6-1: The occupants’ reasoning for occasional adjustment of their room thermostat or thermostatic radiator valve (TRV).

<table>
<thead>
<tr>
<th>Reason for thermostat adjustment</th>
<th>Room thermostat</th>
<th>TRV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning the thermostat up/down if feeling overly cold/warm</td>
<td>CS02, CS03, CS04,</td>
<td>CS09, CS19</td>
</tr>
<tr>
<td></td>
<td>CS20</td>
<td></td>
</tr>
<tr>
<td>Lowering the temperature setting by 1 °C when while away from the house to save energy</td>
<td>CS07</td>
<td>N/A</td>
</tr>
<tr>
<td>Slightly increasing the temperature setting for a couple of hours after opening windows to bring the house up to temperature</td>
<td>CS08</td>
<td>N/A</td>
</tr>
<tr>
<td>Bringing rooms up to temperature to accommodate guests in previously unoccupied rooms</td>
<td>CS01, CS14</td>
<td>CS09, CS11, CS15, CS16</td>
</tr>
<tr>
<td>Experimenting for a period to achieve a better balance between SH availability and cost in electricity bills</td>
<td>CS01, CS10, CS16,</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>CS17</td>
<td></td>
</tr>
</tbody>
</table>

The thermostatic adjustments mentioned so far are captured in Figure 6-5. The balancing loop $[B3]$ [Thermostatic setting adjustments to meet heating needs] reflects the occupants’ tendency to raise or lower the **room/radiator thermostat setpoint** whenever they sensed a **perceived SH availability gap**. Increasing the thermostat’s setpoint is expected to increase the **HP’s operating hours (assuming constant or near-constant flow temperature)** and thus increase **electricity consumption**. The alternative, often unanticipated paths that may influence the HP’s efficiency
and thus also influence energy consumption are explored in subsection 6.2.4. The effect of a *perceived bill threshold gap* on the room/radiator thermostat setpoint is represented by the interlinked, balancing loop [B11] [Thermostatic setting rebound], examined in subsection 6.2.3.

**Figure 6-5**: Causal loop diagram focusing on the area of ‘space heating availability’ and ‘electricity bill size’ in relation to room and radiator thermostat adjustments to meet heating needs and balance energy consumption.

Where multiple-zone control was available, the effects of adjusting individual room thermostats or TRV settings is captured in balancing loops [B4] [Overall spatial adjustments to meet heating needs] and [B12] [Spatial rebound]. Except for the slightly lower temperature settings often encountered in bedrooms, a significant lowering of the thermostat settings in unused rooms was noted in eight large dwellings. Most unused rooms were isolated in CS01, CS11, CS14, CS15, CS16 and CS18 in contrast to CS13 and CS19, where all doors would be kept open for air to circulate freely within the house. The reduction in the **heated area to total area ratio** derives from the occupants’ desire to reduce their **perceived bill threshold gap** by avoiding unnecessary energy consumption in rarely used rooms. A temporary reversion of the lowered thermostat setpoints in unused rooms took place whenever there was an increase in the **number of occupants** to avoid a **perceived SH availability gap** in these rooms [B4].
Ad-hoc adjustments and supplementary heating

Some of the HP settings and adjustments presented in the previous paragraphs related to the alteration of permanent settings to improve the perceived HP performance or meet the occupants’ needs over a specific time period, e.g., during a particularly cold spell or when guests are present. However, many occupants also expressed their need for an impromptu ‘real-time’ adjustment of their thermal environment that they would attempt to accommodate by utilising supplementary heating, putting on additional clothing layers, utilising window opening and/or by arbitrarily adjusting HP settings. Figure 6-6 expands the CLD of Figure 6-2 to represent the aforementioned actions and the consequences that the occupants typically expect, both in relation to their *perceived SH availability gap* or the *perceived bill threshold gap*. The relevant areas of the CLD are described below:

Figure 6-6: Causal loop diagram focusing on the area of ‘space heating availability’ in relation to the use of clothing insulation, ventilation and supplementary heating, both electric and non-electric (i.e., a form of wood fire), to meet heating needs.
- **Arbitrary adjustment of the HP settings** – As explained in the previous paragraph, of those making impromptu adjustments to the HP settings to meet their heating needs [B1 - B4], the majority did so via a room thermostat, including moving a portable thermostat between rooms. Impromptu adjustments were also noted to the programmer settings in CS06 (Quote 8, Appendix J2) and the system’s flow temperature in CS09. Ian and Irene (CS09) also stated they occasionally turned the HP on for a number of hours during the summer (Quote 9, Appendix J2). However, attempting ‘real-time’ control of the HP could potentially trigger the use of resistance heater and disrupt the HP’s continuity of operation (see section 6.2.4).

- **Window and door operation** – As shown in the balancing loop [B5] [Balancing SH availability through window opening], in many cases, window opening was another way of controlling internal temperature during the heating season. **Natural ventilation heat loss** was occasionally used as a cooling method in CS04, CS05, CS16 and CS20 and surprisingly often in CS08, both for cooling and fresh air. In addition, at least five occupants (CS06, CS08, CS13, CS16 and CS20) mentioned they might open internal doors to cool rooms during the heating season to disperse the increased heat gains of a particularly warm room, resulting from either increased metabolic heat gains or heat gains from a solid fuel fire. More information on window opening patterns and the full range of their influencing parameters in the case study sample is included in paragraph 6.3.2.

- **Use of wood or solid fuel burners** – **non-electric supplementary heating** was present in approximately half the case studies (CS01, CS09, CS10, CS12-18, CS20 and CS21). Except CS12 and CS15, where they were intended to be used as a backup system, the remaining case studies would utilise this as supplementary heating to different extents. This is represented in balancing loop [B6] [Adjusting SH availability with non-electric supplementary heating]. Andrew (CS01) specifically mentioned the slow HP system responsiveness as a factor contributing to the use of wood burners. Overall, utilising a wood burner as an occasional SH top-up method was mentioned in five cases (CS01, CS14, CS17, CS20 and CS21), whereas CS10 and CS16 (Quote 10, Appendix J2) appeared to use one regularly but with a very specific plan in mind, i.e., during their long-term renovation works that prevented HP operation in specific rooms and as an alternative heating plan in the hope it would reduce energy expenses, respectively. However, the reason for wood burner use did not always relate to the occupants’ heating needs. In cases CS01, CS09, CS12, CS13, CS18 and CS20, the occupants mentioned the aesthetic value of the wood fire as a major driving force for its use, of which only Rafael (CS18) stated it was regularly used throughout the winter (Quote 11, Appendix J2).

- **Use of standalone resistance heaters** – Slow HP system responsiveness was also found to be linked to the use of **electric supplementary heating** in one case. Clive (CS03) explained that
his neighbours offered a portable electric heater to use upon his return from hospitalisation (Quote 12, Appendix J2). Another occasion of temporary resistance heater use related to a two-bar fire utilised during a HP breakdown in CS06. Overall, regular use of a portable electric heater was reported in the attic of CS10 due to the perceived inadequacy of a HP-connected heat emitter (Quote 13, Appendix J2), and in CS16, in the form of a range cooker used for SH (alongside cooking) purposes (Quote 14, Appendix J2). Setting CS10 and CS16 aside, electric supplementary heating was meant to be used occasionally, i.e., in urgent circumstances only, unless the resistance heater was permanently fitted as a substitution to a HP-connected emitter. Such was the case of the resistance-only towel radiators in CS18 and UFH in CS09, resulting from a reported connection difficulty to the central heating system, post the HP installation and the mistaken belief that towel radiators could not be connected to an UFH system, respectively. This is represented by the **HP-connected to HP-unconnected emitter ratio** variable and balancing loop [B7] [Adjusting SH availability with electric supplementary heating] in the CLD of Figure 6-6. In CS16, the hybrid backup towel radiators were also occasionally utilised in direct mode.

- **Insulative clothing layers** – One of the simplest measures that the occupants often took in order to tackle a perceived **SH availability gap** was adding more layers of clothing, i.e., increasing their **clothing insulation**, represented in Figure 6-6 by balancing loop [B8] [Clothing rebound].

Overall, the ad-hoc actions taken to balance a perceived SH availability gap were found to differ both between case studies and occupants within case studies, with several female partners reporting they would have preferred more warmth than the male partner. Further information on thermal comfort and gender in the case study sample can be found in p. 111 of Appendix J1. The cumulative effects of the occupants’ decisions and adjustments to meet heating needs, whether impromptu or well planned, are discussed in subsection 6.2.4.

### 6.2.2 The occupants’ responses to a perceived domestic hot water availability gap

In all but one case study, the DHW production was delivered primarily by the HP, sometimes in combination with supplementary DHW generation methods. CS20 was an exception since Teo and Teresa utilised a **solar thermal DHW generation** source instead, in conjunction with a stand-alone immersion heater. The CLD of Figure 6-7 depicts the different DHW provision methods in the case study sample: **HP DHW generation**, **DHW generation via the HP incorporated resistance heater** and **standalone electric DHW generation**. The extent of their use depends on the technologies available in each case, their perceived efficiency, the pre-defined DHW settings (e.g., by installer and/or manufacturer) and the **perceived DHW availability gap**. The latter results
from a mismatch between the actual **DHW availability** and the **desired DHW availability**. Drawing information from the full case study sample, the latter was generally found to be linked to the **number of occupants** and the **habits involving the use of DHW**, such as the length of showers and washing up.

![Causal loop diagram focusing on the area of 'domestic hot water availability' in relation to the corrective measures, other than rectifying technical issues, employed by occupants based on their perceived domestic hot water availability.](image)

The balancing loops [B13] [Balancing DHW availability through the HP], [B14] [Balancing DHW generation through the HP-incorporated resistance heater] and [B15] [Balancing DHW availability through standalone resistance heating] of Figure 6-7 depict the actions that are likely to be taken by the occupants due to a perceived DHW availability gap. The following paragraphs describe the HP DHW settings and the use of supplementary heating as observed in the case study sample, the variables influencing them, as well as the possible effects of any changes made.

**Heat pump domestic hot water controls and adjustments**

As shown in Figure 6-7, the **HP DHW heating time (setting-based or instantaneous)** and the **DHW flow temperature** define **HP DHW demand**. In all but one case study with a DHW-generating HP, the occupants reported DHW provision issues. However, the schedule had to be adapted or...
overridden occasionally in some of them, mainly due to a temporary increase in the number of occupants. The scope of this alteration was to increase DHW availability, either through balancing loop [B13] or [B14]. As a result of this interaction with the DHW settings, Ian (CS09) and Nathan (CS14) were not certain whether the HP-incorporated resistance heater was activated or not, whereas Andrew (CS01) was certain he was activating the immersion heater (Quotes 16, 17 and 18, Appendix J2).

In cases CS12 and CS21, the occupants mentioned that it took a noticeable but acceptable amount of time for their hot water to run. A similar situation seems to have been tackled successfully with the installation of a secondary return in CS16 (Quote 19, Appendix J2). However, it was only Gabi and Greg of CS07 that expressed the idea that the HP’s DHW system configuration caused unnecessary DHW wastage due to the lengthy pipework\textsuperscript{17} between the HP and the kitchen tap (named \textit{perceived water wastage due to lengthy pipework} for the purposes of the CLD, and them being in danger of not having sufficient DHW. While the validity of this statement has not been tested, it is likely that this idea was shaped in part by their previous negative experience. Gabi and Greg repeatedly encountered problems with their HP, one of which was described as being left without SH every time a bath “\textit{drained the water out of the tank}” (also see subsection 6.4.2). Even though this problem appeared to have been resolved, they feared that using the HP’s DHW for washing up would waste the DHW available and, thus, decided to use it for showers only. The DHW needed for washing up was supplemented with \textit{standalone electric DHW generation}, which is explored further in the following paragraphs.

\textbf{Use of alternative domestic hot water generation methods}

As a result of the perceived DHW wastage in CS07, leading to insufficiency concerns (explained in the previous paragraph), Gabi and Greg attempted to balance DHW availability by consciously choosing a very energy-intensive water-heating method for washing up, namely a kettle.

\begin{quote}
There is plenty of hot water for us to go and have a shower every day. That’s fine but if I was washing the dishes several times a day and using hot water that way, I don’t know what the situation would be for showers […] I boil a kettle instead because otherwise I’m draining the hot water out of the tank. It takes several minutes to come through before I get any water in the sink […] I boil the kettle, which is probably wasting energy and probably costing a lot of money. But the alternative is to wait several minutes for any hot water to come through. (Gabi, CS07)
\end{quote}

\textsuperscript{17} Insulation level unknown due the pipes running through the loft.
As explained in subsection 5.1.3, of the remaining 19 case studies with HP-generated DHW provision, five also utilised some sort of standalone electric DHW generation system. The electric showers installed by the RSL in the wet rooms of CS02-CS05 left social housing tenants with no other option than to utilise a resistance heater whenever they took a shower. In CS16, it was Patricia and Peter's choice to install an electric shower in one of their two bathrooms (Quote 20, Appendix J2). Thus, the use of electricity for the production of DHW in these cases depended on the electric showers to total number of showers ratio.

6.2.3 Direct, indirect and secondary rebound effects and electricity consumption considerations

As explained earlier in subsection 6.2.1, the difference between the electricity bills and the desired bill threshold is named perceived bill threshold gap for the purposes of the CLD (Figure 6-8). This is likely to cause a series of direct, indirect and secondary rebound effects, where the energy savings by the HP are converted to additional comfort, thermal or other (positive rebound), or there is an attempt to neutralise an increased energy cost at the expense of the occupants' comfort (negative rebound). The direct rebound effects in Figure 6-8 are represented by balancing loops \([B12] \) [Spatial rebound], \([B11] \) [Thermostatic setting rebound], \([B10] \) [Flow temperature rebound] and \([B9] \) [Temporal rebound]. Secondary rebound effects can also be manifested, such as when an alteration of the HP's heat demand via any of the methods mentioned above may trigger balancing loops \([B6] \) [Clothing rebound], \([B7] \) [Adjusting SH availability with electric supplementary heating] and \([B8] \) [Adjusting SH availability with non-electric supplementary heating]. There is also some indication of indirect rebound effects in the sample, such as when the perceived high energy consumption of a HP led to a reduced use of lights and appliances.

In the case study sample, it was usually impossible to distinguish between the energy consumed by the HP and the homes' overall electricity consumption. In particular, some of the case studies used several energy-intensive household appliances (represented by the use of lights and home appliances variable in Figure 6-8), whose electricity consumption cannot be disentangled from that of the HP. This might have led some occupants to mistakenly think that their HP, its SH or DHW function, or another appliance was consuming more energy than it actually was, a perception that could also be influenced by the occupants' previous experiences and beliefs. Confusion may also arise around a home's overall electricity consumption as perceived from the electricity bills that depend on the tariff/unit rate set by the provider, the benefits and entitlements received by the occupants to offset bills and any RES electricity production. Where the occupants engaged with self-monitoring, either through dedicated HP-monitoring equipment [CS01 (Quote 21, Appendix J2) and CS19 (Quote 22, Appendix J2)] or by keeping an eye on
the electricity meter readings (CS09 and CS17), it appeared to have helped them to reduce their electricity consumption through the identification of high energy consumers (which could be appliances or controls). This is represented by balancing loop [B16] [Balancing energy consumption through monitoring] in Figure 6-8.

The direct, indirect and secondary rebound effects resulting from the occupants’ perception of the electricity consumed, as well as those stemming from the system’s technical characteristics are explained in detail in the subsections below.

Spatial rebound and heated area arrangements

A positive spatial rebound [B12], where the heated area to total area ratio is increased in comparison to the previous state and thus the potential electricity savings are converted to additional comfort, can occur both for social and technical reasons. A socially-induced negative

Figure 6-8: Causal loop diagram focusing on the areas of ‘space heating availability’ and ‘electricity bill size’ in relation to the corrective measures, other than rectifying technical issues, employed by occupants a result of a space heating availability gap and a perceived bill threshold gap.
spatial rebound was also identified in the case study sample. This concerns primarily adjustments to the HP heating of rarely used rooms within the insulated building envelope and, more rarely, commonly used rooms. The different types of spatial rebound identified in the case study sample are described in detail below:

- **Technically-induced positive spatial rebound** – This is likely to occur whenever a HP system substitutes a previously non-central heating system. Excluding newbuilds, this was the case in one-third of the remaining case studies, where the HP replaced storage heaters, or coal- or oil-powered systems (see Table 4 of Appendix C).

- **Socially-induced positive spatial rebound** – Variables that were found to support a higher *heated area to total area ratio* were identified in CS20 and CS14. These relate to the presence of *condensation and mould* and the *perceived indoor humidity level* (Quotes 23 and 24, Appendix J2).

- **Socially-induced negative spatial rebound** – A significant number of occupants in the case study sample (CS01, CS11, CS13-CS16, CS18, and CS19) actively sought to avoid unnecessary energy consumption and reduce electricity bills by switching off or lowering the temperature settings in individual, rarely used rooms. This was implemented through TRVs, room thermostats and/or by isolating rooms, where temperature was normally controlled by a single-zone room thermostat. On a few occasions, a reduction of the *usable heated area to total usable area* related to high *perceived home equipment gains* (CS05) and the presence of *draughty hydronic fan convectors* (CS08). In one extreme case of negative spatial rebound (CS07), the occupants’ desire to counteract their *perceived SH availability gap* while maintaining affordable bills led to the reduction of their *heated area to total area ratio* by 60%, thus triggering a significant reduction of their usable heated area, represented in Figure 6-8 by reinforcing loop \[R1\] (Usable heated area adjustments to meet heating needs) (see Quotes 15 and 25 in Appendix J2 and p. 112 of Appendix J1 for further information).

**Temperature rebound**

Temperature rebound can relate to both an alteration of the *room/radiator thermostat setpoint* and the HP flow temperature based on the occupants’ *perceived bill threshold gap*. These are represented by balancing loops \[B11\] [Thermostatic temperature rebound] and \[B10\] [Flow temperature rebound] of Figure 6-8, respectively. There was no clear evidence of a positive thermostatic or flow temperature rebound in the sample, however, there were some cases of negative thermostatic and flow temperature rebound. Technically speaking, HPs favour a negative flow temperature rebound, where lower flow temperature leads to higher efficiencies.
• **Technically-induced negative flow temperature rebound** – Based on the monitoring data (see Table 24 of Appendix I), most HPs in the sample presented maximum SH flow temperatures of between 35 and 55 °C, which is lower than those of the traditional water circulation SH systems.

• **Socially-induced negative flow temperature rebound** – Only in CS09 and CS19 did the occupants attempt to raise the *SH flow temperature* to achieve more comfort and/or test the performance of their HP. However, they were eventually forced into a negative flow temperature rebound as they concluded it was more expensive to run the HP at higher flow temperatures. This is a case of loop [B2] [Flow temperature adjustment to meet heating needs] triggering the manifestation of loop [B10] [Flow temperature rebound].

• **Socially-induced negative thermostatic rebound** – In CS01, CS07, CS10, CS16 and CS17, the occupants stated that their *room thermostat setpoint* reflected their attempt to balance *SH availability* and *electricity bills*. Of those cases CS16 stands out as their occupants tried to curb their electricity bills by turning almost all room thermostats down to 16 °C. This drove a substantial negative thermostatic temperature rebound [B11], which as a result triggered a SH availability gap [B3] and the extensive use of both resistance heating [B7] and wood burners [B6] (Quote 10, Appendix J2).

**Temporal rebound**

Temporal rebounds with HPs tend to be primarily technically induced, since a more continuous operation is necessary in comparison to traditional heating systems, due to the lower flow temperatures a HP normally operates with. In the case study sample, there is also some evidence of a socially-induced negative temporal rebound in two cases. These are represented by balancing loop [B9] [Temporal rebound] of Figure 6-8.

• **Technically-induced positive temporal rebound** – All HPs in the case study sample were found to operate for more hours in comparison to their previous heating systems, *i.e.*, gas, oil, storage heaters, coal and fuel burners. Longer HP operating hours tend to be linked to higher efficiencies for reasons that are explained in detail in subsection 6.2.4. However, this was not straightforward for the majority, if not all, HP users in the sample.

• **Socially-induced negative temporal rebound** – Andrew (CS01) and Dawn (CS04), upon deciding on their HP’s operational schedule, clearly chose a semi-continuous operation in the hope of reducing their perceived bill threshold gap.
Indirect rebound effects

A high **perceived bill threshold gap** was also found to be linked to a higher **level of energy consumption awareness** in some case studies, leading to a reduced **use of lights and home appliances** and the avoidance of **window opening**.

- **Negative light and appliance rebound** – This refers to an indirect rebound effect, represented by the balancing loop [B17] of Figure 6-8. In the two cases where the occupants thought their HP was very energy intensive, Gabi (CS07) and Patricia (CS16) stated they were very cautious with the use of lights and appliances to reduce overall electricity consumption (Quotes 26 and 27, Appendix J2).

- **Negative window opening rebound** – Another indirect rebound effect, stemming from a high **level of energy consumption awareness** is represented by balancing loop [B18] of Figure 6-8. This was linked to the avoidance of **window opening** in CS11, where Kevin and Kate stated they never opened their windows when the HP was on, as part of what they proudly called “a closed doors policy”. For the same reason, they took action to eliminate heat losses through an open fireplace by sealing its chimney and vent. In CS07, where the occupants were deeply dissatisfied with their HP and the associated **electricity bills**, Gabi explained that they very rarely ventilated in an attempt to avoid paying higher energy bills and feeling colder than they already did. The exact mechanisms through which ventilation patterns may affect a HP’s performance and overall electricity consumption are detailed in subsection 6.3.2.

6.2.4 Overall effects of heat pump settings and user adjustments

The previous paragraphs elaborated on the HP settings and the actions taken by the occupants in the case study sample in order meet their needs in terms of SH, DHW and electricity bills, and the consequences, as expected by the same actors. This subsection considers the full range of consequences that may be encountered. Figure 6-9 brings together all the CLDs presented so far (solid lines) and introduces the not so well-known effects to the general public that arise in terms of SPF and thus electricity consumption (dotted lines). Overall, the complex nature of the HP technology and the associated counterintuitive (in comparison to traditional heating systems) actions that need to be taken in many cases to increase its SPF, make it difficult for most users to grasp how to operate the system efficiently.
Figure 6-9: Aggregate causal loop diagram depicting the areas of ‘space heating availability’, ‘DHW availability’ and ‘electricity bill size’, where the dotted arrows represent efficiency impacts that the users may be unaware of.

Space heating adjustment considerations

The reinforcing loop [R1] and the balancing loops [B1], [B2], [B3], [B4] and [B5] of Figure 6-9, show that an increase in the heated area-to-total area ratio, room/radiator thermostat setpoint, SH flow temperature and schedule-based heating hours, as well as higher ventilation rates, are linked to an increased HP SH demand and thus electricity consumption. The reverse also applies. This is a very much expected consequence for the occupants. What might not be so obvious is that a modification of any of these parameters can also have a significant impact on the overall SPF, which also affects electricity consumption. This is explained in detail below.
• **Significantly altering space heating demand** – As shown in the CLD of Figure 6-9, any HP control modification that impacts *HP SH demand* significantly, in relation to the assumed demand (named *effective compared to design heat load ratio* for the purposes of the CLD), can lead to an effect similar to that of an oversized or undersized HP. A significantly reduced *effective compared to design heat load ratio* may negatively affect the *continuity of HP operation* and increase *compressor cycling*. The reverse causes a HP undersizing effect, where any benefits resulting from reduced *compressor cycling* are likely counteracted by the increased *electricity consumption* due to prolonged HP running times, let alone the HP may be unable to provide sufficient heat to meet the occupants’ needs. A HP undersizing or oversizing effect might also arise indirectly, because of frequent *window opening* [B5], frequent use of *electric supplementary heating* [B6] and/or *non-electric supplementary heating* [B7].

• **Disrupting the continuity of operation** – Assuming flow temperature is constant or near-constant, a significant reduction in *HP operating hours* can also disrupt the *continuity of HP operation*. This can result from reduced *schedule-based heating hours*, lower *room/radiator thermostat setpoint*, restricted *heated area to total area ratio* and any other reason causing a significant reduction of the *HP SH demand* directly or indirectly, including standalone supplementary heating methods. Ad-hoc adjustments, such as *moving thermostat between rooms*, and frequent *window opening* (explored further in subsection 6.3.2) may also disrupt the *continuity of HP operation*.

• **Increasing space heating flow temperature** – A higher *temperature lift* can impact the SPF negatively in two ways: (a) through an increased *pressure difference obtained via compression* and (b) through a reduced *continuity of HP operation*. Since less time is needed to heat up the house, the HP runs in shorter bursts that tend to increase *compressor cycling*.

• **Conflicts arising from multiple heating methods and controls** – Whatever the methods and controls utilised to meet the occupants’ heating needs, they rarely act in isolation. The synergy between multiple heating methods and/or controls, if not planned, may lead to conflicts arising, where one act counteracts another, often leading to unexpected outcomes. Such is the case with rooms thermostats and TRVs, the coexistence of which proved to be particularly confusing for some occupants who did not know what the best way would be to handle the latter or could not understand or remember what they had been set at.

**Domestic hot water adjustment considerations**

The case study sample occupants were generally content with their DHW settings and very few intervened to temporarily increase *HP DHW generation*. However, the exact mechanism associated with their occasional adjustment is unclear, especially with regards to the *DHW*
generation via the HP-incorporated resistance heater [B14]. What is certain though is that any action increasing HP DHW demand, whether ad-hoc or setting-based, will lead to an increased electricity consumption, as shown in Figure 6-9. DHW heating involves higher energy consumption per unit time the higher the temperature lift, and even more so if a resistance heater is involved. Given that a DHW-producing HP usually needs to raise the temperature of the water to a higher level than that for SH, a HP generating both SH and DHW is expected to have a lower overall SPF in comparison to the same HP generating SH only, under the exact same conditions. In effect, the higher the fraction of HP DHW generation, the lower its overall SPF and the higher the associated electricity consumption will be.

**Energy consumption-related actions and considerations**

So far, this section has considered how SH and DHW demand may be driving the HP's actual performance and thus electricity consumption. However, dissatisfaction with the electricity consumption itself can also affect the HP's actual performance through different paths. Figure 6-9 shows that a high perceived bill threshold gap can trigger the manifestation of a negative rebound effect, e.g., by reducing the use of lights and appliances (or substituting them with more energy efficient) [B17], eliminating window opening [B18] and/or decreasing the HP SH demand via any of the following paths: a decrease of the schedule-based heating hours [B9], a lowering of the SH flow temperature [B10], turning down the room/radiator thermostat setpoint [B11] and a reduction of the heated area-to-total area ratio [B12]. From the occupants' perspective, some of these actions can have unexpected consequences relating primarily to the deliberate reduction of the HP's heat load (explained earlier on p. 185). Following on from a deliberate HP SH demand reduction to minimise energy bills, the occupants of one case study were found to employ both electric [B7] and wood-fired [B6] supplementary heating to make up for the perceived SH availability gap. Apart from the low efficiency of resistance heating, another issue here is the additional reduction of HP SH heat demand, and thus SPF, as a result of the extensive use of supplementary heating methods.

Since in most cases it is impossible for users to distinguish between the energy consumed or produced by individual systems, it is likely that the systems responsible for what they perceive as high energy bills are not always accurately identified. These, including window-opening patterns [B18] and the use of lights and appliances [B17] can increase electricity production and trigger HP-related actions that reduce the HP system’s efficiency. Additional parameters affecting the HP efficiency and energy consumption that may be hard to pin down are described in section 6.3 on the influence of building heat loss and indoor humidity levels, and section 6.4 on the technical integrity of the HP installation and setup.
6.3 The Influence of Overall Heat Loss and Indoor Humidity Level on Heat Pump Performance

The heat losses of a dwelling depend on the thermal qualities of its building fabric, as well as the heat losses resulting from ventilation. The latter is a function of air infiltration and the operation of the occupant-controlled ventilation systems, e.g., window opening, trickle ventilators and mechanical ventilation systems. Both structural heat loss and the heat loss resulting from the way the occupants control their ventilation systems can have a big impact on HP efficiency. Another parameter affecting efficiency indirectly, which is also affected by the overall building heat loss (among other parameters), is the indoor humidity level and dampness. The following paragraphs explore the interrelationships between the indoor humidity level, ventilation and building fabric heat loss and their effect on actual HP performance.

6.3.1 Indoor humidity and condensation-related actions and impacts

In approximately half of the case studies (CS04-CS08, CS10, CS14, CS19-CS20), the occupants reported the presence of “indoor air dampness” and/or condensation and mould on walls and other structural elements. For the purposes of the CLD of Figure 6-10, this perception is represented by the variable named perceived indoor humidity level, which is expected to be influenced by the actual indoor humidity level, the presence of condensation and mould, as well as the occupants’ personal beliefs. As shown in Figure 6-10, a high indoor humidity level can positively influence the manifestation of condensation and mould but there are also other variables that can trigger this manifestation directly. In at least three cases, the cause of condensation and/or mould appeared to relate to some kind of water-leaking structural defect, such as a leaky window frame (CS14, CS19) or an improperly fitted rainwater path (CS10). In CS20, the likely cause of wall dampness was attributed to the thermal bridging of the compromised cavity wall insulation (explained in subsection 6.3.3). The problem is likely to have been exacerbated in the upstairs bedrooms due to poor ventilation/heating and/or the frequent clothes-drying activity (see Quote 28, Appendix J2).
Figure 6-10: Causal loop diagram focusing on the areas of ‘ventilation and indoor humidity level’ in relation to the corrective measures employed by occupants, including those stemming from the perceived space heating availability and energy consumption.

Overall, insufficient air changes per hour (ACH) and/or SH availability, especially where significant indoor moisture sources are present, e.g., steamy cooking/showers and indoor clothes drying, set the conditions for the manifestation of condensation and mould. In particular, Francis (CS06) and Helen (CS08) reported dampness around the window bathroom, which was addressed in CS08 after a major bathroom renovation, including installation and subsequent use of an extractor fan. Despite the extractor fan presence, the problem persisted in CS06 according to Francis who employed frequent window opening to resolve it. He also felt that the bathroom’s hydronic fan convector was not providing sufficient heat. In CS05, Elva felt there was insufficient heat provided by the bathroom radiator and thus relied on supplementary heating (a wall-mounted electric fan heater) whenever her vulnerable partner was around, and long showers had to be taken. Even though Elva was told “don’t open the window, you put the [extractor fan] system on”, it seems that the improperly connected mechanical ventilation (represented by the perceived mechanical ventilation technical issues variable in the CLD), possibly in combination with insufficient heating, led the manifestation of black mould in her
bathroom. Insufficient ventilation of the cold loft in CS14 also led to the manifestation of condensation and dampness in the windowless dressing room, according to Nicole (Quote 29, Appendix J2).

Another practice utilised by Nicole and Nathan (CS14) for the avoidance of dampness in unused rooms was the extension of heating (represented by the *heated area-to-total area ratio* variable in the CLD), although at a lower room thermostat temperature in comparison to the rest of the house (Quote 30, Appendix J2). Similarly, Teresa and Teo (CS20) felt that they had to extend the heating in rooms they considered problematic in terms of condensation, (Quote 31, Appendix J2). A slightly different situation was described by Gabi (CS07), who complained about her home’s indoor dampness, even though there was no physical evidence of high indoor humidity, *i.e.*, manifestation of condensation, mould or a relevant instrumental measurement. However, based on the occupants’ statements about the insufficient heating provided by the HP, in synergy with their own habits, *i.e.*, drying clothes inside and rarely opening windows, it seems possible that this bungalow may have had a high humidity (Quote 32, Appendix J2). *Dehumidifier use* was noted in CS07 and CS19 due to a high *perceived indoor humidity level* that seems to be influenced, at least in part, by the occupant’s previous experience in CS19 (Quote 33, Appendix J2).

The balancing loops [B19] [Balancing humidity, condensation and mould through dehumidifier use], [B20] [Balancing humidity, condensation and mould through mechanical ventilation], [B21] [Balancing humidity, condensation and mould through natural ventilation] and [B22] [Balancing humidity, condensation and mould via modulation of the heated-to-total area ratio] depict the different actions taken by the occupants in order to reduce the indoor air humidity level or tackle condensation and mould. *Mechanical ventilation use* and *window opening* for the provision of fresh air, among other reasons, are addressed in detail in subsection 6.3.2 below.

### 6.3.2 Building heat loss-related actions

The type and frequency of ventilation practices, natural or mechanical, can have a large impact on a building’s heat loss. Of the 21 dwellings in the sample, only four social-housing cases had a whole-house MVHR system installed (CS02-CS05). The remaining used natural ventilation as their main air-change mechanism, with the assistance of extractor fans in the kitchen/bathroom areas and trickle ventilators in some cases. Except for CS08, the occupants of all other case studies using natural ventilation, stated they ventilated in a limited or controlled way, if at all, during the heating season (see Table 7 of Appendix C). Helen (CS08) was the only one with having a regular whole-house ventilation routine that seemed to be a habit she enjoyed thoroughly (Quote 34, Appendix J2).
As shown in Figure 6-10, both the *mechanical ventilation use* and *window opening* were found to be driven by a range of parameters, predominantly the occupants’ *perceived need for fresh air* during the heating season. The need for fresh air, mentioned in most case studies (CS01-CS09, CS11-CS13, CS15, CS16 and CS19-CS21), is largely influenced by cultural norms and embodied habits of the occupants, such as those relating to *smoking*. Of the three smokers in the sample (CS01, CS03 and CS04), two acted in a way that would increase air changes per hour due to their smoking habit, *i.e.*, Andrew (CS01) would stand at an open door while smoking and Clive (CS03) would ensure the MVHR was kept at a high setting to eliminate the associated odour. Overall, at least nine occupants (CS02, CS04, CS05, CS07, CS08, CS12, CS13, CS16 and CS21) mentioned they ventilated regularly (*i.e.*, multiple times a week) to let in fresh air, either in the whole house or specific rooms, for reasons other than smoking. The length of time the windows or doors stayed open varied greatly, from a few minutes to many hours, and the same was true for the percentage of the windows opened. The latter is predetermined to some extent by the technical specification of the window, as well as any practical inconveniences arising with regards to *window openability*. In particular, the presence of non-functional windows was mentioned by Gabi (CS07) as leading to a reduced bedroom ventilation regime (Quote 35, Appendix J2). However, this was not nearly as disrupting as the case of Clive (CS03), an elderly social-housing tenant who was only able to operate the double doors of the living room in his bungalow, as the rest of the windows had been locked. There was an MVHR system installed though, and Clive seemed to be content with it (Quote 36, Appendix J2).

In fact, Clive was the only one out of four social-housing tenants, whose houses were equipped with an MVHR system who was using it without complaints. The occupants of the remaining three cases all mentioned the presence of unpleasant draughts during its operation (named *perceived mechanical ventilation draughtiness* for the purposes of the CLD). Beatrice (CS02) and Elva (CS05) also complained about the *perceived mechanical ventilation noise level*. In these two cases, both perceived draughtiness and noisy operation led to a significant reduction in the number of operational hours of the MVHR, *i.e.*, Beatrice stated she turned it on during the summertime only and Elva during her morning shower only. By contrast, Dawn (CS04) would let the system run throughout day and night despite the cold air coming through. This could possibly have been linked to her *smoking* habits and the associated higher *perceived need for fresh air*. Elva (CS05) also explained that her MVHR system had never been connected properly and the same seemed to be the case with the kitchen and bathroom extractor fans in CS07 which, according to Gabi, were properly configured only two years after the HP installation. A faulty kitchen extractor fan was also reported in the kitchen of CS16. The mechanical extractors
and/or MVHR systems not working properly, or as intended, might have contributed to a more frequent or extended window opening pattern.

In the case study sample, window opening was often triggered by the presence of condensation and mould (CS06, CS20) and perceived indoor moisture sources, such as cooking (CS02, CS05-07 and CS20), taking a shower (CS04, CS06, CS09 and CS14), using the tumble drier (CS05) and sometimes due to drying laundry indoors (CS07). Window-opening patterns are harder to predict in multi-occupancy households, as they are defined by the interaction of the actors’ individual needs. These are often conflicting and seem to have derived from either different thermal comfort standards (see p. 111 of Appendix J1), resulting in varying perceived SH availability gaps, or different levels of energy consumption awareness.

Other parameters influencing ventilation patterns involved various practical and habitual actions, including some that were often forgotten or disregarded by occupants when asked about their window-opening behaviour, such as standing in an open door while smoking (CS01) or leaving a window slightly open for an electric mobility scooter charging cable to pass through (CS04). The need for prolonged access through doors/windows in the case studies appeared to be affected by the need for electric vehicle charging (CS04), as well as the presence of pets in three cases. Dawn (CS04) explained how she kept her living room door slightly open most of the time, both for fresh air to come through and for her home and garden to be accessible to her dog. The presence of pets, as a factor influencing the need for prolonged access through doors/windows, was also mentioned in CS01 and CS16 (Quotes 38 and 39, Appendix J2).

Finally, the responsiveness of the heating system, as well as the thermal characteristics of the building envelope, may also have affected the occupants’ behaviour with regards to ventilation. In CS10, the slow HP system responsiveness, in conjunction with the high overall building heat loss and high thermal mass of the pre-1919 stone-built dwelling increased the time required to heat up the house. The latter was provided by Jennifer (CS10) as the reason for which the family kept their windows constantly closed (Quote 40, Appendix J2). She also stated that they never felt the need for fresh air, probably due to the high overall building heat loss linked to a higher ACH that would otherwise need to be balanced via window opening and/or the use of mechanical ventilation. These are represented by balancing loops [B23] [The perceived need for fresh air as a window opening driver] and [B24] [The perceived need for fresh air as a mechanical ventilation driver] of Figure 6-10. On the contrary, the low overall building fabric thermal heat loss of the very well-insulated and air-tight (as described by the occupant) detached house of CS13, seemed to lead to an increased perceived need for fresh air due to a reduced ACH and thus more frequent window opening and an increased desire for installation of
mechanical ventilation (Quote 41, Appendix J2). However, the **perceived dryness-induced degradation** of the wooden floor that appeared to be leading to the occupants’ assumptions of air dryness may be more related to the UFH rather than air quality. More information on the energy efficiency of the building fabric characteristics in the case study sample and how it may have triggered occupant interventions can be found in the following subsection 6.3.3.

**6.3.3 Building fabric efficiency weaknesses and interventions**

The efficiency of the building fabric depends on both the way it has been constructed and the way it is being used by occupants. The latter, **natural ventilation heat loss** in the case study sample, was discussed in the previous paragraph, (6.3.2), whereas this subsection focuses on **building overall heat loss** as a result of the level of **building fabric thermal resistance** and **building fabric air tightness**, as shown in Figure 6-11. Detailed information on the building and ventilation characteristics can be found in subsection 5.1.2 and Appendix C.

![Figure 6-11: Causal loop diagram focusing on the area of ‘building fabric heat loss’ in relation to the corrective measures employed by occupants, including those stemming from the perceived space-heating availability and energy consumption.](image)

As shown in Figure 6-11, a **perceived need for thermal insulation/air-tightness improvements** [stemming from a higher **level of energy consumption awareness** in at least one case (CS07)], as
well as the **RHI insulation level requirements**, led to the implementation of **insulation** and/or **draught-proofing retrofit measures**. However, not all improvements necessary, or perceived as necessary by the occupants, to the building fabric take place before the installation of a HP. Any **technical, practical and economic barriers**, including installation disruption, act as barriers towards the implementation of retrofit solutions. In the following seven cases, the retrofit measures took place 1 year or more after the installation of the HP and the reasons behind their delay were not always clear, particularly when implemented by the RSL, who were not interviewed.

- **Delayed RSL-initiated retrofit** – In CS06-CS08, the old cavity wall/loft insulation was taken out by the RSL to install new insulative materials, 1 year or more after the installation of the HP.

- **Identification of improperly fitted cavity wall insulation** – In CS09, the realisation of the need for additional cavity wall insulation came with a bathroom to wet room conversion, revealing an imperfectly insulated cavity wall (represented in Figure 6-11 by the **technical quality of the application of building components** variable for the purposes of CLD), approximately 4 years after the installation of the HP (Quote 42, Appendix J2).

- **Risk-induced delay of cavity wall insulation** – The uninsulated walls of the extension to the Victorian stone-walled house of CS19 were a well-known issue (Quote 43, Appendix J2). The cavity walls were eventually insulated, approximately 3 years after the installation of the HP. Even though this was an **RHI insulation level requirement**, the insulation installation had been delayed due to Samuel’s concerns in relation to brickwork quality and the perceived risk of water penetration (represented by the **technical, practical and economic barriers** variable in the CLD).

- **Other occurrences of delayed retrofit** – In CS10, the kitchen and utility roof parts and/or cavity walls of the otherwise stone-walled Georgian house were insulated approximately 1 year after the HP installation. The addition of floor insulation also took place at around the same time, simultaneously with the addition of the UFH part of the system (kitchen and dining/family room only), whereas draught-proofing was implemented approximately 4 years after the HP installation (on most ground-floor doors). A draught excluder, alongside the replacement of a single-glazed pane door by the RSL after the HP installation, was also installed in CS06 by the occupant himself (Quote 44, Appendix J2).

The improvement of the actual **building fabric thermal resistance** via **insulation retrofit measures** is represented by balancing loop [B25] [Retrofitting effect on building fabric thermal resistance] and the improvement of **actual building fabric air-tightness** via **draught-proofing retrofit measures** is represented by balancing loop [B26] [Retrofitting effect on building fabric air leakage] of
However, the level of building fabric energy efficiency achieved also relies on the technical quality of the application of building components. Both the improvement of thermal resistance and air-tightness can be influenced by the occupants’ perceived building fabric thermal resistance/air-leakage gap, a function of the actual building fabric thermal resistance/air-leakage and the desired building fabric thermal resistance/air-leakage, with the latter being influenced by the perceived SH availability gap (see subsection 6.2.1) and/or perceived bill threshold gap (see subsection 6.2.3) as well as occupant observations, expert opinions and EPC data etc.

A significant number of unresolved (at the time of the site visit) building fabric-related problems or fabric improvements perceived as necessary were reported in at least six cases (CS07, CS10, CS11, CS13, CS18 and CS19), appearing to relate to one or more balancing loops [B27/B28] [Insulation retrofitting/draught-proofing as a cost control driver] and/or [B29/B30] [Insulation retrofitting/draught-proofing as an indoor temperature driver]. With regards to draughts, even when room temperature reaches the desired level, their presence may make occupants feel colder than it actually is and cause them to seek higher internal temperatures, thus increasing heat demand. A summary of the relevant occupant concerns and associated planned or provisional measures is included in p. 112 of Appendix J1. Of those, the application of temporary insulative/draught-proofing measures is represented in Figure 6-11 by balancing loops [B31/B32] [Alleviating the perceived need for thermal insulation/improvements of airtightness with the application of temporary solutions] of Figure 6-11.

In addition to the occupants’ narratives, the case study site inspections revealed some additional problematic areas or imperfections in the building fabric insulation, either through visual inspection of the building elements (such as loft insulation) or via thermal imaging, where this was feasible (see subsection 5.1.2). On paper, the majority of houses in the sample seemed to be well insulated, i.e., based on either the occupants’ descriptions and/or the EPC, however, these sources may not always be accurate. No matter what the assumed U-values for the building construction elements are, there is always an overall building fabric performance gap (D. Johnston, Farmer, Brooke-Peat, & Miles-Shenton, 2016; David Johnston, Miles-Shenton, & Farmer, 2015), relating to the parameters discussed earlier, and thus overall heat loss is often higher than originally assumed. The overall effects of different heat loss mechanisms and indoor humidity level on a HP’s performance are summarised in subsection 6.3.4 below.

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18 Thermal images not available in CS01, CS09, CS13 due to the technical failure of the equipment and in CS12 due to the occupant’s privacy concerns.
6.3.4 Overall effects of building heat loss and indoor humidity level

Paragraphs 6.3.1-6.3.3 discussed the parameters influencing the indoor humidity level and the manifestation of condensation and mould, window-opening patterns, mechanical ventilation use and building overall heat loss and their interrelationships. This subsection details the effects that these may have on HP efficiency. Figure 6-12 is a combination of the CLD of Figure 6-10 and Figure 6-11 (solid lines) with the addition of variables and relationships that influence the overall SPF and thus electricity consumption (dotted lines). Balancing loops [B19], [B20], [B21] and [B22] depict the four ways that the occupants in the sample attempted to control an increased perceived indoor humidity level and/or condensation and mould, i.e., via dehumidifier use, mechanical ventilation use or natural ventilation heat loss practices and an extended heated area to total area ratio. On the contrary, a lack of sufficient heating, ventilation or dehumidification will lead to an increased indoor humidity level. The latter is linked to a higher HP SH demand due to the additional latent heat load required to bring the heated space up to the desired temperature in comparison with the same space with a lower relative humidity.

All of these actions, which attempt to reduce the indoor humidity level involve the use of electricity to different extents, either directly or indirectly. There are two paths through which window opening is positively related to electricity consumption: (a) natural ventilation heat loss causing an increased HP SH demand, which may lead to sizing implications if the actual heat demand is significantly higher than the design heat demand (represented by the effective compared to design heat load ratio variable in the CLD), and (b) abrupt heat loss due to uncontrolled ventilation which causes sudden changes in internal temperature, impacting on the continuity of HP operation, thus increasing compressor cycling.

In terms of building fabric thermal efficiency, the higher the building fabric air tightness/thermal resistance, the lower the overall building heat loss and the higher the HP SH demand is expected to be. As shown by balancing loops [B25] and [B26] the implementation of energy efficiency measures is expected to increase building fabric thermal resistance and building fabric airtightness. However, the extent to which they will be improved depends on the technical quality of the application of building components, which was found to vary significantly between case studies in the sample. The same is true for the technical quality of the HP installation and system setup, which is explored in the following section. Any belated thermal improvements causing a significant change to the actual heat load in relation to the design heat load may also have sizing implications.
6.4 The Technical Integrity of the Heat Pump Installation and System Setup as a Performance Driver

The previous sections, 6.2 and 6.3, discussed the paths influencing SPF, relating specifically to occupant behavioural patterns and preferences, the heating controls available and the building envelope and its indoor environment characteristics. This section investigates the technical aspects of HP installation and setup, their influencing parameters, and how these may impact HP efficiency. The technical parameters taken into consideration in field measurements of SPF...
are discussed in conjunction with the qualitative information collected on site, where possible, in subsection 6.4.1. Subsection 6.4.2 discusses the technical faults, as described by the occupants, and the influences and effects of the stakeholders’ interaction with the technical features of the HP system, both in terms of design and problem-solving skills. Subsection 6.4.2 discusses the overall effects of HP technical characteristics and the stakeholders’ corrective actions on the system’s performance.

6.4.1 Technical characteristics of heat pump installation and setup

The configuration of each HP installation and the number and type of its components depend on many parameters, including HP type, dwelling layout and its heat loss characteristics, linkage to any existing SH and DHW systems, as well as installer practices. Overall, the components and settings present in a HP installation can be much more sophisticated than those described in this subsection. However, this work does not aim to produce a detailed technical feature list of the case study installations but rather understand the variation present in relation to the parameters that are thought to influence SPF. For this purpose, the technical characteristics are considered on the basis of the 5 efficiency boundaries (SPF_H1, SPF_H2, SPF_H3, SPF_H4 and SPF_H5) depicted in Figure 2-2 (p. 38) Figure 6-13 shows the boundary-related technical parameters and their influencing factors in reference to each of the five boundary levels discussed in the following paragraphs. Note the variable named overall SPF, which includes pipework and buffer vessel heat losses, in addition to the DHW cylinder heat losses included in boundary H5. Even though no feedback loops are indicated in Figure 6-13, the diagram is actually linked to the causal loop diagrams depicted earlier in the sequential Figures 6-2 to 6-12. This link is explained in subsection 6.4.3 (see Figure 6-15).
Figure 6-13: Diagram depicting the 'heat pump technical characteristics' affecting a heat pump’s seasonal performance factor.

**Compressor-related energy influencers at boundary level H1**

Starting from the narrowest boundary, H1, which comprises the HP unit only and allows the evaluation of the refrigeration cycle, Figure 6-13 depicts that there is a negative relationship between $SPF_{H1}$ and *compressor power consumption*, which is influenced by the following two variables: *compressor cycling* and the required *pressure difference obtained via compression*. The latter depends on the *temperature lift*, which is driven by both socio-technical influences, as well as *source temperature*, i.e., external air or ground temperature. The positive link between *temperature lift* and *compressor cycling* represents the positive effect of lower flow temperatures on the system’s SPF, which can be enhanced using weather compensation. Both *SH flow temperature settings* and *DHW flow temperature settings* affect the *temperature lift* and can be set by designers and installers, as well as occupants with controller access. However, there was no evidence of occupants consciously influencing *DHW flow temperature* in the study sample. This paragraph examines parameters of the system design that influence the energy consumed by the compressor and for which related information was sourced through the case study sample, namely compressor speed variability, HP sizing calculations and emitter system heat dissipation. Other technical parameters influencing compressor cycling include *hysteresis* settings and the system’s *heat storage capacity* (see Table 2-5). The occupant- and building-related parameters influencing *compressor cycling* were explored in detail in sections 6.2 and 6.3.
Compressor speed variability

The term *compressor speed modulation* is used as a measure of the compressor speed settings available, *i.e.*, single-, double- or multiple-stage, or variable-speed compressors. The more variability available, the more efficient the HP is, as it can run at a lower setting and in a more continuous manner (in contrast to a single-speed compressor that can only run at full power) thus reducing *compressor cycling*. The paragraph on ‘

Technical characteristics: Design and installation quality' of Section 2.3.5 explains how modulating compressors can maintain higher efficiencies than non-modulating compressors at non-extreme part-load conditions. Based on the manufacturers’ specifications, it was established that none of the GSHPs utilised a variable speed compressor, whereas the majority of ASHPs did, except for CS02, CS20 and CS21.

Heat-pump sizing calculations

*Compressor cycling* is also highly dependent on the *effective compared to design heat load ratio*, with the latter relying on HP-sizing calculations. As explained in section 2.2.2, these are currently based on MIS 3005 v5.0 (MCS, 2017), which requires a detailed building heat-loss calculation. However, the HP in the case study sample were installed between 2008-09 and 2013 and thus previous versions of the MIS 3005, involving different requirements, would have been applied. Sizing calculations based on various MIS 3005 versions, which differ significantly, are expected to produce different heat-generation requirements. Even calculations based on the same MIS 3005 version, HP system and dwelling characteristics but implemented by different designers can result in a great deal of discrepancy. This is mainly due to the uncertainty associated with the assumptions made for the required heat-loss calculation. This is explained in detailed in the RHPP MCS Compliance Report (C. Gleeson et al., 2017), the findings of which are summarised in section 4.3 of this thesis. An underestimation or overestimation of *design overall heat loss* (based on *design room heat loss* and *design ventilation heat loss* calculations) can lead to an under- or over-sized HP system, respectively, due to a significant difference between the effective *SH demand* and *design SH demand*.

However, as seen in sections 6.2 and 6.3, even a well-sized HP, based on reliable assumptions, may perform as oversized or undersized due to the occupants acting in a different way from how originally assumed and thus significantly increasing or reducing the assumed heat load. Irrespective of the cause, an oversized or undersized HP will negatively affect energy consumption. As shown in Figure 6-13, a low *HP SH demand* can lead to a low *effective compared to design heat load ratio* (oversizing). An oversized HP tends to switch on and off more frequently due to its higher-than-desired heating capacity, thus disrupting the *continuity of HP operation*,
increasing *compressor cycling* and negatively affecting $SPF_{H1}$ (MCS & RECC, 2018). Conversely, a high *effective compared to design heat load ratio* (undersizing) may force the HP to run almost continuously to reach the desired thermostat temperature settings, which it might still not be able to satisfy. In this case, the energy savings associated with reduced cycling are likely to be offset or even reversed by the increased *continuity of HP operation* (Delta Energy & Environment, 2011; Staffell et al., 2012). An undersized HP may also trigger *SH generation via the HP-incorporated resistance heater*, discussed further down this section, in relation to SPF boundary level H3 - see paragraph on ‘Operation and identification of backup resistance heating’.

Emitter system heat dissipation

As with the HP-sizing calculations, radiator-sizing calculation requirements have changed since 2008-09, when the first HP in the case study sample was installed. However, they still require a good understanding on the part of the installer of the interrelationship between heat loss, flow temperature and heat-emitter type (more information on the latest versions of MIS 3005 and MCS 021 can be found in subsection 2.2.2). This relationship is represented by the *design room heat loss, design SH flow temperature* and *design emitter output* variables on the CLD of Figure 6-13.

Higher emitter surfaces are generally linked to higher *emitter output* and lower *design SH flow temperatures*. The highest emitter surfaces can usually be achieved with UFH. However, radiator emitter output can also be increased using larger radiators or the addition of panels and convectors, thus increasing emitter output but not size (except perhaps for a slight increase in depth). As part of the RHPP MCS Compliance Report (C. Gleeson et al., 2017), a radiator sizing sensitivity analysis was performed for CS20. Based on the emitter characteristics recorded on site, the results indicated that radiator star ratings may vary significantly under different heat loss and heating mode scenarios.

Incorrect emitter sizing can lead to a higher or lower *effective compared to design heat dissipation ratio*, with HP-sizing implications, as it can have an impact on the *effective compared to design heat load ratio*. In the case of an undersized heat-emitter system, any non-dissipated heat will remain in the heating circuit, thus requiring less heat to be generated by the HP in comparison to the design heat load, leading to a lower *effective compared to design heat load ratio*. On the contrary, in an oversized heat-emitter system, more heat tends to be dissipated, in which case there is a higher heat release than originally anticipated, which can lead to a higher *effective compared to design heat load ratio*. 
Apart from the radiator-sizing process, a reduction to the actual *emitter output* can occur because of any of the socio-technical actions described below. Note that even though there were several cases whose occupants reported a perceived heat-emitter inadequacy, this may have been related to more than the sizing of the emitter itself, including radiator type and location (see p. 114 of Appendix J1 for further information).

- **Retaining existing radiators with a lower-than-required heat output** – This may occur in retrofit installations due to *cost, space and aesthetic restrictions*. In at least two cases in the sample (CS09 and CS21), there is some evidence that this may have resulted from a superficial radiator assessment by the contractor (see p. 112 of Appendix J1 for further information).

- **Obstruction of the emitter surface** – A number of radiators were found to be located behind furniture and appliances during the site visit investigations. This is represented by the *percentage of emitter surface obstruction* in Figure 6-13 and likely hindered the emitter’s dissipative capacity and thus the *effective compared to design heat dissipation ratio*. The following obstructions were noted in the case study sample: cupboard (CS02) and kitchen appliances (CS05) in front of a radiator, the sole radiator of a room placed in a narrow, enclosed space to be used as an airing cupboard (CS19), carpeted floors coupled with UFH (CS01)\(^9\).

- **A user-induced reduction of the HP’s heat load** – This concerns processes such as the manifestation of a socially-induced negative temperature or spatial rebound (explained in detail in subsection 6.2.3) and the excessive use of standalone supplementary heating alongside the HP operation (explained in detailed in section 6.2.1).

**Energy-consuming equipment at boundary levels H2 and H3**

Boundary level H2 allows the evaluation of HP operation since it includes the HP unit (H1) and the pump drawing heat from the ground or the supply air fan (H2). It can be utilized for comparison with traditional central heating systems, such as gas boilers. Boundary level H3 consists of the HP unit (H1), the equipment required to draw heat from the ground or air (H2) and the backup resistance heater (if present). The energy consumption associated with the components of boundaries H2 and H3 are described below.

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\(^9\) The presence of carpeted floors coupled with UFH, is expected to block heat transmission to some extent, depending on the thermal resistance of the carpet materials chosen. Even though this is not ideal and should be avoided where possible, the carpeted UFH option is taken into consideration in the Heat Emitter Guide, in which case a denser pipe spacing is suggested, based on the room’s heat loss and the system’s temperature star rating.
Heat drawing/air supplying equipment

The pump drawing heat from the ground or the supply air fan can have a significant impact on the system’s efficiency. As explained in section 2.1.3, technological advancements, such as the transition from non-variable- to variable-speed pumps, can achieve significantly lower energy consumption in comparison to their predecessors. The diagram of Figure 6-13 shows that the supply air fan or ground loop pump power consumption is negatively correlated to SPF$_{H2}$. Auxiliaries such as these can have a significant impact on the energy requirement for HP operation, however, no data were collected on the individual energy consumption of these elements of the HP system as part of the RHPP work.

Operation and identification of backup resistance heating

The extensive use of any type of HP-incorporated resistance heater can significantly reduce overall HP efficiency and the monitoring data revealed a substantial contribution of the resistance heaters to the heat production in the case study sample, primarily for DHW purposes (see subsection 5.2.2). However, their function, operation, and existence, appeared to be a mystery for many occupants, who were generally unable to distinguish between the heat provided through the refrigeration cycle and that from resistance heating. Its adverse effect on the system’s efficiency in Figure 6-13 is represented by the negative relationship between SPF$_{H3}$ and the following variables: \textit{SH generation via the HP-incorporated resistance heater} and \textit{DHW generation via the HP-incorporated resistance heater}.

In the case study sample, none of the occupants thought their system’s backup resistance heater was operating regularly, unless a suspected technical problem emerged. Except for Marvin (CS13), who stated he was able to identify the increased backup resistance heater operation early through the notification system of its HP interface, the remaining cases reporting excessive resistance heater use would only become known to them through the associated surge in electricity consumption (CS17) and high energy bills (CS08 and CS12). Further information on users’ awareness of the HP’s backup resistance heater presence and operation is included in p. 116 of Appendix J1.

**Auxiliary-related energy consumption at boundary level H4**

Boundary level H4 enables the calculation of HP efficiency using the total energy consumed and the total heat produced by the HP. It includes the HP unit (H1), heat-drawing equipment (H2), the electric backup heater (H3) and all installed auxiliary drives, such as circulators and pumps used for the distribution of heat. As shown in Figure 6-13, the \textit{number and power of auxiliary}
Drives are negatively related to $SPF_{H4}$, as an increase in these parameters will lead to increased energy consumption.

In the case study sample, the number of circulator pumps was found to vary significantly between case studies. Some installers favoured the installation of a single pump, whereas others incorporated multiple pumps in their design. It was not possible to ascertain the exact number of circulator pumps present in all HP installations in the sample due to access difficulties. Of the data collected, the case study with the maximum number of circulator pumps was CS14. There were at least nine pumps present (excluding the ground loop pump, which was assigned to boundary level H2 discussed earlier), of which six were serving the multiple UFH zones. Even systems with a single heating zone presented multiple circulator pumps, such as CS19, which featured at least five. It was not always possible to ascertain the role and area served by a circulator pump, however, depending on the case, dedicated circulator pumps were found to drive different parts of the circulation system, i.e., SH zones, DHW and secondary returns (identified in CS10 and CS16).

The size of single pumps identified in the sample ranged between 25 and 50 W. High-efficiency (variable) circulator pumps featured in two cases, namely CS13 and CS17. These were installed alongside fixed-speed pumps, which varied in the sample from single- to three-speed. Variable-speed circulator pumps are expected to run more efficiently in comparison to the traditional fixed-speed pumps, both due to their advanced technological features and controlled speed that adapts to the changing needs of the heating system.

The impact of pipework and cylinder heat losses at boundary level H5 and beyond

Boundary level H5 enables a more realistic estimate of overall HP efficiency by taking into consideration all the parameters mentioned in the previous boundaries, as well as DHW cylinder heat losses. The variable overall SPF of Figure 6-13 extends boundary level H5 to include pipework and buffer vessel heat losses. As depicted in Figure 6-13, these can be affected by the insulation level of pipework and buffer vessel, the exposure of pipework and buffer vessels to weather conditions, the length of pipework and the number of plate heat exchangers present. There is a positive relationship between the system’s insulation level and $SPF_{H5}$, and a negative relationship between the remaining features (pipework exposure/length, number of heat exchangers etc.) and $SPF_{H5}$. As explained in subsection 5.1.3, a visual inspection of the case study HP installations of the case studies revealed that, with some exceptions, the majority of installations were not perfectly insulated and/or laid out:
• **Uninsulated pipework exposed to weather conditions** – Many installations presented long external pipework and inadequately insulated pipework running through uninsulated spaces and cold roofs.

• **Multiple heat exchangers** – Another feature that is likely to contribute to a system’s heat losses is the use of additional plate heat exchangers, *i.e.*, other than those placed by the manufacturer inside the ASHP casing. The presence of additional heat exchangers was noted only in the installations of CS10 and CS1120.

• **Uninsulated pipework within the building’s insulated envelope** – Even though heat losses from uninsulated pipework within the building’s insulated envelope end up as internal heat gains, they may be undesirable for several reasons. Depending on the number of heating zones and the location of thermostats, including the indoor temperature sensor that is linked to the HP (if present), the following effects may take place (see p. 118 of Appendix J1 for specific case study examples):
  
  (a) If an indoor temperature sensor is not affected by pipework heat losses, then excess/unplanned heat dissipation may take place, along with an increase of the **effective compared to design heat load ratio** – see positive connection between **pipework and buffer vessel/DHW cylinder heat losses** and **effective compared to design heat dissipation ratio** on the top right side of Figure 6-13.

  (b) If an indoor temperature sensor is affected by pipework/cylinder heat losses (represented by the **heat source near an indoor temperature sensor** variable), then the localised increase in heat gains may cause the HP to switch off more often, thus possibly under-heating other areas of the house and reducing the **HP SH demand**, which may disrupt the **continuity of HP operation** and increase **compressor cycling**. In fact, any heat source near an indoor temperature sensor, such a fireplace, may lead to the same effect, which is discussed in detail in subsection 6.4.2 below.

The HP installation configuration and features, such as those described in this section, are chosen primarily by the installer and in collaboration with the householder (to some extent). In a few cases, the occupants implemented, or expressed their interest in implementing, changes to the system’s insulation level in order to improve its performance. Such was the case of Quianna (CS17) who stated she insulated some of the exposed pipework running through her house herself (Quote 45, Appendix J2) and Marvin (CS13) who was planning to redo the installation pipework insulation, as he deemed it inadequate. Indeed, Figure 5-18 shows that there was

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20 As explained earlier in subsection 5.1.3, the exact purpose of their existence is not known, however it could serve as a precautionary measure for the elimination of dirt within the circulation system or the avoidance of extensive antifreeze use.
space for insulation improvement, e.g., in terms of uninsulated valves and weakly sealed insulation joints.

Many other occupants intervened to resolve what they perceived as technical issues, other than those relating to the level of installation insulation. These perceived technical problems, along with the actions taken to resolve them and the stakeholders’ technical competence, as this was communicated by the occupants during the interviews, are discussed in paragraph 6.4.2 below.

### 6.4.2 Technical problems and the problem-resolving process in relation to the technical competence of stakeholders

In the case study sample, approximately three-quarters of the cases, i.e., except for CS03, CS10, CS15, CS20 and CS21, reported at least one technical issue disrupting the HP’s ability to fulfil needs to some extent via increasing the perceived SH availability gap, the perceived SH availability gap and/or the perceived bill threshold gap. Some of these issues appeared to be minor, such as power cuts and individual radiators not turning on, possibly due to blockages or accidentally changed radiator settings. Others were major, such as a complete HP system breakdown, leaving the occupants without heating for extended winter periods. The balancing feedback loops [B33] [Self problem-resolving process], [B34] [Expert problem-solving process] and [B35] [Occupant-assisted expert problem-solving process] of Figure 6-14 depict the different paths followed in the case study sample in order to resolve a technical issue. There are also two different paths indicating whether a technical issue was identified via the HP’s ability to fulfil needs or via visual or auditory cues.
Figure 6-14: Causal loop diagram focusing on the area of ‘technical problem resolution process’.

Figure 6-14 shows a negative relationship between the **HP’s ability to fulfil needs** and **emerging issues**, i.e., the higher the **perceived SH/DHW availability gap** or **bill threshold gap**, the more the occupants assumed technical issues impeding the HP’s performance. It also shows a positive relationship between **visual or auditory cues** and **emerging issues**, which proved to be very useful in the early identification of **technical issues**. The following paragraphs elaborate the **technical issues** encountered in the case study sample in relation to the associated problem-resolving process. These are also listed per case, alongside the type of support provided, in Table 21 of Appendix C.
The occupant’s share of technical-problem resolution

Six case studies occupants (CS06, CS11-CS13, CS17 and CS18) reported they were able to identify and resolve at least some of the emerging issues without having to call an expert on site [B33]. Figure 6-14 shows there is a positive relationship between the emerging issues, the problem source identification by occupant and the HP reworking by occupant, providing that the problem source was within the occupant level of access to controls and that the occupants’ level of technical competence was equal or higher than the problem’s required technical specialisation (represented by the occupant level of technical competence-to-problem’s technical specialisation ratio in the CLD). The former depends both on the intuitive system design and on the physical accessibility of controls and components. For example, the visually inadequate insulation of the easily accessible pipework in CS13 and CS17 prompted the occupants to act by improving the insulation, whereas this would be harder to spot for pipework passing through loft. The provision of straightforward instructions/continuous support by the installers and manufacturers can also act as a problem-solving enabler as may the technical competence of the user’s social circle.

Most of these issues did not require highly specialised technical skills, as they could be fixed by either restarting the HP, resetting the thermostat settings, or locating and switching off the resistance heater. In particular, a HP switch-off after a short power cut was an issue encountered in CS11, CS13 and CS18, and since HPs are slow-responding systems, it could take days before the occupants realised it had stopped working. Restarting the HP was an easy and intuitive action for Rafael (Quote 46, Appendix J2), however, it may not always be straightforward or uncomplicated, particularly for older individuals. For example, Kate and Kevin (a retired couple) had to consult the installer before they identified restarting the HP as the solution to their problem, they also described how they had to carefully locate the relevant control buttons, as well as determine the correct order and timing of their actions.

A power cut also led to a heating interruption in CS13, the HP of which came back on automatically but to an incorrect heating schedule (Quote 47, Appendix J2). Being an information technology and management professional, Marvin was able to reinstate the settings himself and also did so for the increased operation of the backup resistance heater that was noted shortly after handover. He was also able to identify or resolve technical issues that require advanced technical skills. These included re-programming of the HP shortly after its installation, as it was “programmed abysmally, it was coming on and off like a yo-yo”, and the identification of a thermostat wiring fault, which triggered the unnecessary operation of the circulation pump, which he was planning to rewire himself (Quote 48, Appendix J2). On the contrary, Francis (CS06), an elementary worker, had to obtain the help of a friend to reinstate the bathroom...
heating. The problem occurred straight after the bathroom renovation works, however, it was not certain whether it resulted from the required power cut or an accidental change of settings by the renovation team (Quote 49, Appendix J2).

As explained earlier in subsection 6.4.1, except for those of CS13, several other occupants stated how they dealt with the extensive use of the HP-incorporated backup resistance heater. The seemingly accidental initiation of the resistance heater, perhaps by a visiting plumbing team, was a complicated task for Lynn (CS12), an elementary worker, who was only able to identify and deactivate the resistance heater with the help of a sibling and the manufacturer’s manual. In CS17, the resistance heater operation was initiated following a HP breakdown, putting the system into an emergency state. However, the occupants Quianna and Quentin only realised this due to the high electricity consumption readings. For them, having a background in physical sciences and electrical engineering made it much easier to spot and control resistance heater use (Quote 50, Appendix J2). By contrast, Helen (CS08) was unable to turn the resistance heater off without the help of an expert and, surprisingly, many of the vising technicians were also unable to do so. This is discussed further in the following paragraph, among other situations, where intervention of an expert was necessary for the resolution of technical problems.

The experts’ share of technical-problems resolution

Even though some occupants were able to resolve issues of low or fairly low technical expertise themselves or with the help of manuals or their social circle, as described in the previous paragraph, most technical problems were referred to technicians and installers for resolution. It appears that some of the technical issues reported had been present since the time of installation, suggesting defective assets were handed over to clients. Others appeared later but not all of them were resolved within a reasonable timeframe, if at all. The variation in technical capabilities of installers and technicians seems to have played a significant role in the timely and successful resolution of technical problems. The balancing loop [B34] of Figure 6-14 represents the expert resolution process, where the emerging issues are positively related to problem reporting and the problem source identification attempt by experts that relies on expert responsiveness for timely resolution. This is then followed by problem source identification and/or HP reworking by technicians, providing an adequate technical competence of technicians. Emerging problems were usually reported by occupants, except for one case (CS09), leading to
the identification of several potentially dangerous regulation incompliances that were uncovered during the **RHP metering team regulation compliance checks**\(^{21}\).

The most frequent technical problems in the case study sample related to failures of system parts, often causing a complete system shut down. Three of the most striking examples of such failures are those encountered in social-housing cases CS06-CS08, all sharing very similar characteristics, including the same RSL, HP installation team and HP type and model (see Quotes 51, 52 and 53, Appendix J2). Francis (CS06) described it as an “explosion” and Greg & Gabi (CS07) as a “burnout”, after which the HP stopped working. To Greg this appeared to be a generalised problem, as he was aware of other HPs in the neighbourhood experiencing the same problem. As per the occupants’ description, the technician’s explanations for the incident were a faulty generator in CS06 and the DHW temperature being set too high in CS07. In cases CS06-CS08, the replacement of faulty HP parts took place on different timescales, *i.e.*, from a few days in CS06 to several weeks in CS08, all during the wintertime according to the occupants.

However, these were not the only severe central heating disruptions in the sample. Dawn (CS04) seems to have experienced the longest winter period without heating when she was left without SH and DHW for 2 months due to antifreeze leak of her GSHP (Quote 54, Appendix J2). Quianna and Quentin (CS17) had to endure 3 weeks of cold winter in North England without central heating, which might have been related to the sudden rise of voltage recorded (Quote 55, Appendix J2). Lynn (CS12) experienced a heating interruption due to a miscommunication between the buffer tank and the controller, and so did Beatrice (CS02) but the cause was not known. Finally, Francis (CS06) and Greg and Gabi (CS07) seemed to have suffered additional heating interruptions to the ones discussed above, due to a blockage in the flow circulation system in CS06 and due to unknown causes frequently preventing the smooth HP operation of CS07, occurring between the first HP installation and its complete breakdown (Quote 56, Appendix J2). Some of the disruptions in HP operation before its complete failure seem to have been eventually resolved with the unavoidable replacement of the HP, however, others arose or persisted.

Other problems whose resolution, according to the occupants, was severely delayed due to technicians being unable to identify and rectify the issues in a timely manner are listed in p. 118 of Appendix J1. In most cases, the long waiting time until a technical issue was resolved related to the expert’s inability to identify the problem source. In CS08, several technicians had to visit

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\(^{21}\) In relation to the unvented hot water system, the installer’s ‘Post Installation Issue Report’ (provided by the occupants) criticised the unconnected “temperature relief on hydro box” and “blow off to hot water cylinder”, as well as the improper width (less than 22 mm in part) and material of the latter, since it was fitted in plastic.
the site multiple times in order to identify a resolution for each of the three problems encountered, i.e., the HP breakdown, the extensive use of the DHW immersion heater and the missing drip tray. Similarly, the technical team did not seem to understand the reasons behind the HP breakdown in CS06 nor the frequent HP operation disruptions in CS07. In CS17, the delay in fixing the broken HP was a result of both the installer company being based far away, to the occupants’ surprise, and the unharmonious collaboration between the manufacturer and installer, who ended up blaming each other and leaving the occupants in an unnerving position in the middle.

Sharing the burden of resolving complex technical problems

Of all case studies facing technical problems, only three occupants were able to identify complex technical problems themselves and/or assist the technicians in the identification process that may not have been timely achieved otherwise, if at all. All three occupants that were involved in the identification process had a technical/natural sciences background, i.e., Andrew (CS01) is a physicist, Marvin (CS13) an information technology and management professional, and Nathan (CS14) a process control and instrumentation expert. Balancing loop [B35] of Figure 6-14 represents this occupant-assisted expert problem-resolving process, where the emerging issues are positively related to the problem source identification by the occupant, either fully or partially, and this is then positively related to problem reporting and HP reworking by technicians. In the three case studies mentioned above, the emerging issues related to improper system design, installation and setup (see p. 119 of Appendix J1 for further information). Given the significant number of technical issues that were reported as being present since the HP installation in these three cases, and requiring the involvement of users with technical expertise for their identification, the presence of additional cases of imperfect handover in the sample that remain unresolved may not come as a surprise. These possibly problematic installations are explored in the following paragraph.

Perceived unresolved technical problems

A number of technical issues perceived as being unresolved were reported by the occupants in the sample, the majority of which were thought to have been present since the HP installation but which the technicians were unable to resolve, or they had not been reported. These relate to:

- **Perceived high electricity bills** – Greg and Gabi (CS07) felt that their HP had “never worked properly since the day it was put in” and none of the numerous visiting technicians was able to provide them with a definitive answer as to whether their perceived high cost in relation to
the SH provided for their small bungalow was the result of a technical fault or not (Quotes 57, Appendix J2). Similarly, Patricia (CS16) felt that the heat provided to their 314 m² farmhouse came at a very high cost, which was being investigated at the time of the site visit by a technician monitoring the energy consumption patterns of their three-phase electric power supply (Quote 58, Appendix J2).

- **Improper radiator sizing and/or placement** – A perceived insufficient heat output and/or placement of emitters was reported in the bathrooms and/or kitchens of CS05-CS07 and in the living room of CS17, however, as explained earlier in subsection 6.4.1, in the case of social-housing tenants this may mostly have been due to the type of heat emitter (HFC).

- **Improper indoor temperature sensor placement** – Ian (CS09) explained that the only room thermostat in the house was originally mounted on the wall next to the fireplace and then moved to the unheated entry hall, thus forcing the occupants to disconnect it and control flow temperature instead²². Nathan (CS14) expressed his concern that placing the only sensor communicating indoor temperature to the HP in a cold spot (i.e., next to an external door in the utility room) was improper. Andrew (CS01) also pointed out that placing the bathroom room thermostat right outside the bathroom was never going to achieve the desired bathroom temperature. The associated HP short-cycling effects, stemming from the influence of heat sources and sudden ventilation heat losses, were described earlier in subsections 6.4.1 and 6.3.2.

- **Dripping issues** – Just like Helen (CS08), Francis (CS06) expressed his frustration over the damp patch next to his external ASHP unit. Both these HPs were installed by the same technician, however, Helen appears to have reported the problem and thus a drip tray was eventually installed, whereas Francis had not, and the problem persisted.

- **Radiator blockages** - Samuel (CS19) though that the reason for the cool spare bedroom was a blockage preventing the radiator from getting sufficiently warm, which is a plausible explanation given that there was a considerably sized radiator present (a 2000×400 mm double-panel single convector) for a 15 m² room surrounded by thick stone walls, with the TRV set at the highest level and just a single heating zone for the whole house.

### 6.4.3 Overall effects of the heat pump technical characteristics and stakeholders’ corrective actions on system performance

Subsections 6.4.1 and 6.4.2 discussed the technical characteristics affecting HP efficiency and the technical problems encountered in the case study sample, as perceived by the occupants,

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²² This control method was utilised for at least four years following the installation of the HP, when a portable thermostat was eventually connected to the system but had not been sufficiently tested at the time of the site visit to report on its operation.
as well as their resolution process in relation to the stakeholder’s technical competence. This subsection summarizes the above, considers their consequences and sets them in perspective in relation to the other parameters explored in Chapter 6.

Figure 6-15 (see Appendix K for enlarged image) depicts a largely linear relationship, i.e., no feedback loops, between the installed characteristics of a HP and its overall SPF and energy consumption, represented by dotted- and dashed-line arrows in the CLD, with the former representing those technical interactions that may not be easily identified or understood by users as they require expert knowledge. However, this linear relationship is not always accurate. It may be true for installations and system setups that have not been altered after handover, however, many of the case studies appeared to have encountered all sorts of technical problems and reworking by users or technicians.

Figure 6-15: Aggregate causal loop diagram depicting the ‘heat pump technical characteristics’ and their effects (dark red dotted-line arrows) and the ‘technical problem resolution process’ (red solid-line arrows) in relation to the other five focal areas identified in this study as influencing heat pump performance and energy consumption, i.e., ‘space heating availability’, ‘domestic hot water availability’, ‘electricity bill size’, ‘building fabric heat loss’ and ‘ventilation and indoor humidity level’.

Most of the technical problems encountered seem to have resulted in an inability of the HP to fulfil the occupants’ needs, represented by the *perceived SH threshold gap, perceived DHW*
threshold gap and/or perceived bill threshold gap variables of Figure 6-15. The corrective actions for the perceived problems, represented by balancing loops [B33], [B34] and [B35], may influence both the HP’s perceived performance and its actual efficiency. Hence, there are four connecting points between the balancing loops concerning the technical problem resolution process and the main body of the CLD. These depict a positive relationship between technical issues and the perceived SH availability gap, the perceived DHW availability gap and the perceived bill threshold gap and a negative relationship between technical issues and overall SPF.

6.5 Prevailing feedback loops and paths influencing efficiency

The model of Figure 6-16 (see Appendix K for enlarged image) was built step by step, based on existing literature and the analysis of socio-technical field data described in the previous sections of this chapter. This section elaborates on the dominant performance influencing variables and relationships, as identified through the relative frequency of certain relationships in the 21-strong case study sample. These are represented by arrow width in Figure 6-16. As the width represents relationships that were frequently identified, these are thought to bear considerable significance. In particular, arrow width represents the number of case studies in which a variable relationship was identified, except for the ‘technical problem resolution process’ area, for which arrow width is based on the count of total incidents in the sample as a whole.

Even though balancing loops appear to be the predominant type of loop in the causal diagram, there are also several secondary reinforcing loops present. These emerge when putting parts of the system together. With the exception of the primary reinforcing loop [R1], the manifestation of the remaining reinforcing loops emerged through the interaction between one or more of the primary balancing loops [B1] to [B35] and the indirect paths stemming from HP operational processes that are often counterintuitive and not obvious to the non-expert. These were described in detail in subsection 6.4.1, alongside Figure 6-13, and depicted in the wider context of the qualitative model in Figure 6-15 and Figure 6-16. Considering all paths influencing performance, the majority converge at two points, namely HP SH demand and continuity of HP operation. From a system’s perspective, these SPF-influencing variables reflect a high degree of centrality since they are included in a particularly high number of feedback loops, i.e., 1450 for HP SH demand and 1366 for continuity of HP operation. This is calculated through a Vensim-based process described earlier at the start of Chapter 6. Additional paths may relate to individual HP components, such as the number and power of auxiliary drives or pipework and buffer vessel/DHW cylinder heat losses.
6.5.1 Dominant adjustments to space-heating availability

As explained earlier in subsection 6.2.1, of all actions taken by occupants in response to a perceived SH availability gap, whether positive (feeling colder than desired) or negative (feeling warmer than desired) or, adjustments to a *room thermostat setpoint* adjustments were by far the most frequently occurring, with four-fifths of the case study occupants making occasional thermostatic changes, some daily [B3]. Feedback loops [B1] concerning the adjustment of *schedule-based heating hours* and [B4] concerning the adjustment of *heated area to total area ratio* to meet heating needs seemed to be occasionally activated in approximately one-third of the case studies. Balancing loop [B4] appeared to rely predominantly on the occasional increase in the number of occupants accommodated in the house, when the HP-heated area expanded, and in only a couple of cases on the perceived heat gains by household equipment, associated with a decrease of the HP-heated area to avoid overheating. The expansion of the
heated area was also perceived to reduce the indoor humidity level. Flow temperature adjustment to meet heating needs [B2] appeared to be the least common control method utilised. This may, in part, have been due to the physical and/or technical difficulty that is usually associated with accessing controls, e.g., social-housing tenants in the sample were locked out of the HP controller and approximately half of the owner occupiers either did not know how to access flow temperature controls or were intimidated by the system’s complexity and any unintended consequences that might arise by such changes. Where flow temperature control was utilised, it appeared to be largely associated with the lack of other methods of indoor temperature control, with the exception of TRVs.

In terms of supplementary heating (also explained in detail in section 6.2.1), the occupants’ narrative revealed that approximately half of the case studies utilised at least one wood or solid-fuel burner to different extents and approximately one-fourth utilised some sort of electric heating. The adjustment of SH availability through the use of non-electric supplementary heating [B6] seems likely to have been influenced equally by aesthetics and thermal comfort requirements. In a few cases, the use of electric supplementary heating [B7] was also influenced by technical arrangements resulting in the installation of standalone, fixed electric emitters in rooms not connected to the central heating system. The addition of clothing insulation as a warming-up method [B8] emerged in approximately one-third of the cases, whereas window opening emerged as a cooling-down method [B5] during the heating season in an equal number of cases. The link between the perceived SH availability gap and window opening was further confirmed by the occupants of three cases that claimed they avoided window opening as a way of keeping their home as warm as possible.

6.5.2 Frequency of adjustments to domestic hot water availability

Actions aiming to increase the DHW produced by the HP in response to a perceived DHW availability gap were pretty rare in the case study sample (see subsection 6.2.2). Most of occupants relied on the pre-set made by the installer while only a small percentage was able to suggest what their timings may have been. In just three cases, the occupants stated they occasionally adjusted the HP DHW production in response to a temporary change in the number of occupants. In none of these cases was it clear whether the DHW was produced by the HP [B13] or the HP-incorporated resistance heater [B14]. Standalone resistance heating for DHW purposes was utilised in approximately one-fourth of the case studies and was more often the result of technical decisions relating to the preservation of pre-existing equipment, e.g., electric showers, as well as a matter of personal preference.
6.5.3 Dominant adjustments in response to electricity bills

A perceived bill threshold gap in the case study sample was found to be linked to several actions taken by the occupants to moderate their household’s energy consumption (see subsection 6.2.3). These relate predominantly to HP SH controls and to a lesser extent to actions limiting the usage of energy consuming appliances (other than the HP) and building fabric heat loss. Even though the inherent technical and operational principles of a HP are likely to induce a positive temporal and spatial rebound, in the case study sample, more than half the occupants appeared to actively seek to avoid what they perceived as unnecessary energy consumption, predominantly via a negative temporal [B9] and/or spatial rebound [B12], followed closely by a negative thermostatic setting rebound [B11]. Flow temperature adjustments [B10] for energy-saving purposes were rarely implemented. Only few occupants considered parameters other than the HP, that have significantly influenced their electricity bills, such as window opening and the use of lights and appliances. In addition, electricity bills were not only based on the energy consumed by appliances but also on electricity tariffs, benefits and entitlements available to at least two-thirds of the case study occupants and RES electricity production contributing to approximately half the case studies. Thus, it is likely that high household energy consumption in some cases might be concealed by the aforementioned bill-offsetting processes.

Identifying high electricity consumption sources is a complicated task for most occupants, especially those without access to dedicated monitoring equipment enabling them to distinguish between overall energy consumption and the energy consumed by the HP. This may lead to erroneous assumptions on what might be the reason for the household’s high energy consumption and to subsequent actions that may increase energy consumption even further. This seems to have been the case on at least two occasions, when the occupants decided to dramatically eliminate the HP-heated area [B12], room thermostat setpoint(s) [B11] and/or schedule-based heating hours [B9] while at the same time increasing the use of electric [B7] and non-electric supplementary heating [B6]. Self-monitoring, with or without the help of dedicated sensor readings, appears to have assisted the reduction of energy consumption [B16] in four cases, either by identifying energy-intensive equipment or by improving HP controls. Without the tools supporting the recognition and moderation of energy-intensive processes by either occupants or experts, high electricity bills can trigger occupant responses that may eventually reinforce the initial problem. These may stem from weaknesses in many areas, including those relating to the building’s heat loss and the HP’s technical aspects addressed in the following subsections.
6.5.4 Dominant actions in relation to indoor humidity and ventilation

In the case study sample, a wide range of variables was found to influence the act of window opening during the heating season. Of those, the occupants’ perceived need for fresh air [B23], the perceived indoor humidity level [B21] and the perceived SH availability gap [B5] emerged as the most potent variables in over one-third of the case studies. Despite the potential for the first two to be controlled through the use of mechanical ventilation [B20] [B24], half of the cases that were equipped with MVHR seem to have encountered problems that significantly hindered their operation and/or utilisation by the occupants. Less frequently occurring window opening drivers included the need for prolonged access through windows/doors relating to the presence of pets and electric vehicle charging. These were explained in detail in subsection 6.3.2

In terms of concerns relating to a high perceived indoor humidity level (see subsection 6.3.2) that manifested in over one-third of the case studies, these were linked predominantly to perceived indoor moisture sources and, to lesser extent, condensation and mould, which were sometimes present in conjunction with a lower level of SH availability. Except for window opening, which was the predominant occupants’ response to a perceived high indoor humidity level, others, reported in a few cases, included dehumidifier use [B19] and the expansion of the dwelling’s heated area [B22].

6.5.5 Commonly implemented belated building fabric retrofit actions

As explained in subsection 6.3.3, building fabric efficiency improvements were not uncommon in the case study sample. This does not come as a surprise since only one-quarter of the buildings were newbuilds. What is surprising though is that in one-third of the cases, building fabric improvements took place only after the installation of the HP, with an equal number of dwellings reporting the presence of unresolved issues for which they were either seeking resolution or had retrofit plans scheduled. The thermal weaknesses identified in the walls and roofs of approximately half of the case studies via thermal imaging should also be noted. These concern, in most cases, building fabric weaknesses that differed from those indicated by occupants. The effect of retrofitting on building fabric thermal resistance and building fabric air tightness is represented by balancing loops [B25] and [B26], both of which significantly affect a building’s overall heat loss.

The drivers behind these belated or unimplemented building fabric improvements were not always known. This is particularly true in the social-housing cases, where the initiative is taken by the RSL (not interviewed as part of this study). However, in a significant number of cases, technical, practical, and economic barriers were found to drive delays in building fabric improvement. The technical barriers concerned imperfections in the application of building
fabric insulation and draught-proofing, emerging even in a few newbuilds in the sample. These resulted from either the poor technical skills of building practitioners or the physical limitations imposed by existing building structures. In addition, the occupants’ narratives revealed that significant delays in the implementation of building fabric improvements can also be related to the disruption associated with them, as well as the high retrofit costs.

### 6.5.6 Frequent technical influencers

A great variation in HP types and configurations was observed in the case study sample. Influences of HP efficiency are associated with parameters that fall into different SPF boundaries, such as *compressor power consumption*, *supply air fan or ground loop pump power consumption*, *heat generation by the HP-incorporated resistance heater*, *number and power of auxiliary drives* and *pipework and buffer vessel/DHW cylinder heat losses* (see subsection 6.4.1). Of these the most frequently occurring, based on the data available on the 21 case studies, concern the following areas:

- **The extensive use of the HP’s resistance heater** – The data collected through monitoring, interviews and site investigations revealed that the backup resistance heater was operating regularly or for long periods in over one-third of the case studies. The data collected also indicate that this was more relevant to DHW production. Technical problems or an accidental actuation have been identified as the likely cause.

- **The poor planning of pipework insulation and layout** – The majority of HP systems in the sample presented low-quality pipework insulation and uninsulated parts, including pumps and valves. A significant number of these were placed in unheated/uninsulated spaces, either fully or in part. Approximately one-fourth presented long pipework between the external ASHP and the house perimeter.

- **A wide range of processes that are likely to affect compressor power consumption** – Such processes may originate from improper HP- and radiator-sizing calculations, however, even a properly sized HP may be influenced by occupant- or building-related processes that significantly alter the *effective-to-design heat load ratio* or interrupt the *continuity of HP operation*, including adjustments to HP control, extensive use of supplementary heating methods, frequent window opening, and improper temperature sensor placement.

### 6.5.7 Frequency of technical problems and efficiency of resolution processes

According to the occupants, one or more technical issues disrupting the HP’s *ability to fulfil needs* to different extents emerged in approximately three-quarters of the case study sample
In some cases, additional issues were identified through *visual or auditory cues* that facilitated the early detection of technical issues before it became evident that the HP was unable to meet the occupants’ SH, DHW and/or economic needs. Just under half the occurrences were referred directly to experts for resolution [B34]. As for the remaining ones, a few occupants did not take any action, however, the majority were able to identify the problem themselves and then either self-resolve it [B33] or subsequently refer it to experts [B35]. The ability of the occupants to identify and resolve problems themselves appeared to be primarily a function of the *occupant level of technical competence-to-problem’s technical specialisation ratio*, providing that the occupants were able to access the installation part in question. Access to *straightforward instructions/continuous support*, as well as the *technical competence of user’s social circle* were found to enhance the problem-resolving process and thus lessen the need for an expert’s contribution. An expert’s contribution was eventually requested for most problems encountered, however, in more than half of these occurrences, the occupants reported significant delays in resolution. The delays were generally attributed by the occupants to the technical incompetence of a large proportion of the visiting technicians, many of whom appear to have failed in handing over a quality design, installation and/or setup in the first place.

### 6.5.8 Key findings

Based on the analysis of the qualitative and quantitative data collected on the 21 case studies and the CLD representation of the parameters influencing HP performance and their interrelations, the key findings are presented below in relation to each of the seven focal areas.

- **Household SH practices**: Common household heating practices, such as thermostatic adjustments and the frequent use of wood fires can significantly increase or decrease the HP’s heat load (in relation to design heat load) or disrupt the continuity of the HP’s operation.

- **Household DHW heating practices**: The use of standalone resistance heating for DHW purposes in tandem with a DHW providing HP was often encountered in retrofit installations.

- **Bill affordability**: Despite the well expected positive rebound due to the “HP embedded script”, many occupants in the sample were found to drive a negative temporal or spatial rebound to avoid what they perceived as unnecessary energy consumption. In the absence of transparency on energy intensive processes, high electricity bills were found to trigger occupant responses that were likely to increase energy consumption even further.
• **Ventilation patterns and indoor humidity level**: Window opening was most often associated with a perceived need for fresh air and a perceived high indoor humidity level. The latter was also found to be linked, although less often, to a positive spatial rebound. One of the less frequently occurring triggers of prolonged window opening that may be of increasing concern in the future is electric vehicle charging.

• **Building thermal characteristics**: Attention was drawn to the poor technical quality of building retrofits, the belated identification of unresolved building fabric weaknesses, and the building fabric improvements that took place only after the installation of the HP.

• **Technical characteristics of the installation**: Multiple technical issues were uncovered in the case study sample, some of which remained unresolved at the time of the study and with many indicating a flawed system handover. The most frequently identified technical issues related to the extensive use of the system’s backup resistance heater (primarily for DHW production), the poor planning of pipework insulation and layout and a wide range of processes that are likely to affect compressor power consumption.

• **Technical problem resolution and control optimisation processes**: Overall, the occupants reported significant delays in resolution that were attributed to the technical incompetence of a large proportion of the visiting technicians. Regular monitoring of energy consumption, either through bill surveillance or with the help of dedicated sensor readings, appears to have assisted users to identify technical issues and ways to run their HP more efficiently.
Chapter 7: Discussion and Implications

HP behaviour is much more complex than anticipated by many and the diverse range of factors influencing performance and interrelations need to be well understood to identify pathways for improvement. This socio-technical study utilised both qualitative and quantitative data to produce a model that revealed a network of underlying influencing variables and mechanisms. The model’s core was based on existing literature and considering relevant thermodynamics and building physics. The model was then expanded based on the findings of the data analysis relating to the 21 RHPP case studies. The data were acquired through a variety of approaches, including monitoring, in-depth interviews with occupants and direct observational methods (Lowe et al., 2017a).

This chapter discusses the findings identified in the previous chapters by comparing them with existing literature and explores their implications. In particular section 7.1 focuses on ‘Theory Development’ and section 7.2 on the ‘Practical Implications’ of the findings, followed by section 7.3 that discusses a ‘Suggested future course of action’. Despite the monitoring data quality issues (described earlier in subsection 5.2.1) that inevitably limited the understanding of the HP systems examined to some extent, the extensive triangulation (see subsection 3.2.3) of the rich empirical data collected using mixed methods has helped counteract validity threats and reach theoretical saturation (Aldiabat & Le Navenec, 2018). Higher quality monitored data might have helped reach saturation earlier.

7.1 Theory Development

7.1.1 Comparison with literature

There is extensive literature available focusing on the technical features of HP systems and the testing of the latest technological advancements that can drive a significant reduction in energy consumption (European Commission, 2009; Huchtemann & Müller, 2012; Rognon, 2008; Staffell et al., 2012). There has also been an increasing interest in the examination of HP performance from a wider perspective, i.e., considering not only the HP system as a whole instead of the HP unit at boundary level H1 (Marek Miara et al., 2014; Riviere et al., 2011) but also the environment it is installed within, taking into consideration building characteristics (Fahlen, 2008) and user behaviour (Kirsten Gram-Hanssen et al., 2017). However, both the qualitative and quantitative data collected as part of the existing studies, including the large
RHPP sample, presented limited capacity in uncovering the range of parameters influencing HP performance, as they were limited in scope. However, the small difference between ASHP and GSHP performance in the large RHPP field trial and the substantially higher capital and installation cost of GSHPs, suggests it may be worth investing in improving ASHP performance (Lowe et al., 2017c).

Figure 7-1 Cumulative causal loop diagram depicting the complex interrelationships of the seven interconnected focal areas influencing heat pump efficiency and energy consumption, where the grey highlighted core depicts the parameters influencing heat pump performance as identified through literature. Arrow width in the qualitative model represents relationship strength, as identified in the 21-strong case study sample (see caption of Figure 6-16) and corroborated with literature.

The current study mapped for the first time the full range of parameters that are likely to influence HP performance based on the in-depth investigation of 21 case studies. As explained in section 3.4, the application of systems thinking to the analysis of the socio-technical data collected from the case study sample facilitated the identification of the underlying complex interactions between the HP system and its environment. It also supported the formulation of theory on the causes of dynamic relationships and, specifically, on the structures responsible for poor HP performance in the UK. The CLD of Figure 7-1 (see Appendix K for enlarged image) depicts the model’s literature-based core against the backdrop of the seven interconnected
focal areas identified or expanded through the case study work. These areas relate to the household SH practices, household DHW heating practices, bill affordability, ventilation patterns and indoor humidity, building thermal characteristics, technical characteristics of the installation, and technical problem resolution and control optimisation processes. The associated findings are compared and corroborated with literature below, followed by a paragraph discussing the likely links between the seven focal areas and the striking difference in HP efficiency between social tenants and owner occupiers, as identified by Caird et al. (2012).

**Focal area I: Effects of household space heating practices**

There are several aspects of user behaviour likely to influence HP performance. These include HP controls in conjunction with the patterns of usage of any additional heating methods present, such as standalone resistance heating and wood fires that increase the complexity of HP regulation. For this reason, Gram-Hanssen et al. (2017) stressed that the competencies required to run a HP efficiently should not consider the HP in isolation but as part of a complex context, including individual material arrangements and the household as a whole. In accordance with Gram-Hanssen et al. (2017), the uncontrolled use of wood fires for aesthetic or thermal comfort-related reasons in approximately half of the case studies in the RHPP sample also highlighted the need to establish household competencies for the wider context a HP belongs to.

In addition, the study stressed the need to carefully consider the reasons for the installation of additional heating arrangements at the design stage and whether these could be avoided or replaced with a HP-provided service in the case of retrofit installations. In particular, several direct electric heaters were identified in the case study as being the sole heating methods available in individual rooms or for a specific function, such as electric towel warmers or electric showers. The reasoning provided for their installation ranged from convenience, familiarity and personal preference to a lack of education on the decision-maker’s side.

**Focal area II: Effects of household domestic hot water heating practices**

The study also supports the careful consideration of additional DHW arrangements at the design stage, since several electric showers (either pre-existing or installed due to personal preference) were present in the case study sample. Overall, occupants relied on the installers’ DHW pre-set and only occasionally adjusted it to accommodate the DHW needs associated with a temporary increase in the number of occupants. However, it was not certain whether the increased DHW requirements were fulfilled by the HP or the system’s backup resistance heater. While there is no evidence from literature focusing specifically on the households’ DHW heating
practices in relation to HPs, this study has identified several paths that are likely to lead to an increased electricity consumption through the use of direct electric heating for DHW purposes.

**Focal area III: Bill affordability**

The well-known rebound effect, where theoretical savings are transformed into increased comfort, has also been documented with HP use (Caird et al., 2012; K. Gram-Hanssen et al., 2012; Owen et al., 2013; Winther & Wilhite, 2014). While the lack of detailed information on energy consumption in this study did not allow the estimation of rebound in the RHPP case studies, there was evidence for positive rebound relating to what Winther and Wilhite (2014) describe as “the HP embedded script” in all cases where the HP replaced non-central heating systems (spatial rebound) and, in general, due the more continuous operation required in comparison to traditional heating systems (temporal rebound). However, there was also evidence of negative rebound in more than half of the RHPP case studies, with occupants seeking to reduce energy bills via a reduction of the heated area, a lowering of the thermostat settings, and, less often, via keeping the HP off at night. An extreme negative rebound was noted in two cases, and this is discussed in detail in subsection 7.1.2.

**Focal area IV: Heat loss uncertainty associated with ventilation patterns and indoor humidity**

The importance of minimising heat losses from both the building fabric and ventilation is well established (Caird et al., 2012; Delta Energy & Environment, 2011; Dunbabin et al., 2013; Kirsten Gram-Hanssen et al., 2017; Staffell et al., 2012; Stafford & Lilley, 2012). The sensitivity analysis performed as part of the RHPP project-stage work (Gleeson et al., 2017) recognised a great deal of uncertainty associated with the detailed heat loss calculations required as part of the HP system- and radiator-sizing process, stemming from the subjective assessment of the building’s thermal properties and ventilation rates, with the latter being highly dependent on transient variables, such as occupant behaviour. Evidence from the RHPP case study sample indicated a wide range of window-opening triggers that were most often associated with the perceived need for fresh air and the perceived indoor humidity level, the latter being reinforced by specific activities and habits, such as drying clothes indoors. Case studies with smokers also appear to be linked to increased window opening or use of mechanical ventilation, however, a wide range of perceived technical issues, including draughtiness and high noise levels, were found to hinder the operation of the latter and thus reinforce window-opening patterns. The emerging need for prolonged access through doors/windows, linked to the presence of pets and electric vehicle charging, may be of particular concern in the light of the increasing rate of
electric vehicle adoption, especially considering the UK’s ban of internal combustion engine vehicle sales by 2030 (DfT & BEIS, 2020).

**Focal area V: Heat loss uncertainty associated with building thermal characteristics**

In terms of building fabric thermal characteristics, this study has identified the poor technical quality of the application of building components in retrofits and less often in newbuilds as an additional source of possible discrepancy between the design and actual building heat load. This may be linked to increased building heat losses that can easily be overlooked. In the case study sample, such technical failures were often picked up and/or rectified by building users at a later stage than the installation of the HP. In other cases, the improvement of well-known building fabric thermal weaknesses of building fabric was delayed until after the HP installation due to technical, practical and economic barriers. It is not certain whether these changes were taken into consideration during the HP-sizing process or not. Focal area VI: Technical characteristics and consideration

**Focal area VI: Technical characteristics and considerations**

Literature has also placed particular emphasis on the importance of well-designed, -installed and -commissioned HPs (Boait et al., 2011; Caird et al., 2012; Delta Energy & Environment, 2011; Dunbabin et al., 2013; Dunbabin & Wilkins, 2012; EST, 2013; C. P. Gleeson & Lowe, 2013; Kirsten Gram-Hanssen et al., 2017; Marek Miara et al., 2014; Staffell et al., 2012). This was one of the major differences between the UK and continental installations, with the latter presenting installations of higher quality (Boait et al., 2011; Delta Energy & Environment, 2011), stemming at least in part from the accumulated experience of installers that have generally been working with HPs for a significantly longer period of time (Rognon, 2008; Roy et al., 2010). The present study also uncovered multiple technical issues in at least three-quarters of the case studies in the sample, some of which remain unresolved, others possibly undetected, and with many indicating a flawed system handover. Some of the most frequently occurring issues identified relate to the extensive use of the system’s backup resistance heater, primarily for DHW production, and imperfectly insulated pipework. It also appears that radiator-sizing issues are more likely to arise (although not exclusively) in retrofit installations due to cost, space and aesthetic restrictions, among other reasons, such as installer convenience that may be linked to a superficial assessment of existing radiators.

**Focal area VII: Technical problem resolution and control optimisation processes**

The significant delays often encountered in the technical-problem resolution process were attributed primarily to the technical incompetence of the installers, highlighting the need for
better installer education and quality assurance programmes. The technical skill of users appeared to accelerate the resolution process, either by identifying the problem source and/or resolving the problem themselves. Overall, a better understanding of a system is associated with higher system efficiencies (Caird et al., 2012). Based on the case study analysis of this present work, higher efficiencies can be linked to two types of users: (a) ‘self-monitoring users’ who can identify how to run their HP efficiently through energy bill surveillance/utilising dedicated monitoring equipment, and (b) ‘technical savvies’ who have the skills required to identify or resolve technical problems of varying degrees of complexity.

Users, of course, should not be expected to be technically skilled to run a HP efficiently, however being adequately educated in order to recognise, prevent and resolve issues of low-level expertise, e.g., knowing when the HP-incorporated resistance heater is on and how to turn it off, can be a valuable skill. Given that HP users in the UK have generally been found to have a poor understanding of the complex HP technology (Durham Energy Institute & Element Energy, 2015; Roy et al., 2010) and that the wider evidence correlates higher levels of perceived complexity with suboptimal control (Boait et al., 2011; Caird et al., 2012; Durham Energy Institute & Element Energy, 2015; Owen et al., 2013), great emphasis should be placed on feedback processes and user education (Caird et al., 2012; EST, 2013).

Most technical issues reported by occupants of the RHPP case studies were identified due to the inability of a HP to fulfil needs, often at a later stage and usually manifesting in the form of high energy bills. However, where visual or auditory cues were present in relation to emerging issues, these facilitated their early detection, highlighting the importance of real-time feedback processes, if they are easily recognised by users. User feedback, e.g., through user-friendly interfaces displaying information on the system’s efficiency and energy consumption, can be particularly helpful when there is lack of clarity on the optimal HP-running pattern, as well as in situations where technical problems emerge, such as the unintentional use of the system’s backup resistance heater. This is explained further in subsection 7.2.3.

As well as robustness, installation simplicity, both in terms of design and controls, was also linked to higher HP efficiencies in both the EST and German Fraunhofer field trial (Marek Miara et al., 2014; Roy et al., 2010). Simpler designs and controls are not only easier for users to understand but they also leave less room for technicians to make mistakes. Significant variation in HP installation practices and the components incorporated was noted in the RHPP case study sample, including some particularly complex designs, e.g., incorporating multiple HP units, heat exchangers and/or circulation pumps and exceptionally long pipework runs.
HP ownership considerations

The striking difference in the efficiency of HP systems owned by social-housing tenants and owner occupiers in the EST field trial (Caird et al., 2012), with the latter performing significantly better, has been attributed to a wide range of parameters, including occupant behaviour and understanding of the system, building characteristics, as well as HP system and installation type. Many of these parameters were also identified in the RHPP case study sample, with the addition of controller ‘lock-out’ (Lowe et al., 2017a) in the case of social-housing tenants, who were either not allowed to interact with the controller or were physically unable to reach it due to its placement in the loft of the small bungalows, a practice that may be common in smaller houses due to the lack of space. Social-housing tenants were also ‘locked-out’ of decision-making relating to the process of HP installation. By comparison, owner occupiers were actively involved in the HP selection and installation process, including any associated energy efficiency measures implemented, and had full access to the controller, thus often having a better knowledge of their system’s features and a higher motivation and capacity to improve its efficiency. However, as explained in the following subsection (7.1.2), this is by no means a guarantee for smooth and efficient HP operation.

7.1.2 Unforeseen interconnections and confounding factors

While the previous section discussed how this work compares and contrasts existing literature, this sections explains how it goes one step further to uncover unforeseen interconnections that may significantly hinder the efficiency of HPs. These are usually hard to control, as they often emerge through processes of the HP operation that are invisible to the user and the confounding factors present tend to further conceal the real impact of actions taken by occupants. There are several reasons why these actions, either in relation to the HP or its peripheral systems, may lead to unpredicted outcomes for the user. These include the complex nature of HP technology and the general inability of users to distinguish between different energy-consuming or -generating sources. The latter, in combination with the widely adopted and intuitively “logical” practices utilised with traditional heating systems, may set the conditions for actions that may eventually lead to unexpected or undesirable outcomes. The general lack of transparency of HP efficiency and the energy consumed by individual household appliances, including the HP, can contribute to the adoption of traditional heating system patterns due to familiarity or a perceived energy saving potential, and can even trigger unorthodox SH/DHW patterns. This was the case in two households in the sample, discussed at the end of this section, where HP use was restricted significantly in favour of direct heating methods, including resistance heating. The implications of these findings are discussed in subsection 7.2.3.
Impacts of traditional heating practices

Contrary to common intuition, several user practices, widely adopted with traditional heating systems, are detrimental to the efficiency of a HP. For many occupants, in the quest for lower electricity bills, the first point of action was to alter one or more of the HP’s SH controls. The majority instinctively attempted to reduce, singly or in combination, the HP heated area-to-total area ratio \([B12]\), room/radiator thermostat setpoint \([B11]\) or the schedule-based heating hours \([B9]\). However, balancing loops \([B9]\), \([B11]\) and \([B12]\) are interlinked, with reinforcing loops that flow through one or more of the SPF influencing variables, i.e., \(SH\) generation and/or compressor cycling. Thus, the fine balance between the energy saved by the reduced HP operating hours and increased compressor cycling suggests there is uncertainty as to whether the occupants’ corrective actions will have a positive or negative outcome.

In a few cases, not only did the occupants dramatically reduce the HP’s operating hours via negative temporal \([B9]\), thermostatic setting \([B11]\) and/or spatial \([B12]\) rebound but, as a result, they also increased the use of standalone resistance heating in an unsuccessful attempt to lower their household’s bills \([B7]\). However, as well as the low efficiency of resistance heating, the use of any direct heating method may significantly reduce HP SH demand (relative to the design heat load) and thus lower HP efficiency.

Impacts of user preferences and interventions in the wider environment of a heat pump

Besides occupant actions taken in response to high electricity bills, there are also actions stemming largely from cultural norms and embodied habits that can influence HP efficiency in ways that are not evident to the occupants. These include window opening habits and the use of wood-fired heating that some occupants utilised surprisingly frequently due to its aesthetic value, which can significantly increase or reduce a HP’s heat load, respectively, while both increase compressor cycling. Another way in which the occupants can alter the HP’s heat load is by changing the thermal properties of the building fabric. It was quite surprising to find that for many occupants in the sample, improvement of their building’s fabric \([B25]\) \([B26]\) was an ongoing project they (or the RSL) kept working on even after the installation of a HP. The reasoning provided for these belated improvements related to technical, practical and economic barriers, including the poor quality of the original construction or retrofit. Even though this is a positive improvement for the building’s thermal performance, it is uncertain whether the building fabric changes post HP installation (if planned) had been taken into consideration in the designers’ heat-loss calculations.
Distinguishing between household energy consumers

Since there are usually plenty of energy-intensive appliances within a household, when coupled with high usage practices, they can significantly add to the overall electricity consumption. This may be more prominent where the occupants have no other option than frequently utilising standalone electric sources of heat. This may be the case for a HP or emitter not providing sufficient heat or, more frequently in the sample, due to the use of standalone electric DHW generation sources (e.g., electric showers) [B15] and the presence of electric resistance heaters where HP-connected emitters could have been installed [B7]. Without the ability to distinguish between different energy consumption sources, the HP tends to be the usual suspect for high energy bills, but this may not always be the case. Certainly, a HP is expected to consume a high amount of electricity, especially if regular electric backup heating is involved, a situation that may be better controlled with good monitoring practices and user awareness. In two extreme cases, described in detail in the following paragraphs, the occupants resorted to the use of resistance heating as a balancing measure towards the perceived high energy bills associated with their HP.

Insights into two extreme case studies

Of all RHPP case studies, the social-housing tenants of CS07 and the owner occupiers of CS16 were notably dissatisfied with the HP running costs, which they both thought were the result of a technical issue. Indeed, based on the bill estimates available, both cases stand at the higher end of the spectrum for their respective building group (based on building size and ownership type)\(^{23}\). Given that both cases present higher occupancy numbers than most of the remaining cases in their group, this might be a link between higher DHW usage and higher energy consumption. Crucially, there is also some indication of the DHW being heated at pasteurisation temperatures daily, which may also be linked to backup resistance heater use, however, this could not be ascertained through the monitoring data.

Looking at the wider environment a HP interacts with, additional influencing variables can be discovered in terms of running costs and comfort. These may relate to the likely high heat losses, triggered by the need for pet access and the presence of faulty extractor fans in CS16. The latter was also reported in CS07, alongside complaints about the high indoor humidity levels and the presence of strong draughts, which were detrimental to both the building’s airtightness and the occupants’ thermal comfort, forcing them to seek higher indoor temperatures. HP system heat losses that could have been avoided may also be linked to the imperfectly insulated pipework that ran through the cool roof in CS07.

\(^{23}\) Electricity bills were in the range of £440 - £700 per year for small social houses and £1000 - £2150 per year for large owner-occupied houses.
For the social-housing tenants of CS07, their dissatisfaction with the system may also have been fed by a wide range of highly subjective factors, including:

- Having no input to the decision-making process for the replacement of the existing heating system.
- Dissatisfaction with the disruption associated with the required energy efficient refurbishment.
- Dissatisfaction with the heat provided by the HP-connected HFC that might be related to the nature of convective heat and/or insufficient heat output.
- Dissatisfaction with the long and highly technical information provided.
- Previous negative experience due to the several technical issues experienced since handover, ranging from gaps in heat provision to a complete HP breakdown.
- Technical issues not being resolved in a timely manner due to the reported incompetence of technicians.
- The occupants’ low affordability level that did not allow raising the room thermostat temperature to a higher level.

In both CS07 and CS16, the occupants resorted to extraordinary practices to alleviate the perceived high HP running costs, i.e., by significantly restricting SH generation and supplementing it with direct heating methods, including standalone resistance heating. Such practices can lead to a dramatic reduction in heat load with significant HP sizing and efficiency implications, while at the same time increasing electricity consumption through the use of resistance heating methods that, by default, present efficiencies lower than that of a HP. Even if such practices succeed in lowering overall electricity bills, they will do so at the expense of comfort while failing to address the real reasons behind the seemingly underperforming HP. Overall, individual variables influencing HPs rarely act in isolation and the resulting synergies may lead to situations where one act counteracts or reinforces another in terms of energy consumption, with outcomes that are hard to predict.

### 7.2 Practical Implications

#### 7.2.1 Rated efficiency considerations

Comparing the manufacturer’s laboratory-based HP efficiencies is not a straightforward process as they are tested under different conditions, and also differ between ASHPs and GSHPs. Manufacturers are generally obliged to release a single COP, but many provide additional COPs or SCOPs voluntarily, with the latter being a requirement for MCS and other certification schemes. Between COP and SCOP, the latter offers a better representation of a system
performing under real conditions, as it takes into consideration the temperature variation of the heat source to some extent, i.e., based on theoretical conditions. The rated efficiency in manufacturer brochures is based primarily on the SH function of the HP, while the efficiency of combination heating for a selected DHW load profile is reported as the ErP rating, using energy efficiency bands. Thus, it is generally not clear what the combined efficiency of a HP is.

The interpretation of rated efficiency is a complex task that requires specialised advice to calculate the expected systems efficiency under site-specific circumstances. Even then, there is a great deal of uncertainty around both SH and DHW rated efficiencies, since they are both based on theoretical conditions. With regards to DHW, in particular, there is no generally agreed HP-sizing method to ensure adequate DHW provision (MCS & RECC, 2018). There are also reliability concerns relating to manufacturer tests not being always carried out by independent test centres, meaning that the testing conditions may not always be followed diligently (Klein, 2012). However, the MCS requirement for tests to be carried out by UKAS-accredited testing centres provides confidence in that aspect.

The crude comparison between the rated COP and the SPF calculated from the case study monitoring data show no correlation between the two. There are several possible sources of discrepancy, including the utilisation of different boundaries and the fact that while rated efficiency is based on laboratory measurements implemented during a short period of time, the SPF concerns real/annual operating conditions. In the real world, there is great variation in control practices for both SH and DHW, as well as social and physical interactions and technicalities that may significantly impact HP efficiency.

In the case study sample, the sole SH-only providing HP (CS20) presented one of the highest efficiencies. Overall, SH-only HPs tend to have higher efficiencies, especially if their SH distribution systems are running at low flow temperatures and HP efficiencies tend to be lower with higher DHW fractions (typically set at a minimum flow temperature of 50-60 °C). While the combined efficiency of a HP is typically not included in the manufacturer’s data, the method for the incorporation of the DHW load in the HP sizing and efficiency calculations is becoming ever more important due to increasing building thermal insulation standards. The lack of explicit information on the presence and the likely effects of backup resistance heaters on efficiency is another area of great importance.
**7.2.2 Implications for policy makers and installers**

**Fairness and incentive considerations**

The UK government currently relies largely on economic incentives to accelerate HP uptake. However, incentives alone may not provide sufficient motivation and, if offered to those willing to pay for the technology anyway, they may even feed an extreme positive rebound effect (Alberini et al., 2016; Jaffe et al., 1999; Parrish et al., 2021). With this in mind, the Green Homes Grant targets low-income and low thermal efficiency houses for the installation of HPs. However, ensuring quality installations and putting people at the heart of the technology uptake should be also prioritised to increase acceptability. This requires the identification of suitable properties and social groups, as well as competent installers and technicians, while respecting social norms and ensuring compatibility with daily routines.

Actively involving tenants in the decision-making process is important for the minimization of psychological implications relating to a perceived forced acceptance of the new heating system. This appeared to be the case in at least five social cases, where the occupants were not given an option to object to the installation of the HP (see Table 4 of Appendix C). In addition, unlike the Green Deal, where the benefits stay with the user, in the social-housing cases of the case study sample, it was the RSL that received the RHI payments. This takes away a significant motivation for the acceptance of this technology by social-housing tenants, who are more likely to be on a low income. Thus, among prospective users, social-housing tenants should be handled with great care by policy and decision makers. As they are not usually the ones deciding on the HP installation, they are less likely to engage with the HP in a productive way and to be willing to tolerate the disruption associated with its installation and any required building fabric improvements.

Targeting those groups that will benefit the most from the installation of a HP is an important consideration. Newbuilds and off-gas properties are obvious candidates, as the currently higher capital and running costs of HPs in comparison to gas boilers are not likely to yield benefits (CCC, 2020b; HPA, 2019). The identification of market areas where HP might be installed at the least cost, disruption and minimal social barriers could assist both public acceptance, technological and skills improvement, as well as unit cost reduction. For example, the installation of HPs in small houses may not be ideal, both due to the loss of critical storage space and the confinement of the HP in spaces that are hard to reach for maintenance and control. Targeting niches to stimulate market growth has been identified as an important strategy by the CCC (CCC, 2020b, 2020a), particularly since the current supply chain for building thermal retrofit and the installation of HPs present weaknesses.
System complexity and quality assurance weaknesses

A HP installation includes several components in addition to those strictly provided by the manufacturer. Each installation is based on a bespoke design that cannot be predicted in advance. In theory, there are infinite combinations in terms of components and their arrangements, which may allow for more mistakes in the process in comparison to traditional heating system installations. The situation tends to be even more complex in retrofit installations, where the possible utilisation of existing components should also be carefully considered. For example, existing heat emitters and pipework may not be adequately sized or compatible with the HP, however the RHPP case study analysis indicated that not all installers were equally thorough.

Between different HP types, some come in ‘packaged’ or ‘combination’ units that include all the essential components in a single container, e.g., the HP unit, DHW cylinder and essential controls and sensors, which may make the installation process significantly less complex but there may be less flexibility where space is limited. This type of installation, adopted by approximately one-quarter of the RHPP case studies, would still require the incorporation of additional components and controls to be considered by the installer, such as the addition of a buffer tank or pasteurisation controls. Thus, packaged systems may simplify the installation in part, however, a solid skills base for installers is still of critical importance. The generally poor technical skillset of the installers in the case study sample was manifested in the form of several technical problems, spanning across case studies and HP types, many of which had been present since handover. This led to a high level of dissatisfaction among occupants, who reported that a great proportion of the visiting installers were unable to resolve the technical issues in a timely manner, if at all.

A problematic handover and the reported technical incompetence of HP installers and technicians across the case study sample indicate that the current systems in place for quality assurance do not suffice and highlight the need for better installer training and certification schemes. Currently, there seems to be a limited base of qualified and experienced installers which needs to be expanded urgently in view of the rapidly increasing HP installation uptake. Ensuring installers and technicians are adequately skilled to deliver high-quality HP installations and to be able to efficiently tackle the technical problems arising is of the utmost importance for HP to perform well in the UK. Both appropriate training and regular knowledge updates are important.

In addition, since HP systems are far more sensitive to building heat losses than traditional heating systems, the implementation of a reliable heat loss calculation is key. This is because (a) part-load impacts HP performance significantly more than gas boilers and is likely to trigger
resistance heating, and (b) the cost per unit of heat capacity is appreciably higher for HPs than gas boilers, making an unnecessary high output for HPs significantly more expensive (see Table 4-1). However, both the heat-loss assessment and the associated HP/emitter-sizing calculations are highly dependent on the technical abilities of the designer, as well as the underlying processes for their calculation, such as the MCS heat-loss calculator and the EPC. The detailed MCS heat loss calculations were not available for the case study sample, however, the examination of the EPC revealed many errors in filling-in forms and erroneous assumptions, thus identifying them as possible sources of discrepancy and highlighting the need for measures that increase their reliability. In addition, in some case studies, the EPC-recommended improvements were not realised before the installation of the HP, as expected, and in others, issues of building fabric efficiency were only identified after the installation of the HP. The inherent uncertainty associated with heat-loss calculations is inevitable to some extent and this tends to be higher in retrofitted properties (e.g., cavity walls are particularly hard to treat). However, it is important that these calculations are based on solid assumptions as much as possible.

**Best practice considerations for installers**

With the expected increase in HP sales in the coming years, quality installations are needed now more than ever. As explained in the previous paragraphs, this requires an adequately insulated building fabric and a strong technical skillset of all experts involved. It also requires certain competencies on the users’ side, which can be fostered to some extent through the intuitive and self-explanatory design of the HP’s interface and its controls (explained in detail in subsection 7.2.3 below). The MCS Best Practice Guide (MCS & RECC, 2018) highlights the main areas that should be taken into consideration for optimisation of HP efficiency. Table 7-1 below draws attention to additional or overlapping areas that were identified as requiring installer attention, through the analysis of the data collected on the 21 RHPP case studies.
Table 7-1: Best practice considerations for installers as identified through the data analysis of the 21 RHPP case studies.

<table>
<thead>
<tr>
<th>Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation location and level of insulation</td>
<td>Where possible, the internal unit of the HP should be located within the heated perimeter of the house, and cylinders and pumps should all be carefully insulated, especially where these are exposed to weather conditions. External ASHP units should be placed as close to the building perimeter as possible to avoid unnecessary pipework heat losses while taking into consideration any associated noise issues.</td>
</tr>
<tr>
<td>Location of temperature sensors and types of thermostats</td>
<td>Thermostats and temperature sensors should be sensibly located, i.e., away from draughts and heat sources, and, where possible, avoiding circulation areas (e.g., entry spaces or landings) and unheated or infrequently used rooms. It may be best to avoid portable thermostats, as they are prone to misleading readings and increased cycling, since they can be easily moved from room to room and placed in random locations or carried by people.</td>
</tr>
<tr>
<td>Room thermostat(s) and decentralized controls</td>
<td>Ensure thermostatic controls are available so that users are not forced to engage with flow temperature adjustment. The presence of multiple room thermostats enables heating differentiation (e.g., to accommodate individual preferences and avoid overheating) and is preferred to TRVs. The latter are less intuitive and are often ignored, thus relying on the original or accidental settings that may be detrimental to both comfort and HP efficiency. Where TRVs are present, they should be easily accessible, clearly labelled and their function should be clearly explained to users.</td>
</tr>
<tr>
<td>Technological advancements</td>
<td>Utilisation of the latest technological advancements, e.g., as dictated by the Ecodesign requirements.</td>
</tr>
<tr>
<td>Backup resistance heater use</td>
<td>Ensure the backup resistance heater does not come on unnecessarily and users are aware of its presence in the system and how to turn it off, if required.</td>
</tr>
<tr>
<td>Secondary DHW return</td>
<td>Consider the incorporation of a secondary return, where there is long DHW pipework between the DHW cylinder and the tap.</td>
</tr>
<tr>
<td>Rules of thumb</td>
<td>Rules of thumb should not be used for the final HP design and sizing of the HP system and its components, whether a clean installation or retrofit. Installers should carefully follow the relevant standards, e.g., MCS MIS 3005.</td>
</tr>
<tr>
<td>Extended handover</td>
<td>Consider revisiting a property a short time after the installation to ensure its smooth operation, resolve any technical issues arising, and respond to any user questions or adaptation requests.</td>
</tr>
</tbody>
</table>

### 7.2.3 User-oriented considerations

HP systems are very different to traditional heating systems that users are typically familiar with, and their controls are complicated and not well understood. Depending on the manufacturer and make, there are many controls a HP owner may experiment with, such as heat curves, timing schedules, flow temperatures and DHW/SH priority settings, often more than most users would like to know about. Given the complicated nature of HPs, allowing full access to controls may lead to unexpected outcomes or even cause chaos in the system. Indeed, many occupants...
in the RHPP case study sample were found to have taken intuitive actions that were unknowingly detrimental to their HP’s efficiency. There needs to be a fine balance between allowing some user access to controls to assist more efficient operation while preventing actions that may inadvertently have the opposite effect or cause the system to fail (e.g., through the use of smart controls and fuzzy logic). Behavioural shifts, including preconceptions, habits and previous experiences, are generally hard to overcome; however, there are steps that can be taken to encourage users to better understand how their HP can be operated efficiently.

User education and manufacturer-enabled feedback processes

Occupant education and feedback processes are critical for users that may otherwise not be able to understand the real effects of their changes on the system. In the case study sample, the instructions and documentation provided were lengthy, complex and hard to navigate through for the resolution of specific issues. Thus, occupants were usually happy with the training provided only when the HP worked well simply by just using the thermostat, as there was no need to interpret any of the complex instructions. Even though the general advice of installers was to run the HP continuously at a low and stable temperature, some users stated they would have liked more tailored information on performance optimisation. Indeed, ideal controls may be different for different dwelling types. Thus, occupants may benefit from simplified feedback processes and correctly integrated and designed controls could provide them with the information required to make sensible decisions.

User behaviour has been found to be influenced by information display on the energy consumption of appliances (Wood & Newborough, 2007). The promotion of self-monitoring in the case of HPs could be achieved through the HP’s interface, including ongoing SPF measurements, summary statistics/reports and system status indicators. Such feedback processes could encourage better performance and the timely identification of critical system features while restricting the inadvertent actuation of controls that may lower the system’s efficiency. This could be further encouraged with simpler and more intuitive design of the controls, such as the incorporation of clearly identifiable alerts (e.g., a large red button that lights up) when the system’s backup resistance heater is enabled, more straightforward instructions both for occupants and installers, and raising consumer awareness, e.g., with regards to the presence of an incorporated resistance heater and under which circumstances its use is triggered.

Minimising ventilation heat losses

Minimising ventilation heat losses is important for the efficient operation of a HP. However, the limited ventilation requirements, combined with increased air-tightness and insulation standards
in newbuilds, alongside indoor clothes-drying habits and the restriction of heating to the main living areas (negative spatial rebound) that was common in larger properties, may create conditions more favourable for condensation and mould. MVHR is often considered a good alternative for the prevention of uncontrolled ventilation, however, the analysis of data collected from case studies utilising such systems in the RHPP sample revealed that this may not be achieved if technical problems emerge, including issues with noise and draughts. Several technical problems disrupting the operation of the widely utilised kitchen and bathroom extractor fans were encountered. Other parameters, such as cultural norms and habits, including the need for prolonged access through windows and doors for pet access and electric vehicle charging, which is likely to be encountered more frequently in the near future, should also be taken into consideration as they are not affected by the presence or not of mechanical ventilation.

**Managing expectations**

While offering motivation so that user behaviour gradually shifts to suit more the complexity of HP technology, it is also important that user expectations are managed and this needs to be taken into consideration when discussing new heating systems with installers and in the guidance provided. Prospective buyers should be aware that an efficient HP is not necessarily linked to low running costs under all circumstances and that savings in comparison to counterfactual heating systems will vary depending on the type of system considered (e.g., gas boilers, oil boilers or storage heaters). As a central heating system and due to their more continuous operation, HPs tend to inherently increase energy consumption. A positive rebound effect, whereby theoretical savings translate into increased comfort, is often confused with a perceived inefficiency of a HP. However, whole heating of a larger house with a well-performing HP might be very expensive to run and the actions taken by occupants to counteract this need to be chosen carefully to avoid unintended consequences. For example, it is highly inefficient to use such a HP for individual room heating.

Prospective users should also know that a HP, being a slow-responsive system, will take a long time to heat up a cold house and that swift changes will generally not be realised, and they may even trigger the system’s backup resistance heater. In addition, a HP typically produces SH at a higher efficiency than DHW. However, the efficiency of both the SH and DHW produced by a HP will always be higher than that of any resistance heater, whether embedded or standalone. Thus, the installation and use of resistance heating in parallel with a HP is likely to be detrimental for overall energy consumption due both to its low efficiency and its impact on HP efficiency (through a significant heat load reduction). Any other direct heating method, such as wood fires, may also affect HP efficiency in the same way.
Overall, the rated efficiency of a HP is based on standard tests and depicts a very different performance to field measurements, both of which can be very different to what the occupants perceive in real life. Occupant-perceived performance is much more subjective, as it may be influenced by the fine balance between the desired SH/DHW availability and their affordability, as well as their general experience with the HP system. Thus, the performance perception of the same HP can be very different for different users. Raising awareness around the parameters feeding this gap would help minimise disappointment arising from unmet consumers expectations.

### 7.2.4 Field study challenges and lessons learnt

The technical monitoring of HP performance and the associated variables is key to our understanding of HP operation. However, the combined analysis of the qualitative and quantitative socio-technical data on the 21 case studies investigated as part of this study revealed that the monitoring data and metadata alone cannot provide sufficient clarity. This is due to the uncertainty associated with the monitoring quality of the technical aspects, as well as with the underlying social aspects that influence performance.

**Areas for improvement in the monitoring process**

The analysis of metered parameters and the associated metadata available for the RHPP case studies revealed a significant number of anomalies and uncertainties that hindered interpretation and undermined the understanding of the behaviour of the HP system. These included missing variables (planned or unplanned) and inconsistent or implausible readings, as well as limited and often unreliable metadata. Of course, all monitoring data are expected to be imperfect to some extent, however, careful planning and processing is necessary to eliminate both systematic and random errors while increasing the validity of the metadata as much as possible (Lowe et al., 2017b).

A close examination of the HP installations in the case study sample revealed improper installation of the monitoring equipment and lack of understanding of which variables should be monitored (Lowe et al., 2017a). Such problems may occur due to the lack of or inadequate training of installers, as well as the presence of multiple contractors, whose practices may vary significantly. Table 7-2 draws attention to those areas of current monitoring practices that could be improved, as identified by the analysis of the monitoring data and metadata available on the 21 RHPP case studies. Ensuring a high monitoring quality is important not only for the statistical analysis of the derived data but also for the robust selection of case studies and their combined analysis (Lowe et al., 2017a). The importance of a holistic approach to the investigation of the HP performance in the field is discussed in the following paragraph.
Table 7-2: Areas for improvement in current monitoring practices.

<table>
<thead>
<tr>
<th>Area for improvement</th>
<th>Suggested action</th>
</tr>
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<tbody>
<tr>
<td>Identification and inclusion of critical variables of the planning stage and data redundancy</td>
<td>Include critical variables that enable the identification of causal relationships and ensure data redundancy to enable verification of data quality. Such variables missing from the RHPP dataset included indoor and DHW tank temperatures; overall household energy consumption; the energy produced by RES and, crucially, by the backup resistance heaters (in-line heaters were not metered and immersion data were often missing). As an example, indoor temperature readings can provide insights into the system’s backup resistance heater use, window-opening frequency, or the presence of erroneous data.</td>
</tr>
<tr>
<td>Contractor commissioning</td>
<td>Commit to a limited number of contractors and focus on achieving higher training effectiveness and greater consistency in terms of monitoring equipment and their installation.</td>
</tr>
</tbody>
</table>
| Installer training | Ensure installers have a good understanding of: (a) the wide range of installation configurations that may be encountered (including multiple and SH-only HPs) and the variables of interest to avoid unintentionally unmetered variables, accidental sensor interchange, or misplaced sensors.  

(b) what comprises good monitoring practice, including proper sensor placement, i.e., to avoid improper equipment installation, and placing them in close proximity to other emitting pipework in the case of temperature sensors. |
| Equipment selection | Carefully consider the range of possible heat outputs in the sample to avoid heat meter pulse frequency limitations restricting data recording. |
| Equipment calibration | Systematic errors, such as those occurring in relation to heat meters as a result of use of glycol-based additives are best eliminated with appropriate equipment calibration, otherwise an on-site investigation would be the only possible way to enable a detailed elimination of the sources of bias. |
| Monitoring data reliability | Ensure availability of a strong wireless signal and enable frequent data transmission and plausibility testing to avoid transmission errors, rectifying any arising data issues arising, e.g., in relation to flat sensor batteries and faulty sensors. |
| Metadata adequacy and reliability | Consistent and careful recording (across all sites) of critical information likely to influence performance, reflecting both the HP and the boundary surrounding the HP installation, including known data incidents, such as HP breakdowns and flat batteries, and any exceptional features of the system. In many cases, the metering database errors identified had been carried over from the MCS certificates, highlighting the need to assess critically the information carried over. |

The importance of a holistic approach
In addition to the reliability of technical monitoring, background information on a socio-technical level is critical for the understanding of the monitored variables. This includes allowing performance investigation on different levels, i.e., large population data gathering, as well as looking into individual case studies and performing in-depth site investigations (Lowe et al., 2017a). The incorporation of different data sources increases data redundancy, which enables
data triangulation and improves the overall accuracy of findings. It also supports the identification of unique system features (e.g., aspects of the HP installation and performance) that cannot be included in the metadata of large trials or confidently identified through their monitoring data (Lowe et al., 2017a). The holistic assessment of the HP installations in this study, i.e., through the incorporation of qualitative and quantitative socio-technical data, portrayed a significantly broader context and enabled a deeper understanding of aspects influencing the performance of HP technology in the field that would not be achieved through the technical monitoring alone. In this study, the in-depth investigations that complemented the monitoring data took place in the latter stages of the large field data analysis. However, case studies can also prove useful during the early stages of large-scale monitoring to help ensure that the data collected are of sufficient quality (Lowe et al., 2017a).

7.3 Suggested future course of action

This study’s outcomes derive from the analysis of 21 case studies and are not meant to be generalised but rather provide a deeper understanding of HP performance in the UK and insights into the reasons for the existence of well- or poorly performing HP systems. Different case studies or other types of studies in future work may raise additional or even contradicting aspects and realisations about HP systems and their interaction with their wider environment. This section interprets the study’s findings and proposes a future course of action in the light of Donella Meadows’ ‘Leverage Points’ (Meadows, 1999) for systems analysis. Meadows defines leverage points as “places within a complex system where a small shift in one thing (a corporation, an economy, a living body, a city, an ecosystem) can produce big changes in everything”. The identification of leverage points requires a deep level of understanding of the existing system structure and actions to be taken in order to deal with the problem source rather than the symptoms (D. H. Kim, 1992). In this study, the following high-leverage interventions proposed derive from the systems thinking qualitative model described in Chapter 7 and focus on the identification and elimination of key factors that impede domestic HP performance:

1. Ensuring quality installation and appropriate control through behavioural change.
2. Enabling feedback about system performance (raising awareness and eventually enhancing existing feedback loops).
3. Allowing the incorporation of smart controls (enable additional feedback loops).

For HP systems, as with many other technologies, the priority should not be the generation of marketable products but of quality installations that will lead to well-performing HP systems. The first step in this direction is ensuring technical competence of all relevant technicians (plumbers,
electricians, builders etc.) through training. Encouraging a mental shift for both technicians and users, e.g., gradually driving them away from practices utilised with traditional heating systems, is equally important. Only then should a higher uptake of HP technology be considered. At the same time, prioritising quality over quantity is expected to lead to a lower initial uptake of a higher proportion of well-performing installations, which in turn is likely to stimulate market growth. However, letting go of the old mind-sets, which are not suitable for this technology and in need of change, takes time.

In addition, designing a system properly is easier than rebuilding or fixing a system and this necessitates knowledgeable stakeholders. The investigation of the existing systems in the RHPP case studies facilitated a deeper understanding of the relevant limitations and bottlenecks to well-performing HP systems on different levels, i.e., technical installation, building fabric and user behaviour. However, there is no point in trying to perfect every little aspect thought to affect HP performance within these boundaries. This would be both very expensive and time-consuming. On a policy level, attempting to implement changes by focusing on the improvement of individual influencing parameters is likely to bring little change. The detailed parameters of a system are not as important as system goals that require behavioural change. However, focusing on behaviour change is eventually expected to induce deep changes to the system’s architecture.

User behaviour change requires both educational and feedback processes. Training is traditionally provided through interaction with the installer and the provision of detailed instructions in the form of manuals that are often too lengthy and technical. While the provision of straightforward instructions would still be useful to some extent (e.g., to provide an overview of the system, raise awareness on critical system features and offer simple problem-solving solutions), generic advice is not likely to be particularly helpful for performance optimisation, since it depends on the individual characteristics of each site, which may differ significantly. Users are more likely to benefit from simplified feedback processes provided through the system’s interface and the promotion of self-monitoring. Enabling feedback processes (e.g., through ongoing and real-time system status indicators and displays providing summary reports and statistics on the system’s efficiency and other critical aspects) can have a significant impact on user behaviour and facilitate the timely identification of technical issues or actions that are likely to be detrimental to the system’s efficiency. This could include information on the operation of a backup resistance heater, the likely impact of setting changes and insights through the monitoring of internal temperature, e.g., addressing window opening as the possible cause of temperature fluctuations. The feedback processes would be further enhanced through the intuitive design of controls.
In addition to feedback processes, technological advancements, such as optimisation or smart controllers, are extremely useful in hiding complexity and bypassing the user to a certain extent by self-organising and adapting to changing conditions in real time. Smart controls can learn from occupant preferences and the building’s behaviour to allow performance optimisation that suits individual household preferences while interacting with signals from grid suppliers to achieve demand-side management and offer higher efficiencies at a lower cost. They are also integral to hybrid HP installations, as they can automatically switch between electricity and other fuels, such as hydrogen. Hybrid HP installations are currently seen as attractive interim solutions that can be particularly useful in familiarising the public with HP technology while offering the best of both worlds (CCC, 2018, 2020b).

Rethinking the rules governing the installation of HPs involves careful reconsideration of the processes relating to the installation of HPs, including testing processes, government incentives and certification schemes and standards. Table 7-3 summarises the relevant areas identified through the analysis of the data collected from the RHPP case studies:
<table>
<thead>
<tr>
<th>Area for improvement</th>
<th>Suggested action</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General policy direction</strong></td>
<td>Prioritise quality of HP installation over quantity.</td>
</tr>
<tr>
<td><strong>Installer training and certification</strong></td>
<td>The currently limited base of qualified installers needs to be urgently expanded, however, better installer training and certification schemes are required to ensure quality assurance for installers and avoid a situation where the incentives available are taken up with a view to increasing profit while compromising quality. The training process should also include regular knowledge updates.</td>
</tr>
<tr>
<td><strong>Incentive rules</strong></td>
<td>Financial incentives should be offered to those that need them to avoid risks associated with an extreme positive rebound effect. Consider incentive arrangements, where the financial benefits, or part of them, stay with the user to increase acceptability. Target groups that are likely to benefit the most from a HP installation, <em>i.e.</em>, involving minimal disruption, costs, social barriers, and risks associated, such as off-gas grid newbuilds. Fewer risks present higher chances of a well-performing HP. Creating a base of well-performing HPs is likely to lead to higher public acceptance rates while the technology itself and the associated technical skills and unit costs are all improving to support further uptake in a wider range of market areas.</td>
</tr>
<tr>
<td><strong>Retrofit installations</strong></td>
<td>Better controls required to ensure quality of retrofit installations that utilise pre-existing heat emitters without appropriate sizing calculations or avoiding their replacement due to cost/aesthetic restrictions.</td>
</tr>
<tr>
<td><strong>Underlying heat loss calculation reliability</strong></td>
<td>Ensure that the heat-loss calculations underlying the HP-sizing processes (MCS calculator, EPC etc.) are based on solid algorithms and assumptions, and work with EPC surveyors and HP installers to minimise erroneous input and increase reliability.</td>
</tr>
<tr>
<td><strong>Building efficiency upgrades</strong></td>
<td>Invest in a strong technical skillset of builders and insulation experts to avoid insulation application defects that may compromise building fabric efficiency. This is particularly important due to the need for extensive retrofitting of existing UK domestic stock to meet the UK’s carbon reduction targets.</td>
</tr>
<tr>
<td><strong>DHW load assumptions and heating patterns</strong></td>
<td>Since higher DHW fractions negatively affect HP efficiency and the DHW heat load is becoming more prominent due to the increasing insulation standards, more attention should be paid to the DHW heating methods utilised and the development of a reliable methods for the incorporation of DHW load in the sizing calculations that will ensure adequate and efficient DHW provision.</td>
</tr>
<tr>
<td><strong>Lifestyle compatibility</strong></td>
<td>Putting people at the heart of the technology uptake by respecting social norms and ensuring compatibility with daily routines. Hybrid HPs may be particularly attractive from this perspective.</td>
</tr>
<tr>
<td><strong>Social housing</strong></td>
<td>Ensure the technology is not forced on social-housing tenants, actively involve them in the decision-making process and respect their needs and decisions.</td>
</tr>
</tbody>
</table>
Chapter 8: Conclusions and Recommendations

This chapter outlines the conclusions of this research study, as they emerged from the analysis of the main findings presented in Chapter 7. In particular, section 8.1 outlines the main research findings, section 8.2 discusses the impact assessment of the suggested future course of action, section 8.3 discusses the research’s original contribution to knowledge and the associated limitations, section 8.4 proposes future work recommendations and section 8.5 proposes dissemination activities.

8.1 Research Findings

This research study has sought to understand the factors responsible for the underperformance of HPs in the field, in comparison to their predicted performance, as well as the ways in which HP field tests could be improved. The findings of the study support the hypothesis that HP performance relies on an extensive network of complex socio-technical system interactions and that there is indeed space for improvement in the current field test practices of this complex technology.

In support of the increasing interest of existing literature in the examination of HP performance from a wider perspective (Fahlen, 2008; Kirsten Gram-Hanssen et al., 2017; Marek Miara et al., 2014; Riviere et al., 2011), this study has uncovered a wide range of interconnected areas influencing HP performance, ranging from the strictly technical aspects and assumptions about the system to a variety of boundary conditions acting within the building envelope and including interactions with the household.

In particular, the study has identified key performance-influencing variables in the following areas:

- **Household SH and DHW heating practices** – these refer to HP controls/adjustments and standalone supplementary heating methods that are likely to increase energy consumption, be detrimental to HP efficiency and may often (but not only) be employed in a balancing act between the desired SH availability and perceived high electricity bills.

- **Bill affordability and the role of confounding factors** – these relate to actions taken by occupants, often seeking to reduce energy bills, presenting unforeseen interconnections that may lead to unexpected outcomes. Such actions may be reinforced by the lack of
transparency relating to HP efficiency and the energy consumed by individual household appliances, as well as the intuitive nature of heating practices that are used widely with traditional heating systems and may lower HP efficiency and increase overall energy consumption, contrary to user expectations.

- **Heat loss uncertainty associated with ventilation patterns and building thermal characteristics** – heat loss uncertainty is tightly linked to sizing calculations but may also stem from the imperfect application of building retrofits, cultural norms and embodied habits relating to window opening patterns. **Technical characteristics and considerations** – the plethora of technical issues encountered (many of which had been present since handover), the extensive use of a system’s resistance heater (primarily for DHW heating purposes) and the delays in resolution of problems imply poor technical competence of installers who often appeared unable to detect/resolve issues as straightforward as the accidental initiation of the system’s backup resistance heater.

- **Technical problem resolution and control optimisations processes** – the findings indicate that ‘self-monitoring users’ and ‘technical savvies’ who have the skills required for the identification and/or resolution of technical issues are more likely to be associated with higher HP efficiencies.

Several concerns were raised regarding the reliability and suitability of the existing rated efficiency indicators, sizing calculations and the selected control strategies. Rated efficiency indicators typically reflect SH efficiency; thus, it is usually not clear what the combined efficiency of a HP providing both SH and DHW is. As there is currently no generally agreed method for the incorporation of DHW into sizing calculations, there is also uncertainty around the adequacy of the designed DHW provision and the predicted overall system efficiency. However, DHW heat load can be a major driver of efficiency reduction, particularly due to the increasing thermal efficiency of the domestic stock. In addition, the great variation in control strategies implemented in real life, for both SH and DHW, make it even more difficult to predict the system’s efficiency while it is not certain which of these strategies would best suit the individual building and household characteristics of each site.

Ample space for improvement was also identified in the current field measurement practices of HP technologies, drawing more attention to the need for better planning and processing. Looking back at the RHPP monitoring campaign, it would probably have been more useful to prioritise quality over quantity, i.e., work with a smaller field trial to achieve higher monitoring quality and/or start with a small pilot study. Crucially, both this study and the RHP project (Lowe et al., 2017c) have highlighted the importance of adopting a more holistic approach. This is because the technical monitoring data cannot be understood well in isolation. The combined
analysis of qualitative and quantitative socio-technical data from both field monitoring and in-depth investigations enables the analysis of performance from different perspectives, increases data redundancy, improves finding accuracy and enables the identification of unique system features woven into the broader context that cannot be identified through technical monitoring alone.

As outlined in section 7.2, the practical implications of those findings in the aforementioned areas have been considered and several of initiatives have been prioritised as part of a future course of action. Overall, the RHPP work has indicated that domestic HPs currently appear to operate at a wide range of efficiencies, however, in accordance with previous studies (Dunbabin et al., 2013; EST, 2013; Roy et al., 2010), the higher end of their performance indicates that a raising of standards in terms of design, installation and control can lead to high-performing HPs in the UK.

8.2 Impact Assessment on the Suggested Future Course of Action

The future course of action detailed in section 7.3 suggests a slightly different strategy to that employed by the current government, focusing more on building pathways to improve the overall quality of HP installations in the UK in the first instance and then on accelerating their uptake. This would require careful consideration of all current expert practices relating to HP installations and their boundary environment, the incorporation of user-oriented technological advancements and policies supporting quality assurance and behaviour change. The prioritisation of quality installations might be linked to a lower initial uptake, however, once a critical mass of well-performing HPs is installed, market growth is expected to be self-stimulated due to the market reaching "the minimal share of users, which is necessary to make the choice of this technology the best response for any remaining user" (Keser, Suleymanova, & Wey, 2012).

A slower initial adoption rate of high-performing HPs will have a positive but slightly delayed impact on HP uptake. However, the HP installations involved are expected to be more robust and thus produce a higher average ratio of renewable heat output to energy input, which will offset to some extent the impact of a higher HP uptake but at a lower overall quality. This slower initial phase, focusing on market areas that enable the installation of HPs at the least cost and disruption and with fewer social barriers, will enable the gradual incorporation of improved technological features and technical skills while supporting the domestication of HPs and stimulating increased competition and cumulative production. This strategy will eventually serve a steadfast market growth of high-performing HPs. On the contrary, a forced acceleration,
leading to a domestic HP stock of questionable performance, might in fact delay uptake due to the associated distrust.

Ensuring a highly efficient stock of domestic HPs in the long run is of key importance, as it will enable more energy and carbon savings to meet the UK’s emission reduction goals. Under the current grid electricity fuel mix, HPs might not be the cheapest or most carbon-efficient heating technology but this is set to change as the proportion of renewable grid electricity grows (CCC, 2019a). Grid decarbonisation, smart grids and demand-side management will contribute towards HPs becoming increasingly more competitive in relation to traditional heating systems. However, gas subsidisation and the fact that electricity bears the full cost of decarbonisation currently act as barriers towards the HP competitiveness against gas-fired heating (CPLC, 2020). As HPs become more efficient, they will enable more savings, thus becoming more attractive to consumers. Even if the carbon reduction potential of HPs is somewhat curbed as a result of direct and/or indirect rebound effects, HPs will still be the only heating technology that can provide a heat output multiple times in excess of its electricity input and thus prioritising their performance improvement and, as a result, their uptake, is key.

Given the complex mechanisms and wide range of factors that are likely to influence HP performance, as well as their increasingly important role in a Net Zero future, it is suggested that this work will be of interest to:

- Policy makers, such as Government departments and other regulatory agencies who are responsible for the introduction and development of policies and regulations relating to the incentivisation and installation of domestic HPs in the UK, as well as those involved in the training and certification of HP products and installers.
- Research institutes and testing laboratories investigating HP performance.
- Installers and manufacturers of HP systems and their components.
- Trade associations representing manufacturers and HP distributors.
- Builders, designers and housing associations involved in building retrofit projects and/or the design of domestic developments.
- Social landlords and housing managers who oversee HP installations.
- HP users seeking to improve their understanding of HP operation.

### 8.3 Contribution to Knowledge and Limitations

This work took a pragmatic approach to examining performance variation of domestic HPs in the field through the integration of quantitative and qualitative socio-technical data. In achieving
the stated research aims, the study makes an original contribution to knowledge in the field of domestic HP in the following ways:

- Mapping for the first time the full range of the parameters influencing HP performance based on an extensive range of interacting boundaries.
- It is the first study in the field to utilise systems thinking as the integrating framework for the interpretation of data collected through field monitoring and in-depth site investigations, leading to the identification of a complex network of underlying interconnections.
- The detailed and comprehensive overview of influencing variables and interconnections enabled a deeper perspective on performance influencers and achieved new insights into the requirements for well-performing HPs.
- Identified key performance influencers and developed a qualitative model that served as a framework for the prioritisation of critical initiatives that formulated a suggested course of action.
- Offered a comprehensive assessment of RHPP technical monitoring practices and highlighted the importance of a holistic assessment in the performance investigation of complex technologies, such as the HPs.
- Detailed recommendations were formulated based on the study’s findings, addressing a wide range of stakeholders involved in the testing, monitoring, installation and use of HPs.

As explicitly stated in the final RHPP report (Lowe et al., 2017c), neither the case studies, nor the larger RHPP sample are thought to be representative of the domestic HP stock in the UK. This also applies to the findings of this study that are specific to the 21 case studies investigated and which are not meant to be generalised but provide a deeper understanding of domestic HP performance in the UK. This was achieved through a multiple-case study approach, which is generally considered more robust and reliable since it enables the unique contexts of several case studies to be considered. However, the generalisation potential of the causal relationships identified still needs to be confirmed through further research. Some distinctively important biases in the study include the involvement of occupants being restricted to those spending most of their time at home, and the lack of interviews with installers and RSLs that could provide valuable insights from their perspective and experiences. The more subtle biases that may stem from possible misconceptions, misinterpretations or miscommunications between the occupant and the researcher were counteracted to some extent by triangulating between data sources and data collection methods. Overall, the study examined HP performance from a more holistic perspective, considering the wider environment a HP is installed within. However, the time
restrictions during the site visit investigations inevitably limited the amount of socio-technical data collected, restricting to some extent the understanding of the complex HP system and the wider environment it interacts with. Further information on the study limitations and delimitations can be found in sections 1.3 and 3.5.

8.4 Recommendations for Future Work

Based on the issues discussed in this thesis, several gaps were identified in existing knowledge, suggesting opportunities for future research. These concern primarily further work relating to the key influencing areas identified, as well as the verification of findings against the wider UK HP population and the extension of the investigation to other HP populations:

- **HP installation target groups** – Future work could investigate which properties/users are most suitable for the installation of HP, *i.e.*, where they are more likely to operate on higher efficiencies and lower costs.

- **Control strategies for SH and DHW** – It is currently not certain which is the most suitable SH control strategy (*e.g.*, continuous or intermittent) per building and household type, and such an investigation of best suited HP-running patterns could also extend to hybrid HPs. The same applies to DHW control strategies.

- **DHW sizing calculations** – More work is needed on HP-sizing calculations to enable the incorporation of detailed DHW-sizing calculations that will ensure sufficient DHW production at higher efficiencies.

- **Heat load reduction** – The emerging issues of socially-induced heat-load reduction could be investigated further in terms of its impact on the HP efficiency.

- **Damp and mould risk** – There is some indication that HPs may create conditions more favourable to the development of damp and mould (*e.g.*, due to the increased requirement for air-tightness) and the exact conditions and likelihood of this could be investigated further.

- **Utilising mechanical ventilation** – Examining the extent to which the presence of mechanical ventilation could prevent uncontrolled ventilation through window opening.

- **Finding generalisation** – Since the current findings are specific to the case study sample they derive from, future work could investigate the extent to which they could be generalised, *i.e.*, future deductive research could be informed by the current inductive research.
• **System dynamics** – The framework for the model that serves the improvement of HP performance is now in place. Future work could focus on the formulation of algorithms enabling a detailed system dynamics simulation to investigate the relative impact of individual variables.

• **Extending the scope of the study** – The holistic methodology established could be utilised in studies beyond the UK and/or include HP populations with different characteristics (e.g., hybrid HPs).

### 8.5 Dissemination Activities

The findings of this study will be disseminated to the wider academic community through publications in peer-reviewed academic journals and conference presentations or posters. Each of the following key publications focus on areas of the study that can be valuable for different stakeholders (e.g., policy makers, installers and homeowners). The list includes provisional titles and target journals, as well as conferences relevant to the area of the research study:

**Provisional title**: Domestic heat pump performance: understanding the complex network of underlying interconnections  
**Target journal**: Energy Research and Social Science

**Provisional title**: Domestic heat pumps: user behaviour as a performance driver  
**Target journal**: Energy Efficiency

**Provisional title**: Exploring the role of professional installers in achieving high quality domestic heat pump installations in the UK  
**Target journal**: Building Research and Information

**Provisional title**: Heat pump monitoring practices: lessons learnt from a UK heat pump field trial  
**Target journal**: Energy and Buildings

**Conference submissions**:

- **11th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL'22)**, June 1-3, 2022, Toulouse, France (contribution accepted)
- System Dynamics Society, **40th International System Dynamics Conference (ISDC)**, 18-22 July 2022, Frankfurt, Germany (contribution submitted)
- **32nd European Conference on Operational Research (EURO 2022)**, 3-6 July, Espoo, Finland (contribution accepted)
References


Combination Hybrids Gas Boiler and Heat Pump A simple English stock model of different heating system scenarios Authors Corresponding Author


BSI. BS EN 14511-1:2018 Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors - Part 1: Terms and definitions (2018).

BSI. BS EN 14511-2:2018 Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors - Part 2: Test conditions (2018).

BSI. BS EN 14825:2018 Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance (2018).


DECC. (2015a). *Green Book supplementary guidance: valuation of energy use and greenhouse...


The impact of housing energy efficiency improvements on reduced exposure to cold — the ‘temperature take back factor.’ Building Services Engineering Research and Technology, 32(1), 85–98. https://doi.org/10.1177/0143624410394532


