Exploring home heating practices:

A social and technical analysis of space heating with hybrid heat pumps operated by smart controls

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

Abstract

The adoption of heat pumps (HP) with smart heating controls (SHC) for demand response (DR) is expected to play a critical role in the decarbonisation of heat in the UK. It could successfully contribute to electrifying the heating demand and adapting it to the variable generation of low-carbon electricity sources. However, in most cases, these technologies optimise the provision of heat considering only one input from householders: their minimum temperature preferences for each time of the day. This approach implicitly assumes that householders are only concerned about minimum temperatures and times, and, moreover, that these are non-negotiable requirements. This thesis explored these assumptions by analysing heating practices with smart heat pumps in a case study developed by the industry sponsor. The study takes a Social Practice Theory (SPT) approach and uses mixed methods, combining householders' recounting their experiences with the technologies, monitoring key physical environmental variables and analysing householders' communications with the customer service team (CST).

The investigation found that for the technologies to operate as designed, they require adapting heating practices, which does not always happen. The operation of these technologies affected parameters that play a critical role in the existing practices. In particular, the analysis measured lower flow temperature and average heat output, longer and different heating times, less temperature oscillation and less temperature drop during non-warmth requested periods. Some of these parameters define the meanings of comfort and/or the know-how to minimise waste. Changes in them generated conflicts and led to householders' actions to manually operate the system, which reduced its capacity to forecast the heating demand. Therefore, this thesis highlights the need to consider the complexity of the existing heating practices and develop technologies that are more aligned with them. Moreover, the findings suggest the importance of developing strategies to help householders transform these practices.

Impact statement

This research has investigated domestic heating practices with hybrid heat pumps and smart heating controls for demand response. The work mapped some of the new aspects of the indoor conditions and the running of the heating system after the adoption of the technologies and explored the householders' reactions to them. This analysis has also explored the evolution of heating practices, identifying different trajectories for them, mainly linked to the adoption of new expectations for indoor conditions and heating running times and the delegation of the control of the heating activity to the algorithm. The work has the potential to impact a wide range of stakeholders in the areas of research and industry (heat pump and heating controls installers and manufacturers) and, to a lesser extent, policymakers.

The research findings have several implications for academic research. The measurement of certain aspects of the indoor conditions and the heating operation has confirmed the findings of previous modelling or climate chamber studies on the topic. At the same time, it has contributed to understanding why some of these changes are accepted and others are not. It has also demonstrated the importance of the changes beyond comfort. For instance, the study is the first to explore in detail the understandings of waste in heating practices and how new technologies challenge them. It is hoped that these findings will trigger further academic research on the topic. The research is also expected to contribute significantly to industry. The study helps to better understand how householders use the controls and their expectations for the new heating system and indoor conditions. The research should contribute to developing heating controls that are more relevant for householders, helping them navigate the energy transition and providing them with what they want. Some of these findings are also expected to contribute to improving the existing policies for heat pumps and smart heating controls and help the United Kingdom (UK) to meet the installation targets for the technologies by helping policymakers to develop new tools that help householders to avoid some of the conflicts identified in this research.

The research reported here has already been shared with academics, industry and policymakers. The findings have been presented at different research events organised by the Energy Resilience and the Built Environment Centre for Doctoral Training (ERBE CDT), and the pilot study developed to test some of the methods used in the PhD has been included in a peer-reviewed conference paper (see Martin-Vilaseca *et al.*, 2022) and presented at the ECEEE 2022 conference. The research has been extensively discussed with the industry sponsor through regular meetings with various departments. Additionally, a presentation was given to the team responsible for developing the new smart heating platform, and feedback was provided on the design of the new app to the team responsible for that. Finally, the findings have been presented in meetings with two different groups at the Department for Business, Energy & Industrial Strategy (BEIS).

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Moltes gràcies.

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Abbreviations

ASHP Air Source Heat Pump

BEIS Department for Business Energy and Industrial Strategy

BREDEM Building Research Establishment Domestic Energy Model

CH Compact Hybrid heat pump

COP Coefficient of Performance

CRM Customer Relationship Management

CST Customer Service Team

DESNZ Department for Energy Security and Net Zero

DHW Domestic Hot Water

GSHP Ground Source Heat Pump

H Hybrid heat pump

HP Heat pump

LPG Liquified Petroleum Gas

MPC Model Predictive Controller

RHI Renewable Heat Incentive

SHC Smart Heating Controls

SPT Social Practice Theory

TRV Thermostatic Radiator Valve

1. Introduction

In 2008, the United Kingdom (UK) committed to reducing carbon emissions to 80% of 1990 levels by 2050 (HM Government, 2008). That target was increased to 100% (net zero) in 2019 (HM Government, 2019). There is broad agreement that achieving net zero requires important changes in almost all sectors, including the building sector. Buildings account for 17% of the UK's greenhouse gas emissions, and these carbon emissions are mainly driven by the energy used for heating in domestic buildings (CCC, 2020b). This is because most heating demand in the UK is met by natural gas (74%) or petroleum (10%) (CCC, 2020b). Thus, to meet the net zero aspirations, there is an imperative need to decarbonise heating.

Several technologies have been proposed to contribute to this task. Among them, heat pumps (HP) are expected to play a key role (Trask, Hanna & Rhodes, 2022). The UK government has set a target of 600,000 heat pumps to be installed annually by 2028 (HM Government, 2020b), and the Committee on Climate Change (CCC) expects that 19 million homes will be equipped with this technology by 2050 (CCC, 2019a). However, the progress made so far is slow, and the UK is at the bottom of more than 20 European countries in terms of sales of heat pumps (UKERC, 2023). According to Trask et al. (2022), several factors explain the low numbers. First, the upfront costs are higher than conventional boilers. Second, there is a lack of trained installers. Third, they require more space to be installed than combi boilers, and they might require additional changes in the house, such as installing bigger radiators or improving the efficiency of the building. All these factors are accompanied by low public awareness of this technology (Trask, Hanna & Rhodes, 2022) and criticism from parts of the media (Rosenow *et al.*, 2022). For that reason, Rosenow et al.

(2022) suggest that it is critical to build trust and consumer confidence to achieve the required levels of deployment.

Heat pumps are well-established and cost-effective technologies that can provide hot water and space heating. They are powered by electricity and can transfer heat from an external source into the building when the heat source is at a lower temperature than the building. For that reason, they are highly efficient, being able to deliver three to five units of heat for each unit of electricity used (Rosenow *et al.*, 2022). However, heat pumps operate differently from the boilers that they replace (Trask, Hanna & Rhodes, 2022), and the indoor conditions they provide might not be the same (Crawley, Wade & de Wilde, 2023). For example, heat pumps' efficiency improves at low flow temperatures, and they require longer heating periods. That means that householders need to adapt to living with a heat pump.

To overcome some of these limitations, hybrid heat pumps have been proposed. They combine a heat pump and a boiler and can operate one or the other when needed. The Committee on Climate Change (CCC) (2019b) sees them as a low-regrets option because they allow householders to get used to heat pumps while still conserving some of the functionalities of a boiler (e.g., high responsiveness to temperature changes). Therefore, the CCC (2019b) has recommended rolling them out at scale to on-gas grid areas and suggests that around 10 million hybrid heat pumps could be installed between 2020 and 2035. However, while these technologies conserve some of the functionalities of boilers, they also have characteristics of heat pumps (e.g., low flow temperatures). While they have already been successfully tested in field trials (e.g., Carter, Lancaster & Chanda, 2017), it is still unclear how they are used and integrated into the existing heating practices.

However, the challenge of getting used to heat pumps is not only for householders; it is also for the electricity system. Heat pumps are powered by electricity, so using them instead of gas-fired heating will increase the electricity load, both across the year and at times of peak demand (Love *et al.*, 2017a; Trask, Hanna & Rhodes, 2022). Indeed, it could potentially contribute to more than doubling the electricity demand of the UK before 2050 (HM Government, 2020a), which would be critical for the UK energy system. Nowadays, electricity generation is demand-driven: the generation plants are activated to match the varying electricity demand. This is only possible due to the relative ease with which fossil fuels can be stored and be ready when needed (Grunewald & Diakonova, 2018). However, this is becoming increasingly complex as more solar and wind installations are deployed. The renewable capacity installed in the UK has already grown five-fold since 2010 (HM Government, 2020a), and it is expected to continue growing in the next 25 years (CCC, 2020a). Therefore, the increase in electricity demand while supply becomes less flexible can pose a threat to the energy security of the country and can contribute to increasing the costs of the energy system (Grunewald & Diakonova, 2018; BEIS, 2021c). To avoid that, the UK government and OFGEM expect to provide additional flexibility in the system and balance supply and demand through other mechanisms (BEIS, 2021c). They suggest a combination of four alternatives: electricity storage, flexible demand, flexible generation and/or shifting electricity across grids (BEIS, 2021c).

Flexible demand, also known as demand response, is defined as a "change in electricity consumption patterns in response to a signal" (Element Energy, 2012:p.9). Demand response programs aim to reduce electricity use when demand exceeds supply and/or increase electricity use to make use of excess electricity generated by renewable sources. Demand response programs can be divided into incentive-based programs and price-based programs (US Department of Energy, 2006). The former approach involves paying customers to reduce their electricity demand at times requested. The latter offers customers time-varying rates (e.g., time-of-use (TOU) tariffs) that reflect the different costs of generating electricity at different times and assumes that users will respond to the time-varying costs by reducing electricity demand during periods of high price. While it is expected that demand response will play an important role in the UK Energy system, it is unclear which of the two strategies will be chosen. The proposal presented in the UK government road map envisions a combination of the two (BEIS, 2021c). This entails some flexibility providers remotely controlling some electric loads while others optimise energy use at the local level in response to changes in the energy price through home energy management. However, in both cases, the vision presented suggests that demand response will be automated (BEIS, 2021c; Crawley, Higginson & Eyre, 2023).

In the UK, heat pumps are expected to be equipped with some smart functionality to participate in providing this demand response (BEIS, 2021c; DESNZ, 2023a). There are many ways in which that can be done. Albadi and El-Saadany (2008) identified two types of domestic demand response with heating systems: temporarily reducing the electricity demand or shifting it. The former involves the non-provision of the service and "potentially" a loss of comfort, while the second implies that the energy service is rescheduled to other times. Commercially available demand response offerings exist for both. For example, the EVU-Sperre scheme (Bosch, 2024) in Germany allows energy suppliers to turn off heat pumps remotely, letting the temperature drop during demand response events. In contrast, Austin Energy's internet-connected thermostats (Austin energy, 2024) pre-heat or pre-cool (shifting the heat load) in advance of a demand response event to ensure that certain indoor conditions are maintained during the event. In the UK, the few commercially available demand response controls for heat pumps aim to shift the electricity demand while maintaining indoor conditions. The most well-known options are the smart energy platform developed by PassivUK and the Homely smart controller.

These types of controls usually optimise the heating operation to minimise costs or carbon. They do that through an algorithm that considers the thermal characteristics of the construction, the weather forecast and the electricity price. During periods in which there is an excess of production of electricity (and the electricity is cheaper), the heat pump pre-heats the building (e.g., thermal mass) and this heat is released during peak periods (when the price of electricity is higher) (Le Dréau & Heiselberg, 2016). Householders are required to communicate the temperature setpoint they want for each time of the day and avoid interfering with the heating controls' planned operation, allowing the algorithm to forecast the heating demand in advance: set and forget. However, that is not how householders conventionally use their heating systems. For example, according to the nationally representative EFUS study (BEIS, 2021a), 92% of households with central heating in the UK directly control the heating times, using a timer, a room thermostat or manually switching the boiler on or off when they want. Adopting smart heating controls for demand response could challenge how householders use their heating systems as they will need to delegate the control of the heating system to the new controls.

Therefore, the use of heat pumps and hybrid HP with smart heating controls in residential buildings is doubly challenging for householders. First, as explained before, the heat pump operates under a different logic and provides different indoor conditions than the system it replaces and hybrid heat pumps add variability to this operation. Second, to maximise the efficiency of the heating system, thereby minimising costs or carbon emissions, the smart heating controls require changes in how people operate the heating systems. Therefore, installing the technology is not enough to achieve the expected energy savings and provide the required flexibility to the system. Householders need to accept the new indoor conditions and heating patterns and operate the heating system in a certain way. There is very little social research on the combination of the two technologies (hybrid heat pumps and smart heating controls), and existing research has focused on specific aspects, such as the process of learning about the technology (see Parrish, Hielscher & Foxon, 2021) or the householders' reaction to the disconnection between the times when heat is requested and when the heating is on (see Hanmer, 2020). Therefore, further research is needed on householders' heating practices with these technologies, their expectations, experience, and interactions with them.

1.1. Aim of the research and research questions

The overall aim of this research is to explore domestic heating practices with hybrid heat pumps equipped with smart heating controls. By doing that, it also aims to assess the indoor conditions with the new technologies and the householders' reaction to them. The findings of the research should help to better understand how people use hybrid heat pumps with smart heating controls and what they want from them. That should help to improve these technologies, making them more relevant to the householders' needs.

The research aims to answer the following research questions:

1. What are the indoor conditions and the heating running patterns after the adoption of the new heating technologies?
2. How do people experience the indoor conditions and the heating running patterns after the adoption of the new heating technologies?
3. How do heating practices evolve as a result of these experiences?

Therefore, this thesis contributes to a better understanding of how the new heating technologies are adopted into domestic environments and how they challenge or not the existing heating practices. As will be explained in Chapters 5 and 6, the research has focused on comfort and waste-related aspects of these practices. Regarding the first, the analysis helps to understand why certain changes in the indoor conditions and heating characteristics are accepted, others are opposed and what that entails. Regarding the second, the research provides a detailed picture of the existing competences for minimising waste and identifies some of the ways in which the new technologies conflict with them. This thesis helps to understand the evolution of the performance of the heating practices as a result of those conflicts.

This research was developed in collaboration with industry. This PhD was partially sponsored by Passiv UK, a British smart controls manufacturer that develops software solutions for hybrid and stand-alone heat pumps. In terms of scope, the focus of this project was geographically constrained to the UK as this is where the industrial sponsor and the cases studied were located. The smart heating controls tested were those developed by the industrial sponsor, Passiv UK; these are outlined in the following section.

1.2. Case study: Passiv UK smart heating controls

The smart heating controls tested in this research are developed by the industry sponsor, Passiv UK. They are Model Predictive Controllers (MPC) that optimise the operation of the heating system to minimise the energy costs and the comfort costs. The process in which they do that has two steps. First, the heating controls characterise the thermal performance of the building where they are located, using temperature data collected through a room thermostat, external weather data, and information about the operation of the heating system. With that, they create a digital twin of the building that can model the effect of the heating system on the indoor conditions. Second, they carry out an optimisation calculation that considers the learned thermal properties of the building, the temperature setpoints chosen by the householders for each time of the day, the local weather forecasts, the energy costs, and the variation of heat pump and boiler efficiencies with local conditions. This optimisation function aims to minimise costs. Usually, these costs incorporate (a) any time-of-use tariff householders had signed up to and (b) the relative costs of the two fuels in the case of hybrids. However, this objective can be modified depending on the requirements of the project where the smart controls are deployed[1]. This is done by changing the price of the energy used in the calculations to reflect the objectives of the project (e.g., artificially increasing the price of electricity used in the calculations). Alternative objectives include maximising the operation of the HP in hybrid systems or minimising carbon emissions. The outcome of this function defines what heating system should run (boiler or heat pump) and the flow temperature that should be provided for each period in the following 24 hours.

The Energy Saving Trust (EST) carried out independent field trials of the smart heating controls developed by Passiv UK and found that the controls increase the Coefficient of Performance (COP) of a heat pump by 0.54 or 17% compared with standard manufacturer controls and 0.65 or 25% if the heat pump is part of a hybrid system (a system that combines a heat pump and a combi boiler). At the same time, the controls also increase the utilisation rate of the heat pump in hybrid systems from an average of 47% to 82%. However, those results have been calculated using standardised conditions and might vary depending on several factors, such as the householders' interactions with the controls.

As explained, the optimisation algorithm only considers one input from householders: the temperature setpoint for each time of the day. Householders can communicate this

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[1] More information about the specific objectives for the optimisation algorithm tested in this thesis is available in section 3.2.1.

information to the system through an app or a wall interface using two variables. First, they can schedule (through the App only) timings for IN (hereafter, referred as warmth-requested period), OUT, ASLEEP and AWAY periods (for each day of the week), which are intended to match the occupation of the house. Second, they can choose setpoints for IN am, IN pm, OUT and ASLEEP, which are applied to the occupancy periods (with the intention that OUT and ASLEEP temperatures are usually low and not relevant). Through these temperature setpoints, householders define when they want to be warm rather than when the heating system should run. However, they can also temporarily change the temperature setpoint (manually overriding the temperature schedule) until the next scheduled period, which can be done through the app or the wall interface. The controls allow remote control and monitoring by Passiv UK.

The controls are designed to be set and forget. While the system offers the opportunity to manually override the temperature schedule, it is expected that most of the operation will be scheduled, and the householder would not manually alter the temperature schedule often. This is because the more advance notice the system has of the householders' requirements, the more potential there is to (a) run the heat pump as efficiently as possible and (b) provide grid services (e.g., demand response). Hereafter, heating practices involving low levels of manual overriding will be referred to as "expected" practices.

1.3. Structure of thesis

This thesis has 8 chapters. Chapter 2 starts by introducing the technology studied: hybrid heat pumps with smart heating controls. It then analyses the potential changes it can trigger in the indoor conditions and the heating operation and reviews the existing trials of the technology. It finally introduces social practice theory, the framework used in this research.

Chapter 3 presents and justifies the research approach and the choice of methods used to address the research questions presented in Chapter 1. It also describes in detail the cases studied.

Chapters 4 to 6 present the findings of this research. Chapter 4 measures how certain characteristics of the heating system activity and indoor conditions change after the adoption of the new technologies using the technical data collected. It also analyses the householders' manual overrides of the temperature schedule. Chapter 5 looks at the experience of comfort after the adoption of the technologies and analyses how heating practices related to comfort change when these technologies are used. Chapter 6 focuses on the householders' understanding of waste and presents the conflicts that arise after the adoption of the technology. It also identifies three different trajectories for heating practices with distinguishable know-how for minimising waste.

Chapter 7 is a general discussion of the findings from the three research chapters, including the limitations of the research approach chosen and the applicability of the results to heating practices with other technologies. Chapter 8 summarises the findings and discusses the contributions of the research for academy, policy and control manufacturers.

2. Background

The research presented in this thesis aims to understand how heat pumps with smart heating controls for demand response are adopted into heating practices. However, before introducing this research in detail, it is important to understand its context and how it fits into the existing literature on the topic. This chapter aims to do that. It begins by presenting the technologies studied and their specific characteristics. Later, it explores the potential impact these technologies could have when adopted into homes, paying attention to two different aspects. First, the chapter explores the *expected changes* in heating system activity and indoor conditions after adopting the new technologies using physics principles and literature on modelling studies. Second, it discusses the *experienced changes* in heating and indoor conditions reviewing the existing social research in field trials of the technologies. Before finishing, social practice theory, the approach used in this research to understand the experience and actions of the householders, is presented.

2.1. The new heating

As explained in Chapter 1, combining the electrification of heating demand with demand-side response (DSR) mechanisms represents one of the most promising options to decarbonise the domestic sector (Skea, 2012; Grunewald & Diakonova, 2018). It is suggested as an opportunity to move away from fossil fuels while adapting the heating loads to the intermittent production of renewable energy sources (solar and wind) and reducing the need to reinforce the grid (Pratt & Erickson, 2020). Hybrid heat pumps with smart heating controls (SHC) make it possible to electrify heating efficiently and to automate DSR (Direct Load Control -DLC-), which is regarded as one of the most effective options for demand response

(Frontier Economics & Sustainability First, 2012). In the next two sections, each of these technologies will be presented in detail.

2.1.1. Electrification of heat: the case of (hybrid) heat pumps

Heat pumps are a technology used for heating with a high-energy performance. They achieve this performance because, in contrast with other domestic heating technologies that burn fuel to produce heat, they move heat from a colder space to a warmer one (Roy, Caird & Potter, 2010). In this process, they obtain heat from the environment, which is free, plentiful and zero carbon (Staffell *et al.*, 2012). Despite the recent policy interest in heat pumps, these technologies have been known for more than 150 years (Staffell *et al.*, 2012). Heat pump technologies are used in a wide range of common domestic technologies such as air conditioners or refrigerators. In these two cases, heat pumps remove the heat from one location and move it to another at a higher temperature. In contrast, in heating, heat pumps transfer heat from outdoors to a space at a higher temperature indoors.

To move heat against its natural gradient (second law of thermodynamics) from a colder source to a warmer one, heat pumps use mechanical work (Staffell *et al.*, 2012). They do that by pumping fluid through a cycle in which (1) a refrigerant below ambient temperature absorbs heat from the environment through an external heat exchanger; (2) the refrigerant is compressed, increasing its pressure and temperature; (3) a heat exchanger or condenser distributes the heat of the refrigerant to the home (e.g., internal air or hydronic distribution system); (4) an expansion valve reduces the pressure of the refrigerant, thus reducing its temperature to below ambient temperature again (Staffell *et al.*, 2012). And this cycle starts again. This process can also work in the opposite direction, removing heat from indoors to outdoors in summer (air-conditioning).

The performance of the heat pump is higher than that of other domestic heating systems. This is because while heat pumps require energy to compress or expand the refrigerant, they also absorb heat from outdoors (Staffell *et al.*, 2012). For that reason, heat pumps use less energy in the form of electricity than the heat that they provide, and their coefficient of performance (COP) can be greater than 1, and often it is between 2.5 and 3.0 (Carmichael, 2022). Additionally, as much of the heat comes from almost inexhaustible environmental sources, even with today's electricity mix, heating with heat pumps instead of fossil fuel heating technologies reduces carbon emissions compared to heating with a gas boiler (Rosenow *et al.*, 2022; Lowes *et al.*, 2020).

However, the efficiency of the heat pump is highly dependent on the temperature difference between the heat source (from where heat is obtained) and the output to the home (where heat is delivered) (Staffell *et al.*, 2012). The COP drops by 0.6-1.0 for every 10ºC increase in the difference between the two (Staffell *et al.*, 2012). For that reason, they achieve higher performances if they are set to provide low flow temperatures and are combined with large-area radiators or underfloor heating (Staffell *et al.*, 2012). Heat pumps are used to provide space heating or domestic hot water. They are usually sized for space heating. For that reason, they do not usually provide hot water on demand, and they are combined with a domestic hot water (DHW) cylinder.

Heat pumps can be classified into two main categories depending on where they obtain the heat from. Heat pumps are called Air Source Heat Pumps (ASHP) if they draw heat from the air and Ground Source Heat Pumps (GSHP) if they obtain it from the ground. GSHP are less common than ASHP in the UK and have higher capital costs (Staffell *et al.*, 2012). However, because they obtain heat from the ground, they benefit from more constant temperatures, achieving more stable performance throughout the year (Roy, Caird & Potter, 2010). Other heat sources exist, such as water (e.g., from rivers) or exhaust air, but they are less common. According to Oikonomou (2022), heat pumps can be configured in three different ways: outdoor monobloc, indoor monobloc and split systems. Outdoor monoblocs have the main parts of the system (compressor, expansion valve, etc.) installed outdoors, and insulated water pipes connect them to the main hydronic system in the house. Indoor monoblocs have the main components of the heat pump installed indoors, and they require air ducts (inlet and outlet) or pipes connecting them to the outdoor air (ASHP) or ground (GSHP). Split systems have an indoor unit and an outdoor unit. The indoor unit contains the condenser, and the outdoor unit includes the rest of the system's components.

Hybrid heat pumps

In recent years, hybrid heat pumps have been proposed as an alternative to stand-alone heat pumps because of their advantages in terms of the householder's experience and the integration of the system into the grid (CCC, 2018). The Committee on Climate Change (2018) suggests that 10 million hybrid heat pumps could be deployed by 2035 in on-gas grid buildings.

Hybrid heat pumps combine an electrically driven heat pump and a traditional fossil-fueled heater within a single control strategy (International Energy Agency, 2019). However, there are many potential configurations in which these two technologies can be combined. Element Energy (2017) classified hybrid heat pumps depending on various parameters. Regarding the hybrid configuration, they can be classified into (1) add-ons, if the heat pump is installed alongside an existing boiler; (2) integrated, when the boiler and heat pump are installed together as one product; and (3) packaged, when they are sold as separated products but installed together. Regarding the heat pump size, there are (1) oversized heat pumps relative to the heat demand and (2) undersized ones. Regarding the integration between the boiler and the heat pump (hybrid mode), Element Energy (2017) distinguishes between (1) systems in which the heat pump and the boiler never run at the same time and (2) systems in which they operate in parallel. Each of these configurations has a different impact on the performance of the system, the installation costs, the flexibility that they can provide to the grid and the outcome provided to the householders.

Combining a boiler and a heat pump with specific heating controls offers more opportunities than stand-alone heat pumps to make electricity demand more flexible during peak periods. As Hanmer (2020) explained, they can operate like a smart stand-alone HP and shift the electricity demand to an earlier time. But at the same time, the hybrid system can switch fuels between electricity and gas, using gas during periods of peak demand or on the coldest days. This double strategy could bring benefits to the grid as it might reduce the need to reinforce it or might require less additional electricity generation capacity (Imperial College London, 2018).

However, these technologies not only have benefits for the grid. Hybrid heat pumps can also be very attractive to householders. First, they allow the installation of smaller heat pumps without the need to increase the thermal insulation of the building or replace the heat distribution systems, reducing the installation costs and the disruption caused by the works (International Energy Agency, 2019; Parrish, 2021). At the same time, hybrid heat pumps conserve some of the characteristics of combi boilers, such as providing domestic hot water on demand and being highly responsive if needed (International Energy Agency, 2019).

2.1.2. Smart heating controls for demand response

As explained in Chapter 1, smart heating controls (SHC) play a critical role in managing hybrid heat pumps (fuel switching between electricity and gas) and helping to reduce the impact of the additional electricity load into the grid (Parrish, 2021; Beccali *et al.*, 2022). Smart heating controls are the last addition to heating controls for domestic heating systems, which have been evolving since the development of central heating systems in 1800 (Lomas *et al.*, 2018). Because smart heating controls are not common in the UK (5% of homes had them (BEIS, 2021b)), it is important to explain what differentiates them from other types of controls.

There exist many types of heating controls and ways to classify them. Morton (2016) distinguishes between boiler switches, central heating timers, room thermostats, thermostatic radiator valves (TRVs), programmable thermostats and smart heating controls. Some of them, such as boiler switches and timers, control the heating running times. Others, like room thermostats and TRVs, control temperatures (although they can also be manually used to control heating running times). Programmable thermostats and smart heating controls manage the temperature and the heating running times at the same time.

According to the results of the EFUS survey, most households in the UK (56%) control their central heating system using a timer (BEIS, 2021a). This timer allows them to schedule the times when the heating is on or off. Almost all the rest of the households control these times manually through a room thermostat or a switch (BEIS, 2021a). Regarding the control of heating temperatures, most households in the UK use a room thermostat in combination with TRVs (77%) (BEIS, 2021a). Both technologies allow them to define a temperature setpoint that the heating system uses as a threshold to define when to run or not. The combination of the control of the heating times and the temperatures means that householders in the UK usually have almost full control of the heating activity. However, this is not the case with smart heating controls with automation.

There is not a unanimous definition of smart heating controls. A brief look at the academic studies reveals different understandings of what defines them (BEIS, 2018): automation of its operation (e.g., Lu *et al.*, 2010; Heinen, Burke & O'Malley, 2016; Yu *et al.*, 2017; Lomas *et al.*, 2018; Miu *et al.*, 2019), optimisation of its operation (e.g., Heinen, Burke & O'Malley, 2016; Yu *et al.*, 2017), predictive/learning algorithm (e.g., Kleiminger, Mattern & Santini, 2014; Dimitrokali *et al.*, 2015; Lomas *et al.*, 2018), digital communication technology (e.g., Lomas *et al.*, 2018), remote control by the user (e.g., Yu *et al.*, 2017), remote control by the utility or the demand-side response (DSR) system (e.g., Miu *et al.*, 2019), and/or enhanced usability (e.g., Munton *et al.*, 2014). While all of these technologies are often referred to as "smart controls", the experience with them is unlikely to be comparable.

In this thesis, smart heating controls are defined as those that incorporate an algorithm that automates the control of the heating running times and temperatures to achieve a certain objective (e.g., minimise costs), and they do that based on contextual information. The contextual information can vary from the home occupation, the activities carried out by the householder, the weather, the thermal characteristics of the building, the price of electricity, etc. (Nacer, Marhic & Delahoche, 2017). The interest in this thesis, as introduced in section 1.2, is in smart heating controls that model the thermal characteristics of the building and optimise the time when the energy is consumed to minimise the costs for the householder or the environmental impact.

According to that, the main difference between smart heating controls and non-smart heating controls is the automation of the heating running times and temperatures. Although these controls usually incorporate options for the householders to overrun the automated operation, doing that makes it more difficult for the algorithm to achieve its objective.

Therefore, there is an implicit requirement to delegate the control of the heating times to the system. Many researchers have seen the difficulties in delegating control as one of the barriers to the adoption of these technologies (e.g., Rubens, S. Knowles, 2013; Balta-Ozkan *et al.*, 2013; Fell, 2016). At the same time, academics using social practice theory (SPT) have argued that the automation of heating and the way it is currently implemented might conflict with how householders currently heat and live (e.g., Verkade & Höffken, 2018; Strengers *et al.*, 2020). However, the existing evidence for how hybrid heat pumps with smart heating controls conflict or not with the existing heating practices is limited. This research aims to bridge this gap.

2.2. Expected heating operation and indoor conditions compared to boilers

The hybrid heat pumps with smart heating controls analysed in this research differ from conventional boilers that use gas, oil or LPG. They can use electricity, which can be "decarbonised", hence the interest in replacing conventional boilers with them. However, to improve the performance of the system, they also heat differently when on heat pump mode (e.g., at lower temperatures), entailing new operating patterns. When that happens, the changes can alter the indoor conditions in the buildings where they are installed. While there is no comprehensive analysis of the changes that the adoption of hybrid heat pumps equipped with smart heating controls for demand side response causes in indoor conditions, there is partial evidence of these changes in the literature. This section looks at the expected changes in the operation of the technology and indoor conditions compared to combi boilers. It does that by reviewing the academic literature on the topic, which mainly reports modelling studies or climate chamber studies. The aim is not to assess the results obtained but to present some differences between heating technologies and set the context for the analysis, in the next sections, of the findings of field studies of the technologies.

A hybrid heat pump with smart heating controls is often presented as a single piece of technology. However, it is constituted by different elements. These elements can be installed together as part of an integrated solution (compact hybrid) or installed as single pieces of technology that are connected (conventional hybrid). These elements are a boiler, a heat pump, and the smart heating controls (an algorithmic heating control for demand response). This section presents the differences that result from the addition of a heat pump and smart heating controls to a system with a combi boiler heating a hydronic system when the smart heating controls are operated with minimum interactions (as "expected"). However, the changes will be analysed separately for each technology. It is important to point out that some of the expected changes are shared between the different components of the system, and it is difficult to identify which one of the two is the main driver of change. For example, the HP requires low flow temperatures to maximise its efficiency, and this is enacted through the smart heating controls. In this review, these changes will be analysed from both perspectives.

2.2.1. Heat pump

As explained in section 2.1.1, heat pumps, in contrast with other heating systems, do not heat "directly" (transform the energy stored in a fuel into heat) but move the heat from a colder space or body to a warmer one using a compressor. They present some differences with conventional heating systems (e.g., combi gas boiler). Those differences are summarised in Figure 2.1 and can be grouped into two technically related themes: the flow temperature[2] and the heat output, and the heating duration.

Lower flow temperature and heat output

Combi boilers are usually sized to provide domestic hot water (DHW) on demand. As this requires a higher output than the space heating demand, they are usually oversized in relation to the space heating needs. Therefore, they can be operated intermittently during the day because they can react fast and bring the temperature of the space to the requested setpoint (Reguis, Vand & Currie, 2021). They are usually operated at flow temperatures between 60ºC-88ºC (Rossi & Bennett, 2024). Although condensing boilers improve their

[2] The temperature at which the boiler heats the water before sending it off to the radiators.

efficiency if they are set to provide below flow temperatures of around 55ºC (Jones, 2014) because they start to operate in condensing mode, further improvements to the efficiency of the system are limited and may be offset by a more stop/start operation which decreases efficiency (Bennett, 2019).

In contrast, heat pumps obtain part of the energy from the environment (air or ground). The efficiency of this process is affected by the temperature differential between the flow temperature of the heating system and the source temperature, as defined in the Carnot equation (Fischer & Madani, 2017). The lower the flow temperature, the higher the system's performance, which creates a strong incentive for reducing the flow temperature of the system as much as possible (e.g., 38ºC was the average flow temperature in a recent heat pump trial by the Energy Systems Catapult (2023)). Additionally, costs and space constraints make it more economically feasible to install smaller heat pumps sized primarily to meet a relatively constant space heating demand and to combine them with DHW tanks (Cantor, 2011). Consequently, when using a heat pump, the flow temperature is usually reduced between 30ºC and 40ºC (from 60-88ºC to 30-45ºC) compared to a combi boiler.

That has two consequences: (1) a lower temperature of the radiators and (2) a lower power heat delivery. The first affects the radiant heat exchanged by the radiators. With a constant emitter area (no change in the size of the radiators), the radiant heat emitted to surfaces in the direct line of sight only depends on the temperature difference between the radiator and these surfaces (Stefan-Boltzmann law) (Wang, 2016). Therefore, with the reduction in the temperature of the radiators, the radiant heat from the radiators is reduced. The second affects the temperature differences between the area near the radiator and the rest of the room, which contributes to lowering the convective air velocity within the room (Eijdems, Boerstra & Op't Veld, 2000; Myhren & Holmberg, 2008). At the same time, this change can have two consequences. First, it is likely to reduce the number of suspended particles, which, together with the reduction in the dust burnt (because the radiators are colder), contributes to improving the air quality in the house (Eijdems, Boerstra & Op't Veld, 2000). Second, it can contribute to creating broader vertical temperature gradients and more stratification because the speed of the convective cycle is reduced (the heat flux density on the surface of the radiator over which air flows is affected by the temperature differences between the radiator surface and the room, as defined in the Newton-Richmann relation (Wang, 2016)). The latter might be compensated by the longer heating duration, as will be explored in the next section.

Continuous heating or longer heating hours

As a result of the differences in the flow temperatures and the heat output, heat pumps are slower at heating (Schellen *et al.*, 2010; Crawley, Wade & de Wilde, 2023) and to provide the same amount of heat, they need to heat for longer periods (Watson, Lomas & Buswell, 2021). In some cases, it becomes more efficient to maintain the temperature during short periods when warmth is not required (e.g., when not at home) rather than turning the heating off and allowing the temperature to drop. Therefore, in contrast to the intermittent heating typical of combi boilers, heat pumps usually run almost continuously (Crawley, Wade & de Wilde, 2023). This difference contributes to higher average indoor temperature when heating with a heat pump (and increased heat losses because of the increased difference between indoor and outdoor temperatures). At the same time, it reduces the oscillations in temperature because the rooms have time to reach a temperature equilibrium. The changes in the length of heating and the higher average temperature in the building increase the heat stored in the building fabric. That serves to stabilise internal temperatures when the heating is turned off and thereby slowing the temperature drop during periods with no heating. At the same time, the temperature equilibrium reached reduces the vertical temperature gradients (cold and hot spots have more time to exchange heat), which somewhat offsets the effects of having lower convective air velocities, as described in the previous section. The exact change in the vertical temperature gradient will depend on the size of the changes in those two parameters, but some authors believe that the adoption of the technology usually reduces the vertical temperature gradients (e.g., Eijdems, Boerstra & Op't Veld, 2000; Myhren & Holmberg, 2008; CIBSE, 2014; Sarbu & Sebarchievici, 2013). Finally, the constant heating is likely to reduce the temperature differences across rooms because the heat transfer between warmer and colder rooms is not stopped until it reaches an equilibrium.

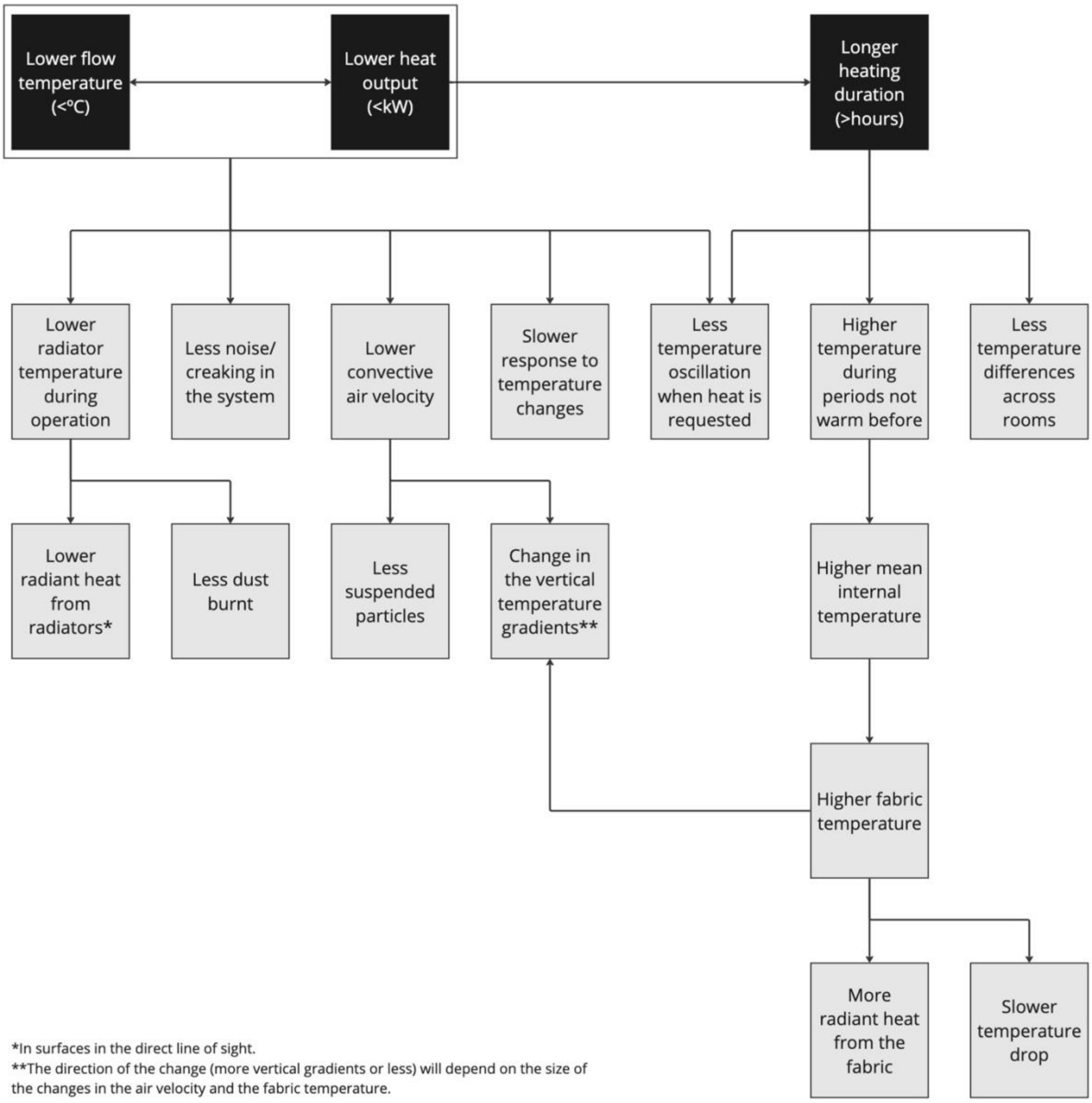

Figure 2.1. Expected changes in the operation of the heating system and the indoor conditions when replacing a combi boiler with a heat pump.
In black, the main changes in the heating system activity. In light grey, changes in the indoor conditions.

2.2.2. Algorithmic heating controls

One of the distinguishing characteristics of the heating technology studied in this research is the algorithmic heating control for demand response, introduced in section 1.2. The studied controls can optimise the operation of the different parts of the hybrid heating system (conventional boiler and heat pump) for different objectives (e.g., minimise costs, minimise the carbon footprint, maximise the contribution of the HP to the heating demand) and considering multiple parameters such as the thermal properties of the building, the temperature setpoints chosen by the householders for each time of the day, the local weather forecasts, the prices or carbon content of the different fuels used, and the variation of heat pump and boiler efficiencies with local conditions. The main differences with conventional heating controls are the number of parameters considered and the capacity of the controls to control the heating system activity (e.g., when to direct the boiler or the heat pump to operate). To achieve the planned objectives, the system uses two main strategies, which are often indistinguishable from the other: it can pre-heat ahead of the periods when heat is requested (e.g., to avoid peak periods) and heat above the temperature setpoint to be able to reduce the heating demand and therefore the costs during specific periods while ensuring that the air temperature is above the requested setpoint during these periods. Those operation strategies affect indoor conditions, for example, by increasing indoor temperatures during periods in which warmth is not requested (which increases the mean internal temperatures, the heat stored in the fabric and the radiant heat from the walls) and by achieving air temperatures above the temperature setpoint. Additionally, the algorithmic controls ensure that the minimum temperature setpoint requested at each time of the day is always achieved, which often does not happen when heating with conventional heating systems (Bennett & Elwell, 2020).

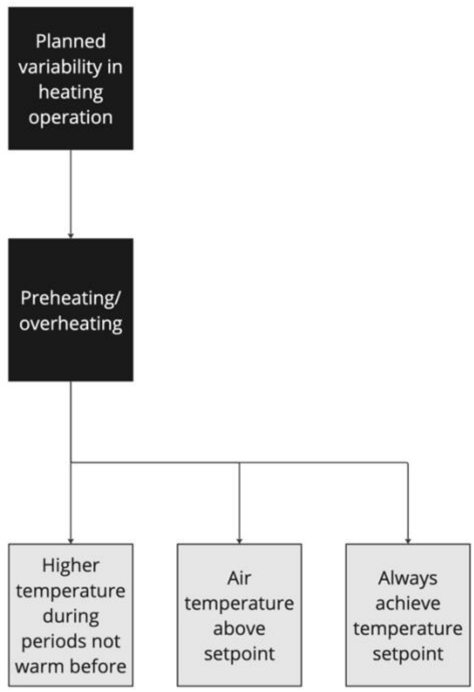

Figure 2.2. Expected changes in the operation of the heating system and the indoor conditions replacing conventional heating controls with Passiv UK algorithmic control (or a similar one) In black, changes in the heating operation. In light grey, changes in the indoor conditions.

The summary presented in the previous two sections assumes that the temperature setpoint before and after installing the technologies is not changed and that the heating technologies are operated with low numbers of manual overrides of the temperature schedule. That means that the heat pump is heating almost constantly during the heating season at a low flow temperature and that the householders program the temperature setpoints in advance through the smart heating controls and do not manually override the temperature schedule. If these conditions are met, the change in the operation of the heating system compared to a combi boiler are likely to create different indoor conditions.

2.3. Experienced changes in heating and indoor conditions

The previous section has analysed the expected changes in indoor conditions after the adoption of novel heating technologies (heat pumps and algorithmic heating controls for demand response) by introducing the physical principles that affect them and reviewing some of the modelling studies on the topic. However, the interest of this research is not in the physical changes in the indoor conditions but in how they are experienced by householders and shaped as part of the heating practices. Therefore, the previous analysis lacks one key element: people.

This section aims to review some of the studies on heat pumps and/or smart heating controls with participants using the technology in domestic settings. However, the published articles on the combination of these technologies are very limited as the research has often been more interested in analysing the barriers to the adoption of the technology or the potential grid benefits (energy savings, capacity to shift loads, etc.) than in studying the householders' experience with the technology. Therefore, the review also includes those studies that focused on just one of the two technologies, and the analysis is divided into three parts depending on the technology being tested. The review mainly focuses on studies based in the UK. This is because heating practices vary across the world (see Wilhite *et al.*, 1996; Sovacool *et al.*, 2021) and as the research in this thesis is based in the UK, the studies carried out in the UK might be more relevant and comparable. However, a small number of relevant studies from other European countries are also presented.

2.3.1. Heat pumps with smart heating controls

Heat pumps and hybrid heat pumps with algorithmic heating controls for demand response are not widespread, but they are commercially available across the world (e.g., Homely controller or PassivUK controller in the UK) and have been successfully installed in domestic buildings (e.g., Carter, Lancaster & Chanda, 2017). Despite that, the existing research on the adoption of these technologies and the householders' experience with them is scarce. Most of the reviewed research (see Table 2.1) is based in the UK and has been promoted by a single heating control manufacturer, Passiv UK, with only a few other trials in other parts of the UK and in Denmark. The fact that most of the research has been developed together with a single manufacturer raises some concerns, particularly because the variety of technologies tested is very limited, as most of the trials studied involved the same heating controls. Fortunately, these studies have different aims; different researchers have carried them out and used data obtained in different trials and populations.

Table 2.1. Summary of the studies on heat pumps with smart heating controls reviewed

Authors	Year	Sample (population of interest)	Methodology (aims)	Country
Fell	2016	23 households (social housing residents, mainly elderly)	Mixed methods: Survey (n=45) and pre and post-trial interviews (n=15/12).	UK
Sweetnam et al.	2019	76 households (social housing residents, mainly elderly, and a beta-testing group -socio-demographics not provided-)	Mixed methods: Monitoring indoor conditions (n=76), survey and pre and post-interviews (n=15/12).	UK
Hanmer et al.	2019	71 households (social housing tenants and homeowners)	Mixed methods: Analysis of the data available from the heating controllers (n=71) and semi-structured interviews (n=12).	UK
Parrish et al.	2021	Various (social housing tenants and homeowners)	Mixed methods: Initial and follow-up interviews (n=14), installation observations (n=6), installer interviews (n=2).	UK
NEDO	2017	Various (social housing tenants)	Mixed methods: Telephone survey (n=70) and face-to-face interviews (n=16).	UK
Calver, Mander and Abi Ghanem	2022	Various (social housing tenants)	Mixed methods: Face-to-face interviews with households (n=14), face-to-face interviews with staff members (n=3), documentary research.	UK
Nyborg and Ropke	2013	Various (information not provided)	Mixed methods: semi-structured interviews and house tours (n=49), a questionnaire on lifestyle and demographics, workshops and content-analysis of participants' contribution to an online forum platform.	Denmark
Nyborg	2015	Various (information not provided)	Mixed methods: semi-structured interviews and house tours (n=49), a questionnaire on lifestyle and demographics, workshops and content-analysis of participants' contribution to an online forum platform.	Denmark
Jensen, Kjeldskov and Skov	2016 2018	8 households (homeowners, middle income)	Mixed methods: semi-structured interviews (pre, during and post-trial) and home tours and quantitative analysis of householders interactions with the controls.	Denmark

Passiv UK trials

As explained before, most of the published studies on heat pumps with smart heating controls for demand response reviewed tested technology developed by Passiv UK (e.g., Fell, 2016; Sweetnam *et al.*, 2019; Hanmer, 2020; Parrish, Hielscher & Foxon, 2021). However, despite testing the same technology on similar groups of participants (mainly, social housing tenants with small groups of homeowners) who received the technology for free, the interest of the research varied from study to study. For example, Fell (2016) studied the perceived loss of control when using these technologies, as it is one of the most reported barriers to the adoption of automated third-party controls (Balta-Ozkan *et al.*, 2013). Working with a small group of participants (n=23 received the controls, but only between 12 and 13 participated in each part of the research), he found that the difficulties experienced by participants in connecting their actions with the outcomes of the system reduced their sense of control. He also found that while demand response was acceptable "in principle", the experienced problems during the trial were seen as caveats and resulted in quite negative feedback and lack of trust in the technology in some cases. Although some of these problems could be easily solved through improvements, others, such as noise and overheating at night, might be intrinsic to the provision of demand response and difficult to address. The findings are echoed by Sweetnam et al. (2019), who also reported on the same project but included an analysis of monitoring data involving a control group. They suggest that better accounting for the thermal limits of the participants or zoning heating might minimise some of the above-mentioned problems. They calculated that the average night temperature increased 1ºC compared to the previous heating system.

In addition to these studies, the technology developed by Passiv UK has also been tested in one of the main trials of hybrid heat pumps with smart heating controls in the UK, the Freedom project trial, and is reported by Hanmer et al. (2019b), Hanmer (2020) and Parrish et al. (2021). Hanmer et al. (2019b) and Hanmer (2020) were interested in the reactions to the changed temperature patterns after the adoption of the new technologies. The authors explain that the more constant daytime temperatures were positively experienced or not discussed by the participants and they echo the findings of the previously reported studies:

the increased night-time temperatures were negatively experienced in one-third of the cases (also reported by Parrish et al. (2021)). Therefore, they suggest that the assumption that householders will accept changes in the heating patterns as long as their minimum temperature setpoint is provided during the times when they request heat might not always hold. Parrish et al. (2021) interest was not in the experience of the technology but in how the process of learning about the technology could influence policy trajectories for the technology, and they provide some insights into how learning affects the knowledge, use and meaning of the technology. They suggest that the information provided by installers and available in leaflets might be contributing to some misconceptions about the technology (e.g., explaining that the heat pump is less efficient when the outdoor temperature is below a certain temperature might erroneously contribute to thinking that the heat pump is not effective at those temperatures) and shape the meanings associated with it. They also explain that these meanings are also built as a result of the householders' positive or negative experience with the technology.

Other trials

The PassivUK heating controls are not the only set of controls tested in trials of heat pumps with smart heating controls. In Denmark, Jensen et al. (2018) and Jensen et al. (2016) designed a smart heating control for the heat pump that optimised the heating operation within a temperature boundary defined by the householders. They explored the topics of convenience, control and complexity. The authors explain that the controller was well-received by the householders because they experienced it as convenient, as it was easy to operate; they trusted the system to provide their needs while still having some options to amend the indoor temperature, and it released participants from the task of shifting electricity. However, the automation of the process of decision-making and the wide range of parameters that were considered meant that householders found it hard to see a connection between their actions on the controls and the outcome of the heating system and their thermal comfort. This is also reported by Fell (2016) and might contribute to householders not feeling in control of the system. To make the system reasoning more transparent, the controls provided information regarding the consequences of the temperature settings chosen in an effort to help householders make sustainable decisions. The authors saw that feedback as critical for the adoption of automation, but they explain that participants found the feedback provided not useful. It is therefore unclear if the shortcomings of this approach have to do with the limitations of the specific design chosen. Alternatively, it might be that the assumption that transparency will help householders to accept automation simply does not hold.

The previously reviewed trials tested heating controls with algorithms optimising the heat pump operation at the household level. However, this is not the only way to provide demand response with heat pumps without the active involvement of the householder. For example, the NEDO project (NEDO, 2017; Calver, Mander & Abi Ghanem, 2022) and the project reported by Nyborg and Ropke (2013) (also reported by Nyborg, 2015) relied on external direct control of the heating system during demand-response events. In both cases, the authors report an overall acceptance of the external control of the heat pump, with participants not reporting comfort loss (Nyborg & Røpke, 2013) or, in some cases, not noticing the demand response events (NEDO, 2017). However, Nyborg (2015) explained that some conflicts happened, mainly because the provision of flexibility depends on a network of domestic practices, which might be challenged during these events. Calver et al. (2022) suggest that the impact of the adoption of the technology might amplify the existing injustices for some householders. It is important to point out that the high level of acceptance could be affected by the sample of participants chosen. In NEDO, the participants volunteered to get the technology for free and were social housing tenants (and they are probably more used to having external parties such as the housing association involved in their home life). And in the project reported by Nyborg and Ropke (2013), the participants were do-it-yourself enthusiasts or lead users. Unsurprisingly, Nyborg (2015) explains that householders were active innovators regarding the use of the new technologies and the associated practices rather than passive consumers (which is consistent with Hyysalo, Juntunen & Freeman, 2013). She suggested that they have great potential to play a key role in creating low-carbon energy systems.

2.3.2. Heat pumps

While the lack of studies on the experience of heat pumps with smart heating controls could be explained by the novelty of the technologies and lack of field trials, this is not the case for heat pumps with standard controls. As explained before, heat pumps are a mature technology that has already been deployed at scale in many countries (particularly, Scandinavian countries). However, still, there are not many large-scale studies exploring the experience of householders with it (Crawley, Wade & de Wilde, 2023). In an article published 10 years ago, Devine-Wright et al. (2014) explained that most of the social research on heat pumps in real homes is concerned mainly with motivations and barriers to the adoption of these technologies or the technical performance achieved with these systems. Ten years later, the situation has not changed very much, as it became evident during the analysis carried out as part of this PhD.

The few existing studies on the topic (see table 2.2) are varied and follow different approaches. While in some cases, the experience of the householders with the technology (or parts of it) in the context of the home was the main focus of the study (see Devine-Wright *et al.*, 2014, for example), in others, it is investigated as part of the analysis of other issues. For example, some studies explored the topic to try to assess the impact of householders' actions on the performance of the technology. Examples of that are some of the reports for the RHPP scheme (such as Lowe *et al.*, 2017b) and the EST trial (such as Caird, Roy & Potter, 2012). Other studies analysed it as part of their interest in understanding the triggers and barriers to the adoption of heat pumps. Studies such as Owen et al. (2013) fall into this category. Additionally, in some cases, they work with specific niche groups, such as the elderly (Devine-Wright *et al.*, 2014; Tweed, Humes & Zapata-Lancaster, 2015), fuel poor (Owen, Mitchell & Unsworth, 2013) or social housing tenants (Judson *et al.*, 2015). In the following subsections, the main topics explored in these studies will be presented.

Table 2.2. Summary of the studies on heat pumps reviewed

Authors	Year	Sample (population of interest)	Methodology (aims)	Country
Caird and Roy	2010	48 individuals[3] (early adopters above average income)	Quantitative: Surveys (Performance of the HP)	UK
Boait et al.	2011	10 households (social housing tenants, elderly)	Mixed-methods: monitoring indoor conditions and energy usage and interviews. (Performance of the HP)	UK
Haunstrup-Christensen et al.	2011	Various (information not provided)	Mixed-methods: survey (n=480), electricity metering (n=185), semi-structured interviews and technical inspections (n=12). (Experience/Practices with the technology).	Denmark
Gram-Hanssen et al.	2012	Various (information not provided)	Mixed-methods: survey (n=480), electricity metering (n=185), semi-structured interviews and technical inspections (n=12). (Experience/Practices with the technology).	Denmark
Caird, Roy and Potter	2012	78 individuals (mixed group: social housing tenants and homeowners)	Mixed-methods: focus groups and survey. (Performance of the HP).	UK
Owen, Mitchell and Unsworth	2013	Various (households at risk of fuel poverty)	Qualitative: Semi-structured interviews (6 individuals, 2 programme managers, 4 installers). (Barriers to adoption)	UK
Heidenstrom et al.	2013	-	Secondary data from previously published studies. (Experience/Practices with the technology)	Norway and Denmark
Devine-Wright et al.	2014	104 individuals (elderly, some living in private households and some in care homes)	Qualitative: Semi-structured interviews. (Experience/Practices with the technology)	UK

[3] 285 individuals who had experienced a low carbon technology were surveyed but only 48 of them had experience regarding heat pumps (ground source heat pumps).

Tweed et al.	2015	104 individuals (elderly, some living in private households and some in care homes)	Qualitative: Semi-structured interviews. (Experience/Practices with the technology)	UK
Bell et al.	2015	18 households (social housing tenants)	Quantitative: Interviews and home tours. (Experience/Practices with the technology)	UK
Judson et al.	2015	18 individuals (social housing tenants)	Qualitative: Semi-structured interviews. (Barriers to adoption and Experience/Practices with the technology)	UK
Winther and Wilhite	2015	Mixed (mixed but mainly homeowners in detached homes)	Qualitative: in-depth interviews with 28 households and 1 technical expert. (Experience/Practices with the technology)	Norway
Lowe et al.	2017	21 households (mixed, homeowners and social housing tenants)	Mixed-methods: Semi-structured interviews and technical survey of the system. (Performance of the HP)	UK
Oikonomou	2021	21 households (mixed, homeowners and social housing tenants)	Mixed-methods: Semi-structured interviews and technical survey of the system. (Performance of the HP and Experience/Practices with the technology)	UK

Satisfaction with the technology

Satisfaction with the technology was one of the most commonly studied topics, particularly in those projects measuring the impact of householders' behaviour on the efficiency of the system. The projects reviewed found that most people living in houses equipped with heat pumps were satisfied with them. For example, Lowe et al. (2017b) reported that 86% of the participants were satisfied with the technology. Pither and Doyle (2005) also explained that the majority of the participants in their study were satisfied with the technology. However, the concept of satisfaction is complex and sometimes does not reflect what happens inside the home. Even some of the studies measuring this concept acknowledged that being overall satisfied with the technology does not mean that the householder did not face problems or limitations when using it (see some of the cases reported by Lowe et al. (2017b)). To try to explore this topic in detail, Caird, Roy and Potter (2012) and Caird and Roy (2010) divided their analysis of householders' satisfaction into different elements and found high levels of satisfaction with the indoor thermal conditions provided by the technology (83% in both studies) and the heat pump reliability (77% and 85%, respectively) and slightly lower satisfaction with the controls (55% in Caird, Roy and Potter (2012)) and the running and maintenance costs (62% and 58%, respectively). However, it is important to explain that those studies reporting on satisfaction mainly involve early adopters, who might be more interested in the technology than other groups, or social housing tenants who received the technology for free. Caird, Roy and Potter (2012) report lower satisfaction levels among social housing tenants compared to private owners, which suggests that the results might differ depending on the group studied.

Running costs

The running costs of the system seem to be one of the main sources of dissatisfaction. Unsurprisingly, Caird and Roy (2010) found that only 40% of the participants reported achieving the expected energy savings[4] and Pither and Doyle (2005) reported that 34% of the participants thought that the heat pump was "slightly expensive" or "too expensive" to run. The findings of the reviewed studies also suggest that householders often experienced difficulties assessing the running costs and the efficiency of the system (Caird & Roy, 2010). Oikonomou (2022) explained that the running costs are often monitored through bills, but those might be misleading and contribute to erroneously believing the heat pump as more expensive than it actually is. Owen et al. (2013) suggest that the perception of the costs was shaped by the householders experience of the installation process, among other things. This is because when people lacked an understanding of the technicalities of the technology, they used this experience as a proxy for the efficacy of the technology. When the installation was messy or disruptive, the system was perceived as less efficient. The findings contrast with Winther and Wilhite (2015), who explained that most of the householders interviewed did not keep track of the energy consumption of the system but instead relied on what they

[4] It is important to point out that the study was carried out during a period of major fuel rises in the UK, which might have affected the experiences reported.

heard about the potential savings, and they often had a feeling of saving energy rather than concrete evidence of it. In this case, the participants were all based in Norway, which might explain the differences with other studies.

Comfort

As mentioned before, most of the documents reviewed found high levels of satisfaction with the new system regarding comfort (see Boait, Fan & Stafford, 2011, for example). Most participants valued the constant and whole-house warmth (Caird, Roy & Potter, 2012; Lowe *et al.*, 2017b), with private householders reporting slightly higher values than social housing residents (Caird, Roy & Potter, 2012). Additionally, Gram-Hanssen et al. (2012) explained that participants in their study noticed an improvement in air quality (less moisture, cleaner air and more air circulation) when using the heat pump. However, the study analysed air-to-air heat pumps, and the results might not apply to heat pumps with hydronic systems (underfloor heating or radiators). In their review of studies, Crawley et al. (2023) noticed differences in the experience of comfort with a heat pump between women and men but pointed out that most of the research relies on climate chamber experiments and that more studies are needed.

Despite the overall satisfaction with the system, the studies reviewed also point out some limitations regarding comfort. According to Caird and Roy, 12% of the householders reported being unable to achieve their heating or hot water needs with the new heating system. Complaints about the indoor thermal conditions that the system contributed to creating or its noise were the most common issues discussed. A small group of householders seem concerned about the system's low responsiveness to warm up the house (10% of the households, according to Caird and Roy (2010) or 21%, according to Caird, Roy and Potter (2012)) and how that affected the times when the heating system was on. For example, overheating at night or complaints about heating when nobody was at home were reported by Caird, Roy and Potter (2012) in 14% of the cases. The high night temperatures were still problematic even two years after installing the technology, according to Boait et al. (2011). Aside from that, the noise of the system is one of the issues that householders reported more often (19% of the cases, according to Caird, Roy and Potter (2012)), despite the lack of detailed studies on the topic[5]. Caird, Roy and Potter (2012) explained that it mainly affected householders in properties equipped with air-source heat pumps, not ground-source heat pumps, and according to Owen et al. (2013), the problem was less relevant than expected by installers and mainly in social housing where houses are close to each other. Finally, other authors reported that householders missed the glow or heat blast after adopting the technology (e.g., Devine-Wright *et al.*, 2014; Judson *et al.*, 2015).

Rebound effect

One of the main interests of the reviewed studies was the analysis of the potential rebound effect after the installation of the technology. So, the interest was in analysing whether there was an increase in the consumption of energy services following an improvement in the efficiency of these services (Sorrell & Dimitropoulos, 2008). However, analysing the rebound effect after the adoption of heat pumps presents some challenges. As explained in section 2.2, to improve their efficiency, heat pumps are operated at low temperature, and require longer heating durations or constant heating. Therefore, it is likely that there will be an increase in the number of heated hours after adopting the technology and that might not be a consequence of the reduction in the costs of the service (as conventional approaches to the rebound effect suggest) because it is intrinsic to the efficient operation of the heating system. Oikonomou (2022) and to a lesser extent, Winther and Wilhite (2015) discussed this subtle difference, but this is an overlooked topic in most of the research on air-to-water or ground-to-water heat pumps. For example, Caird and Roy (2010) found a rebound effect after adopting low-carbon technologies (Solar hot water and GSHP) in 25% of the cases, but that included increases in the heating duration as well as the number of heated spaces, and they did not distinguish the results for each of the two technologies tested. Owen, Mitchell and Unsworth (2013) also reported comfort taking with the new technologies in cases where

[5] The existing studies on people's experience with the noise of the system is very limited. Other authors, such as Torjussen et al. (2023) and DESNZ (2023b) have also studied the topic but their sampling methods and approach are not described in detail or properly justified.

they found that the expected savings were not achieved, but that might result from many other issues such as a low COP due to a poor installation. Oikonomou (2022) found that in some cases, the adoption of the technology was accompanied by an active decision to reduce energy consumption and bills (e.g., with a smaller heated area), which caused a negative rebound effect.

However, the most complete studies of the rebound effect with heat pumps are with air-to-air heat pumps. This is because they do not require longer heating hours compared to other heating systems, and the effect is easier to observe. The two most complete studies on the topic are the one carried out in Denmark and published by Christensen et al. (2011) and Gram Hanssen et al. (2012) and the one in Norway developed by Winther and Wilhite (2015). The Danish study focused on air-to-air heat pumps and observed some comfort taking after the adoption of the technology (mainly through an increase in the number of rooms heated and the setpoint temperature and, in a small number of cases, beginning to use of the cooling function in summer), but, despite that, energy savings were achieved in most cases. They explain that the heat pump is often seen as cost-efficient, which contributes to relaxing concerns for energy conservation. The Norwegian study combines homes with air-to-air heat pumps with a small number of cases with air-to-water and ground-to-water heat pumps and describes two types of rebound: a spatial rebound (more rooms heated) and a temporal rebound (rooms heated for longer periods). They identify several factors contributing to that. First, they suggest that the characteristics of the technology and the sometimes-ambiguous technical information provided encourage opening doors to allow the airflow to travel across the house and heating constantly, even when going away. Second, they explain that the rebound effect might result of the householoders' experience of the limitations of the previous heating system (e.g., feeling cold in certain rooms).

Operation of the controls

As explained before, some of the studies reviewed found low levels of satisfaction with the controls (Caird & Roy, 2010; Boait, Fan & Stafford, 2011; Caird, Roy & Potter, 2012). Additionally, Caird and Roy (2010) explained that several of the participants in their study reported being uncertain about how to operate the system efficiently and found the controls difficult to operate. This is consistent with Judson et al. (2015) and it is a common situation with programable thermostats, not just heat pump controls (see Meier & Aragon, 2010, for example). Lowe et al. (2017b) and Oikonomou (2022) looked at the operation of the controls and observed a wide range of strategies across the cases studied, from simple on-off operation to complex settings with multiple thermostats in different rooms and changes in the weather compensation curves. Despite the relevance of this topic, particularly for the efficiency of the system (Caird, Roy & Potter, 2012), all the reviewed articles rely on self-reported behaviours and do not monitor the interaction with the controls.

As the heat pumps studied did not have any algorithmic control of the heating periods, the most discussed topic in the studies reviewed was how householders chose the heating running times. Caird, Roy and Potter (2012) explain that despite the fact that the continuous operation of the heat pump was linked to higher system efficiencies (also discussed by Boait, Fan & Stafford, 2011), they found that a quarter of the participants did not use the heat pump at night or when away and a fifth ran it only for short periods during the day. The Energy Saving Trust (2013) reported that two-thirds of their participants ran the heat pump continuously and the rest of them non-continuously.

The studies suggest a range of factors to explain the strategies householders choose. Caird and Roy (2010) and Caird, Roy and Potter (2012) suggest that the strategy chosen might be explained by the level of knowledge of the householders, and they found that greater reported knowledge of the technology was linked to higher system efficiencies (Caird, Roy & Potter, 2012). Additionally, they, as well as other researchers, observed that some participants did not see the efficient patterns of operation of the technology (running the system continuously, overnight or when the house was unoccupied) as the most economical way to operate the system (Caird, Roy & Potter, 2012; Owen, Mitchell & Unsworth, 2013; Judson *et al.*, 2015). Oikonomou (2022) suggests that intermittent operation results from expectations about running costs, noise level and intermittent operation beliefs. She introduces the concepts of the perceived bill threshold gap (difference between desired and actual bills) and the perceived space heating availability gap (difference between the desired and actual indoor conditions) to explain how householders operate the controls.

Most of the studies on the topic also found that after installing the new technologies, participants continued to use secondary heating (almost half of the participants, according to Caird, Roy and Potter (2012)). However, studies also found that the role of these secondary heating devices often changed (Judson *et al.*, 2015). Some participants used the secondary heating for cosiness or decorative purposes (Devine-Wright *et al.*, 2014; Judson *et al.*, 2015), for social purposes (Energy Saving Trust, 2013), as a backup system (Judson *et al.*, 2015), to reduce the energy bills (Oikonomou, 2022) and to increase the responsiveness of the system and change the indoor temperature quicker (Oikonomou, 2022). Lowe et al. (2017b) explained that not all the participants used secondary heating on a regular basis, and Judson et al. (2015) found that some householders abandoned them entirely after adopting the heat pump because the new system already provided the expected level of comfort.

Heat pumps as part of a socio-technical system

Most of these studies presented in the previous subsections tried to isolate and measure the outcomes of the adoption of the technology, often overlooking what surrounds and drives this process. However, heating technologies are not experienced in vacuum chambers. They are adopted in an existing socio-technical system, the home, that combines physical, emotional and behavioural dimensions in ways that often cannot be disentangled (Devine-Wright *et al.*, 2014). A few of the reviewed studies have tried to acknowledge this complexity and explored how the heat pumps are integrated (or not) into the home, considering its multiple dimensions. Owen et al. (2013) suggested that to be successfully adopted and achieve the expected efficiency and targets, either the technology design must reflect the existing socio-technical system (the multiple dimensions of the home), or this socio-technical system needs to change. However, as explained in section 2.2, the characteristics of the heat pump technology make the first option not feasible (e.g., the system needs to run at low temperatures) and therefore, the successful adoption of the technology requires accepting the differences and adapting accordingly (Cantor, 2011).

Some of the reviewed studies tried to understand the previously described findings as a result of this process. For example, Devine-Wright et al. (2014) explained how certain characteristics of the heat provided by conventional heating systems, such as the heat blast, are associated with home-making and the provision of hospitality. The lack of a heat blast could have contributed to dissatisfaction with the new technologies, even when achieving the requested air temperatures, and triggered the usage of secondary heating sources. The findings show the complexity of thermal comfort and the critical role of the heating system in the meaning of the home.

The findings suggest that to successfully adopt the heat pumps, householders (and the socio-technical system that they are part of) need to adapt to the specific characteristics of the new technologies. However, that contrasts with the existing models of deployment. Several authors (e.g., Owen, Mitchell & Unsworth, 2013; Judson *et al.*, 2015; Crawley, Wade & de Wilde, 2023) explained that heat pumps are often promoted as boiler equivalents without considering the important differences between the two technologies and preparing householders for the required transition. Additionally, Judson et al. (2015) emphasised that householders are often framed as passive recipients of energy services, which does not acknowledge the need to adapt to the new technology.

2.3.3. Smart heating controls for demand response

The previous sections have explored the literature on householders' experience with heat pumps, including heat pumps with heating controls for demand response and those without such controls. Thus far, none of the reported studies included smart controls for demand response unless they were installed together with heat pumps. The existing literature on smart heating controls (without HPs) is very varied, but mainly comes from two different streams. First, some authors have analysed these technologies as part of the analysis of heating controls and with a strong focus on understanding the householders' interactions with them. Secondly, some researchers have explored householders' thermal comfort reactions to third-party control of the heating or cooling loads, usually manually replicating the conditions that an algorithmic controller would create and without an interest in the heating controls per se. These two areas will be explored separately in the next subsections.

Smart heating controls

The literature on smart heating controls encompasses a wide range of technologies that often aim at different things and have different features and characteristics. This analysis is interested in the experience of living with a specific set of smart controls: heating controls that can model the thermal characteristics of the building (e.g., Model Predictive Controller (MPC) algorithm) and optimise the time when the energy is consumed to minimise price or environmental impact. Published field studies of this type of algorithmic controls for heating are scarce. However, control manufacturers might have carried out additional research on the topic but not made it available to the public. Only two studies were reviewed, one by Miu et al. (2019) and another one by Alan et al. (2016). Both projects tested an algorithm that optimised the heating operation to minimise costs considering a temperature schedule defined by the householders. In both cases, householders had opportunities to override the schedule.

Both studies have mainly been concerned with studying the delegation of the control of the heating running times from the householders to the algorithm and understanding the interactions with the controls. These two topics correspond to two of the three distinguishable approaches to control in the smart home literature as described by Hargreaves et al. (2016): perceptual control and artefactual control. The former is concerned with people's feelings and perceptions of control when using the technologies. The latter focuses on how the technologies are controlled and their usability. Therefore, lacking in these studies is the third approach: the relational approach. This is the one concerned with how the technologies affect lives, everyday activities, and relationships. Hargreaves et al. (2016) suggest that the three approaches have to be considered as it is the inter-relationship between them that matters.

Table 2.3. Summary of the studies on smart heating controls reviewed

Authors	Year	Sample (population of interest)	Methodology (aims)	Country
Alan et al.	2016	30 households (not reported)	Mixed methods: Semi-structured interviews (n=25) and analysis of the householders' interactions with the controls and the indoor temperatures. (usability)	UK
Miu et al.	2019	23 households (not reported)	Qualitative: before and after installation semi-structured interviews (n=23/10). (usability)	UK

Delegation of the control of the heating operation

As explained before, the perceived loss of control is one of the most cited barriers to the provision of demand response (e.g., Balta-Ozkan *et al.*, 2013; Fell, 2016) and issues attributed to it have been blamed for the problems experienced in some of the existing demand response projects. For example, Meier and Aragon (2010) explained that the proposal to implement external control of internet-connected thermostats by utilities in California under extreme situations was rejected because it was seen as a "Big brother". However, that was not the case in the project reported by Alan et al. (2016). They found that participants were happy to delegate control of the heating system to a third party. The reasons behind the results obtained are unclear but might have to do with the specifics of the project: the population (small trial of 30 households), the agent controlling the device (researchers instead of utilities), the objective of the external control (cost minimisation instead of grid services), or the specific design of the heating controls, among others.

To help make the external control more transparent, the smart controls studied by Alan et al. (2016) provided feedback on the scheduled operation of the heating system (estimated impact of the chosen temperature settings), which is common in other projects of smart technologies previously reviewed, such as Jensen et al. (2018). However, while the authors found that feedback was very welcomed by householders, it is unclear how it affected the actions of the householders, the energy used or the delegation of control. The role of feedback in energy practices has been extensively studied before, and authors such as

Hargreaves et al. (2010) suggest that its effect might depend on the context where it is provided, how it relates the to the practices affected, who receives it and whether the social and political context is supportive of the changes that the feedback aims to trigger.

Use and usability of the heating controls

Miu et al. (2019) explained that householders reported an improvement in the usability of the heating controls after installing smart heating controls. They explained that before installing the new heating controls most householders did not set any temperature schedule on their programmable thermostats and preferred to maintain their heating at a constant temperature throughout the day (even when not at home). This is consistent with previous research (Meier & Aragon, 2010; Consumer Focus, 2012), which has noted that programmable thermostats are often used as manual on/off controls or simply not used as designed (not used for setting a temperature schedule). This "incorrect" way of operating the heating controls is often seen as a consequence of the poor usability of the controls and the existing public misconceptions about how these devices work (Meier & Aragon, 2010; Consumer Focus, 2012). The findings by Miu et al. (2019) seem to reinforce this idea. In the case that they reported, the adoption of the new controls triggered an increase in the scheduled operation (more participants set a temperature schedule). Therefore, the authors suggest that the change can be explained by the improved ease of use of the new heating controls. However, the evidence provided is very weak.

At the same time, Miu et al. (2019) noticed that not only did more householders start using the temperature schedule, but the authors also found an increase in the number of unscheduled changes, an issue that is likely to complicate demand forecasting. However, the study relies on self-reported interactions by householders. In the study by Alan et al. (2016), the authors analysed the reasons behind unscheduled changes in detail. They explain that the adjustments did not only respond to discomfort. Other interests, such as adapting to the weather, the price of electricity or changes in the routine or the activities at home, were also important. For that reason, they suggest that the design of the heating controls should consider factors behind price and occupancy patterns.

The interest of these academics in measuring the perceived usability of the controls and the interactions with them is not a coincidence. It is symptomatic of an approach that frames the problems experienced or the barriers to the successful/expected adoption of the heating technology as computer-interaction challenges, trying to solve them by improving the control of these devices. Davidoff et al. (2006) have criticised the assumption that householders want control (or a sense of control) of the technology and argued that what they want is "control of their lives". In their study of dual-income families in the US, they found that daily life is often not routine but organic, opportunistic and improvisational, and technology plays a key role in the construction of social identity. Accordingly, the authors suggest that the new devices should work with and integrate this complexity. The findings are supported by a growing body of research that demonstrates the heterogeneity of heating practices and householders' needs (e.g., Gram-Hanssen, 2010a).

Direct load control and thermal comfort

As explained before, the existing literature on heating controls is not the only relevant literature on smart heating controls for demand response. Academics interested in thermal comfort have also studied demand response with automation technologies. However, their focus has usually been on assessing people's tolerance to temperature changes during demand response events rather than the householders' use and experience of smart controls. Underlying this interest, there is an understanding that people's thermal comfort requirements limit their capacity to shift energy demand (Reynders, Nuytten & Saelens, 2013; Kong *et al.*, 2020): the narrower the acceptable thermal comfort band is (the difference between the maximum and minimum acceptable temperatures), the smaller their capacity to provide demand response. Therefore, studying these thermal comfort limits is seen as critical for assessing the demand response potential. Unsurprisingly, these studies into acceptable thermal comfort bands do not discuss the technologies involved in demand response and do not provide details about the heating controls used. To analyse these limits, the studies assume that during the event, the space is not heated and the temperature decays (in winter) or increases (in summer).

Most existing research on the topic is on shifting summer cooling loads. This is because current problems of grid constraints happen in summer possibly because, in many areas, the major grid constraints are currently caused by air conditioners (e.g., in the United States most of the regions experience peak electricity demand in summer (Keskar, Galik & Johnson, 2023)).

The interest in the topic is not new, and one of the first studies was published in 1992 by Kempton et al. (1992). Since this paper was published, many other studies have followed. Aghniaey and Lawrence (2018) published one of the most detailed literature reviews on the topic, focusing on cooling demand response events in commercial buildings. They report the maximum tolerable temperature increases and rates of temperature change. They report from a combination of field trials and climate chamber studies. They report negative impacts on thermal comfort during demand response events, especially when the indoor temperatures are higher than 28ºC.

These studies and experiments have informed most of the technological developments in the area, which assume that as long as the air temperature is kept within a certain temperature band, householders will accept direct load control of their heating or cooling system. However, that can be criticised for two reasons. First, demand response can affect people physically, psychologically and socially in ways that cannot be assessed simply by measuring thermal discomfort (e.g., decreased productivity, change in the perceived air quality, etc.) (Aghniaey & Lawrence, 2018). Second, not only temperatures determine thermal comfort (Aghniaey & Lawrence, 2018). Thermal comfort is a dynamic and participatory process (Cole *et al.*, 2008) that is contextually determined (Parkhurst & Parnaby, 2008; Hitchings, 2009). Simplifying the limits of demand response to temperature bands is useful for those involved in building energy management or demand response providers because it allows them to define conditions applicable to a wide range of people, buildings and situations. However, it might contribute to missing other opportunities to provide demand response that challenge current established expectations of indoor temperatures. At the same time, as Strengers (2008b) noted, it might be contributing to escalating comfort expectations by taking thermal comfort needs as universal and non-negotiable.

2.4. Understanding heating practices

The previous sections have explored how people experience (hybrid) heat pumps with smart heating controls in real settings. The review showed that these experiences have been studied from a wide range of perspectives. Narrowly focused approaches to thermal comfort have gathered data through comfort scales and have been interested in measuring temperature tolerance during demand response events. In contrast, detailed studies of the social and emotional dimensions of the home have explored how the technologies constitute or conflict with these dimensions of the home. Each of these approaches represents a different understanding of human actions and society. Because of that, each is useful to answer different questions (Wilson & Chatterton, 2011). This thesis takes a Social Practice Theory (SPT) approach to study the heating practices with hybrid heat pumps with smart heating controls. This section presents this framework in detail.

2.4.1. Theories of social practice

Despite its name, Practice theory is not a single, well-defined, unified theory (Schatzki, 2001). It is a body of theories developed from different disciplines, such as philosophy, cultural theory, sociology, science and technology studies, etc., that is still evolving today. Despite this diversity, thinkers within this field share a belief that practices are what constitutes the social (Schatzki, 1997). Schatzki defines practices as a "spatial-temporal manifold of actions whose constituents form a nexus" (Schatzki, 1997:p.285) or "temporally unfolding and spatially dispersed nexus of doings and sayings" (Schatzki, 1996:p.89). Social practice theory offers an alternative to the dichotomy between individualistic and systemic approaches to human action by situating practices at the centre and seeing human action as the outcome of these practices.

In the next subsections, some of the concepts and ideas central to social practice theory will be discussed. First, the work of Giddens and Bourdieu will be presented to understand the ideas of the duality of social structure and habitus. Second, Schatzki's critique of some of the ideas introduced by Giddens and Bourdieu will be reviewed. Third, the role of things and objects in social practices will be discussed. Finally, an approach to study the dynamics of the practice, will be presented.

Duality of social structure and habitus

Practice theories draw on the ideas of the *duality* of social structure developed by Giddens in his "Theory of Structuration" (1986) and *habitus* introduced by Bourdieu (1977). Therefore, it is important to present these two concepts before presenting SPT in more detail.

With his idea of the *duality* of social structure, Giddens (1986) suggests that human action is shaped by social structures that are, at the same time, the result of these actions. Giddens proposes that social structures, in contrast to structuralism, do not exist on their own; they "exist only in so far as forms of social conduct are reproduced chronically across time and space." (Giddens, 1986:p.XXI). The process of enactment and reproduction of the social structure happens through practices, which are the nexus of actions performed according to certain "rules". In this case, Giddens understands rules as generalisable methods or procedures of action rather than complete detailed descriptions of how to act in each situation. These rules are carried in "practical consciousness", which is the knowledge "which actors know tacitly about how to "go on" in the contexts of social life" (Giddens, 1986:p.XXIII), and that minimises the otherwise unbearable cognitive effort of carrying out daily activities. Giddens (1986) distinguishes this "practical consciousness" from the "discursive consciousness", which is the explicit articulation and communication of the social structures.

Bourdieu also acknowledges the central role of practices in the social structure and describes them as groups of activities carried out in a given field (Schatzki, 1997). He explains that these activities are produced by dispositions called *habitus,* the core of which are skills acquired from other people under certain objective conditions (e.g., social position or cultural capital) and then internalised in the body and mind (Schatzki, 1997). The body-mind nature of the habitus is a key aspect of Bourdieu's analysis of social practices and represents an alternative to the rule-action approach developed by Giddens to explain the reproduction of day-to-day actions (Galvin & Sunikka-Blank, 2016). But Bourdieu refers to *habitus* not only to discuss the performance of actions but also to explain motivation, understanding, etc. (Galvin & Sunikka-Blank, 2016). Therefore, he suggests that *habitus* not only generates actions but also selects which actions to generate (Schatzki, 1997). Actions are selected to be appropriate given the situation and to make sense to the actors used to the practice to which the action is linked (Schatzki, 1997). To describe the process of selecting an action, he introduces the idea of "practical logic": The action selected is the one that maximises the actor's capital (economic and social) (Schatzki, 1997; Galvin & Sunikka-Blank, 2016).

Schatzki's critiques of the work of Giddens and Bourdieu

The ideas introduced by Giddens and Bourdieu set the foundations for developing practice theory. However, over time, some of these ideas have been challenged, and new theories have been proposed. It is worth analysing Theodore Schatzki's critiques of the work of Giddens and Bourdieu because of their impact on the current understanding of social practices. In his paper Practices and Actions (Schatzki, 1997), Schatzki acknowledges the effort of Giddens and Bourdieu in understanding the practical nature of human activity and the bodily know-how as a non-representational. This contrasts with most social theories, which rely only on mental representations of the world (beliefs, desires, values, etc.) to explain action. He particularly highlights Bourdieu's description of habitus as "bodily schemes" and Giddens's discussion of the "practical consciousness", which is a collection of know-hows that cannot be verbally formulated and represented. However, he argues that those authors still rely on mental representations to explain the role of those non-representational elements. For example, Schatzki explains that Giddens's "practical consciousness" implies the existence of rules that are followed. While Giddens suggests that part of this rule-following happens in the unconscious mind (Giddens, 1986), Schatzki (1997) critiques that explaining that there would never be enough rules to describe all human action fully. At the same time, he critiques Bourdieu's attempt to link the *habitus* to a "practical logic" that takes a capital maximisation approach. He believes that the existence of this "practical logic" suggests some rational decision-making and does not account for the complexity that drives action (for example, by leaving the importance of emotions and moods out of the picture).

To overcome these limitations, Schatzki (1997) suggests a different organisation of practices. He still acknowledges the importance of practical understanding in governing actions. However, drawing on Ryle and Wittgenstein, Schatzki limits the role of practical understanding to the know-how to carry out actions: It is important for the performance of bodily activities and the ability to recognise the circumstances of the action (e.g., identify that a gesture is a greeting). However, he adds two additional elements to the action's governance: explicit rules and teleoaffective structures. Explicit rules, in this case, do not equate to Giddens's understanding of rules as articulations of practical understanding ("discursive consciousness"). They are explicit formulations that not only describe how actions have been conducted in the past but specify what the correct or appropriate action is in a given context. Teleoaffectivity expresses feelings and emotions connected to aims, end goals and purposes (Galvin & Sunikka-Blank, 2016). In this case, these aims are not treated as discrete "mental states" that causally determine an action, but they represent the conditions of life that a person holds and articulate what makes sense for people to do (Schatzki, 1997). An action belongs to a given practice when its three dimensions (practical understanding, rules and teleoaffective structures) are consistent with the practice.

The role of materials in social practices

The theories of practices presented so far are almost entirely social and objects or things barely intervene in them. In recent years, authors like Reckwitz (2002) or Shove et al. (2012) have tried to incorporate these elements into the understanding of social practices. Reckwitz (2002) explained that practices often involve using things in a certain way and noted that in addition to bodily and mental activities, objects are also part of these practices. To acknowledge that role they borrowed concepts from Science and Technology Studies (STS). Authors like Shove et al. (2012) emphasise the important role of things in social practices and, as STS academics (e.g., Akrich, 1992), acknowledge that competences can be distributed between things and people. However, they do not share STS academics' suggestion of the equal status between humans and non-humans and the central role of objects in constructing social order (as in Latour, 2000). Objects are not the only elements that constitute social practices. Shove et al. (2012) identify three elements holding social practices together: materials, competences and meanings. Materials include things, technologies and physical entities. Competences encompass skills, know-how (which probably includes Giddens's "practical consciousness" and Schatzki's rules and practical understandings) and different forms of shared understandings of good or appropriate performance. Meanings include mental activities, emotion, and motivational knowledge, and they resemble Schatzki's teleoaffective structures. Other academics have proposed alternative configurations (e.g., Gram-Hanssen, 2010a).

The dynamics of social practices

Theories of social practice have often been criticised for focusing only on the routine reproduction of social life and not addressing innovation or change (Shove, Pantzar & Watson, 2012). Practices provide a template that is used to shape and calibrate actions. However, how do new practices emerge and existing practices change or disappear? Shove et al. (2012) suggest that "practices emerge, persist and disappear as links between their defining elements are made and broken" (links between meanings, competences and materials). Therefore, the evolution of practices is the history of how these links have evolved over time by connecting new elements or disconnecting/abandoning others. The definition suggests that elements exist before links are made and might continue to exist as they disappear from the practice, for example, by existing in other practices or reservoirs (e.g., in an old book describing the rules for carrying out a certain action).

Shove et al. (2012) identify different ways in which these links are created or destroyed. For example, materials can literally be physically transported from one place to another or accessed in cases in which there was no previous access. New competences or meanings can be adopted through face-to-face interactions (e.g., teacher and pupil) but also beyond these limits through processes of abstraction, transportation and re-contextualisation or through transference between practices (e.g., lighting a fire for keeping warm and lighting a barbecue). The creation or destruction of links often depends on the existence of appropriate transformation structures. For example, driving academies might be needed for the adoption of new driving rules. Also, it is often the case that the circulation of one element (e.g., a certain material) is not enough for it to be successfully adopted into a practice. It needs to be joined by others (Shove, Pantzar & Watson, 2012). For example, the adoption of certain carpentry tools might need to be accompanied by know-how on how to use them to be successfully adopted into the practice of furniture making.

This approach does not suggest that practices are homogeneous or uniquely defined. Old, new and contradictory links (and, therefore, elements) can co-exist (Shove & Pantzar, 2007). For example, Shove and Pantzar (2007) explain that when digital cameras and digital photography were established, different meanings and competences associated with analogue photography (e.g., printed copies of photos) co-existed with new understandings and know-how (e.g., digital edition and digital storage). To explain that, Shove et al. (2012) distinguish between practice-as-entities and practices-as-performances, as presented by Schatzki (1996). The former is the recognisable conjunction of elements that endures over time and space (Kuijer & Bakker, 2015). The latter is the specific reproduction of the practice in a setting and time by certain actors (Kuijer & Bakker, 2015). Therefore, multiple performances of a practice for the same practice-as-entity might exist.

2.4.2. Studying heating practices

In recent years, the approaches developed by Schatzki, Reckwitz and, particularly, Shove have gained interest because of their suitability to understand energy and heating-related topics. Warde (2005) explained that consumption of resources occurs as items are appropriated in the course of reproduction of specific practices. And Shove and Walker (2014) suggested that energy use can be explored, not as a resource but as incidental to the reproduction of social practices: "energy is used, not for its own sake, but as part of, and in the course of, accomplishing social practices" (Shove & Walker, 2014:p.47). At the same time, that means that energy demand can be understood not as the outcome of an individual process of decision-making but as the result of the evolution of social practices (Higginson *et al.*, 2015). Academics have used social practice theories to explore a wide range of energy-related topics including: studying how energy is used by householders (e.g., Gram-Hanssen, 2010a), suggesting new approaches to policy-making (e.g., Shove, 2010), or understanding energy demand at national level (e.g., Torriti *et al.*, 2015), etc.

However, the interest of this research is not in energy-consuming practices in general but in those practices that involve heating systems. Defining what constitutes a practice or not is sometimes complex and arbitrary (Galvin & Sunikka-Blank, 2016). This research is concerned with comfort practices as defined by Strengers (2010:p.7313): "the activities householders undertake to heat and cool their bodies and homes". As the research focuses on heating rather than cooling and aims to explore heating beyond thermal comfort, the practices studied will be called heating practices. This is not new, as other researchers have already used the term (e.g., Petersen, 2008; Doyle & Davies, 2013; Rinkinen & Jalas, 2017; Madsen, 2018).

Heating practices provide the material background for other domestic practices; that is, they provide the necessary thermal environment for activities in the home (Gram-Hanssen, 2010a). In heating practices, energy flows, governed by people and/or technologies, are controlled to ensure that the desired objectives are achieved: from feeling at the right temperature to minimising the environmental impact (Royston, 2014). People are not seen as passive recipients of certain indoor conditions that can be studied using physiological variables alone (Strengers, 2010). Instead, these conditions are constantly negotiated between the body, the materials and the social (Cole *et al.*, 2008). Most of this research is devoted to analysing this negotiation.[6]

In this thesis, the 3-element model detailed by Shove et al. (2012) (Competences, Meanings and Materials) will be used to develop data collection instruments and frame the data analysis. This model was chosen for several reasons. First, this is a simple and easy-to-understand model (Higginson *et al.*, 2015). As the interest of the research is not in social practice theory as a framework but in applying it to the study of heating, keeping the model simple should help to focus on what is important. Second, it acknowledges the role of materials in social practices. Given that the interest of the research is in heating practices

[6] This paragraph is partially reproduced from Martin-Vilaseca et al. (2022) and it was originally written by the author of this thesis.

with a particular set of technologies, incorporating materials as one of the elements of these practices was critical. Third, it is a widely used model in energy-related research (e.g., Kuijer, De Jong & Van Eijk, 2013; Madsen, 2018). Fourth, the distinction between "rules" (formal instructions) and "know-how" (practical understanding) described by Gram-Hanssen (2010a) in one of the other most-used models of social practices in energy research, was found not to be relevant for this research.

Throughout this thesis, this three-element model will be presented as in Figure 2.3. This diagram is adapted from Kuijer (2014a) which, at the same time, is an adaptation of the that introduced by Shove et al. (2012). In Shove et al.'s (2012) figure, practices were diagrammed as three balls representing each of the three elements that constitute them and lines connecting each of the balls with the other two. These lines represent the links between the different elements that hold the practice together. Kuijer (2014a) added complexity to the diagram by presenting each of the balls as groups of bubbles and each of the lines as multitude of links. According to Kuijer (2014a), this variation helps to explain the difference between practices as entities and practices as performance and to explain how practices change and evolve. The elements that constitute the practice are not homogeneous and well defined. Each performance integrates varying sets of elements (bubbles) and combinations (links) and those that are shared across performances are the ones that constitute the practice-as-entity. At the same time, practices evolve as some of these elements are removed or captured and/or links broke or connect. The diagram introduced here, further emphasises the diversity of these links by representing them with different types of lines (e.g., dashed, solid, dotted).

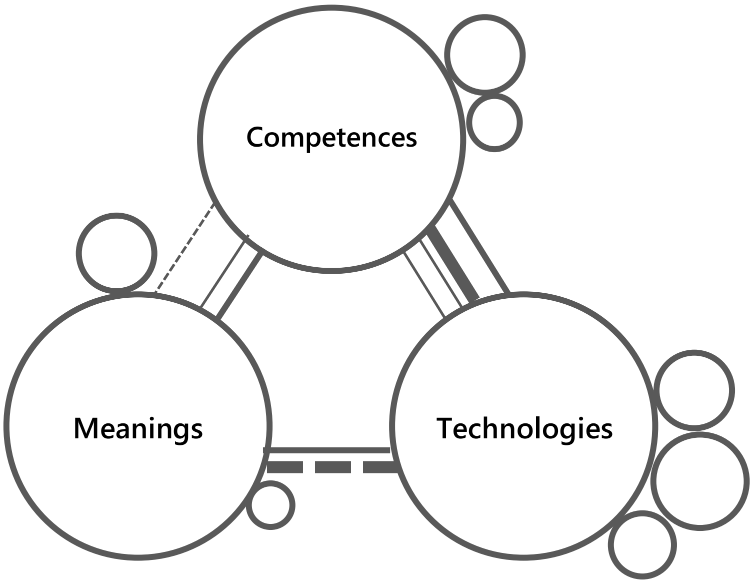

Figure 2.3. Social practices represented as groups of elements linked. Adapted from Kuijer (2014b).

2.5. In conclusion

The chapter has presented the challenges that the energy system is facing and the potential for heat pumps and smart heating controls to play a key role in the energy transition through the electrification of the heating demand and the provision of demand response services to match the heating loads to the variable electricity generated by renewable energy sources. However, as the review showed, the adoption of each of these technologies by households is not always straightforward and can present some challenges. As section 2.2 evidenced, these technologies are not boiler equivalents, and their intrinsic differences require specific heating practices that allow the smart heating controls algorithm to run the system with the lowest costs.

Current heating practices are built around the specific characteristics of gas combi boilers: high flow temperatures and discontinuous operation. Because the heating system is highly responsive, people only turn it on when they are at home and are able to enjoy the heat directly. However, this is not how heat pumps with smart heating controls work efficiently. Heat pumps require longer heating times at lower flow temperatures, which has consequences for indoor conditions and the heating operation times. The heat pump might work at night or when people are not at home to maintain the temperature or bring the house up to temperature slowly for the next warmth-requested period. Moreover, the smart heating controls tested choose the times when the heating is on and require delegation of this control. All these changes might conflict with the existing heating practices: they require accepting new indoor conditions (e.g., higher temperatures at night), delegating the control of the heating times, not having preferences for the heating periods, etc. It is unclear how householders will experience the technology and if they would adapt.

The literature on householders' experience with the technology has often focused on measuring satisfaction and the number of interactions with heating controls. These outcomes are undoubtedly important for understanding the capacity of households to shift demand and accept novel technologies. However, they offer a somewhat superficial picture of the conflicts and problems experienced at the household level and provide little detail about householders' everyday experiences adapting to these new technologies. Some of the reviewed studies have incorporated these critiques and have explored the adoption of these technologies in the context of the home, acknowledging its multiple dimensions and complexity. However, due to the effort required to carry out this detailed analysis, these studies have usually focused on specific elements of the process of adoption of the technology or worked with very niche groups. Moreover, the evidence for hybrid heat pumps with smart heating controls is even more scarce. If these technologies have to be installed at scale, it is critical to explore the householders' experience with them and to better understand how they are integrated into the existing heating practices. Theories of social practice offer a unique approach to doing that.

In the next chapter, the research design chosen to address these knowledge gaps is presented, and the cases chosen for this study are introduced.

3. Methodology

The literature in the previous chapter has shown that the adoption of hybrid heat pumps with smart heating controls for demand response is a social and technical phenomenon. The new technologies have intrinsic differences compared to conventional boilers, resulting in different heating operation and indoor conditions. At the same time, they require different practices, entailing adaptation by householders. The social and technical nature of the topic was also captured in the research questions presented in section 1.1, with the first research question being mainly technical and the second and the third mainly social. The research design for this study needs to be able to capture this complexity.

This methodological Chapter describes the methods chosen to address the research questions presented in section 1.1. The methodology chosen for this study was informed by the literature review presented in the previous Chapter, the pilot projects developed as part of this PhD (see section 3.4) and the literature review of the methods prepared for the Report for Upgrade.

3.1. Research design

As explained in section 1.1, the research presented in this thesis studies householders' experiences with hybrid heat pumps with smart heating controls in real settings to try to understand what indoor conditions they create, how people experience them and how they are incorporated into heating practices. Therefore, the interest is not in the technology per se but in how the technology is integrated into domestic environments. Given the lack of research on social practices with these technologies, the research reported here is necessarily exploratory.

Moreover, practices are socially constructed and context-specific. Consequently, the research design is grounded in the context within which the technology is used and informed by an interpretivist epistemology and constructivist ontology. This research is interested in the experiences of individuals within their context (Bryman, 2012). Moreover it recognises that the physical context shapes social practices. As Love and Cooper (2015:p.997) argued, energy is "fundamentally socio-technical - physical factors interact with and may be indistinct from social factors". Therefore, the research design chosen should be able to capture the experiences of participants within their material contexts.

To understand this phenomenon, this research combines a social and technical analysis of a series of case studies of the adoption of hybrid heat pumps with smart heating controls. This primary data collection and analysis is complemented with a secondary data analysis of a Customer Relationship Management (CRM) database. The CRM dataset is a record of communications between the customer service team (CST) and householders in a large-scale project where the technologies were installed. The combination of the two approaches aims to improve the robustness of the results through triangulation of findings.

The research design is similar to most of the studies covered in the literature review on the experience of living with heat pumps both with and without smart heating controls (see Section 2.3). Most of these projects used case studies as the main approach to the topic (e.g., Jensen, Kjeldskov & Skov, 2016; Hanmer, 2020). However, in some cases, they also combine that with a quantitative analysis of a larger number of cases within the same project (e.g., Haunstrup Christensen *et al.*, 2011; NEDO, 2017). This allows them to gauge general trends, which are then explored in detail using qualitative methods with a smaller number of cases. The number of cases in the projects analysed as part of this thesis was not sufficient to carry out quantitative analysis. However, the study of the CRM dataset provides an alternative to guestimate the frequency of some of the issues identified in the case studies.

3.2. Multiple case studies

Case study research is an approach that allows to investigate in detail a contemporary phenomenon in its context, usually when the limits between the phenomenon and this context are not clear (Yin, 2017). According to Gerring (2004), what distinguishes case study research from other research designs is its attempt to generalise (understand a broad set of units) by analysing the variation of one single unit across time and/or more than one units across space. Yin suggests that case studies are indicated for analyses in which a "how or why question is being asked about a contemporary set of events, over which the investigator has little or no control" (Yin, 2017:p.9). In this case, this research design was chosen because the study is exploratory, aims to take a broad look at a phenomenon in its context-specific setting, and no hypotheses are being tested (Bouma, Ling & Wilkinson, 1993; Yin, 2017).

Case study research is not a method but a design frame that can incorporate different methods (Thomas, 2011); case studies can be analysed using qualitative and quantitative approaches (Gerring, 2004). For that reason, case studies have been widely used in building and energy research, as they are very useful for studying the inherent complexity of buildings, considering the social and the technical (Lowe, Chiu & Oreszczyn, 2018).

The research reported in this thesis analyses in detail ten cases in which hybrid heat pumps with smart heating controls were installed. The cases were recruited from two different projects, which are described in detail in section 3.2.1. Each of the cases was analysed over time (longitudinal analysis) using a mixed-methods approach, combining qualitative and quantitative methods. The longitudinal mixed-methods approach was chosen for various reasons. First, the research aims to understand the heating practices with the new technologies from a social and technical point of view. Therefore, the interest is not only in analysing the experience of the householders with the technology but also in exploring their actions and the outcomes of the heating system. Additionally, as Schatzki (2002) has explained, social practices involve doings and sayings, and combining social and technical approaches could help to better understand both aspects. Second, the longitudinal approach is useful to understand the evolution of the heating practices over time. Third, combining quantitative and qualitative methods offers an opportunity to triangulate the results obtained, improving the robustness of the findings.

Sovacool et al. (2018) define a hierarchy of evidence to assess the robustness of different types of case studies. Moving from those approaches that provide stronger evidence to those that provide weaker evidence, they divide projects that use case studies into "literature review of a large number of case studies", "collection of more than two case studies that differ in type or time or space", "two comparative case studies with no variation", "single case study" and "anecdotal evidence". This project sits in between various categories. It can be understood as a single case study because, despite analysing a series of cases, they are all quite similar. However, in contrast to single case studies, the variation of the cases over time is analysed. In the classification developed by Gerring (2004) the research constitutes a type II case study: a series of case studies with multiple subunits (households) that are analysed over time. It is important to point out that the fact that multiple cases are analysed does not mean that these can be compared. The analysis is interested in the performance of heating practices with the new technologies. These performances are importantly affected by the spatial configuration of the building, its thermal performance and the specifics of the heating system (e.g., size of the radiators), among others. However, these differences are not analysed in detail in this project. Therefore, the usefulness of comparing cases is limited.

3.2.1. Introducing the cases studied

In his seminal work on case study research, Flyvbjerg (2006) explained that the selection of the cases to study critically affects the capacity of the study's findings to be generalised to a wider population. He suggested that typical or average cases are often not the richest in information and that atypical and extreme cases might be more useful to understand the issue studied in detail as they usually involve more complexity. As the interest in the case study research was not to assess the representativeness of the results (this was better addressed through the analysis of the CRM dataset), it was decided that it would be better to select cases that are not representative but useful for the research.

The cases studied were recruited from the B-Snug project and the HyCompact project. The first involves the installation of full-size conventional heat pumps on top of an existing oil or LPG boiler in off-gas grid properties. Hereafter, I will refer to this combination of technologies as hybrid heat pumps (H). The second involved the installation of a compact hybrid heat pump, a device that is installed inside the house and that combines a small heat pump (4kW output) and a condensation gas boiler under the same casing. Hereafter, I will refer to this technology as a compact hybrid heat pump (CH). Both technologies were installed in combination with the smart heating controls that the industrial sponsor developed and that have been presented in section 1.2.

The selection of cases was, to a certain extent, opportunistic and was shaped by the collaboration with the industrial sponsor. Given the small number of installations of hybrid heat pumps with smart heating controls in the UK, the researcher took the opportunity offered by the industrial sponsor to use two of their projects. Despite that, it is still important to consider what type of cases they are. According to Flyvbjerg's (2006) classification of case study selection strategies, the selection of cases studied here is "paradigmatic" and "extreme"/"critical". It is paradigmatic because the projects represent two of the few examples of hybrid heat pumps with smart heating controls. They are critical because they include some characteristics that make them unique. First, in both projects, the participants volunteered to receive the technology and they received it either at a discounted price or for free. It seems highly likely that if conflicts arise in such positive scenarios, in other situations where householders are forced to get the technology, there might be even more problems. Further, the hybrid project is unique because it is installed in off-gas grid properties and includes an oil or LPG boiler, which are uncommon in the UK (CCC, 2020b). That makes the cost proposition more favourable to householders because oil, and LPG are significantly more costly than natural gas, so the running costs of the new system are expected to be cheaper than the systems they replace. The compact hybrid project is unique because the heat pump is installed inside the building, which make some issues such as noise more noticeable for householders. Despite the differences, the projects are similar enough and separate enough to treat them as instances of the same phenomenon.

Initially, the case study was only going to be the hybrid case (not the compact hybrid case). It was thought that the technology tested in this project was more representative of the type of hybrid heat pumps that will be deployed in the UK in the future. In those cases, the heat pump is able to provide all the heat demand of the building and the boiler is only used on extreme days or to provide domestic hot water (DHW) on demand. Also, the fact that the heat pump is bigger in those systems was expected to make some of the differences in the operation of the heating system and the indoor conditions more noticeable. This project started in January 2020 and was presented as the case study in the upgrade report. However, the project was cancelled soon after the upgrade as one of the companies involved went into administration. While the project included installing the technologies in over 100 properties, the number of participants recruited at this point was insufficient to carry out the research as planned. Therefore, it was decided to include cases recruited from the compact hybrid project in the research.

In the next subsections each of the projects is presented in detail.

Hybrid project

The B-Snug project (referred to as the Hybrid project (H) in this thesis) was a joint venture between Passiv UK and Shell UK to install hybrid heat pumps and smart heating controls in homes that already had an oil or LPG boiler. The technology was openly publicised and promoted as a "viable solution particularly for larger and hard-to-insulate homes where fitting an all-electric heat pump in isolation may be too expensive" (Shell UK Ltd, 2019). The households who decided to participate received a Samsung Air Source Heat pump (ASHP)[7] and a set of smart heating controls developed by Passiv UK. The ASHP was combined with the existing boiler, and they were controlled through the smart heating controls, which decided whether to use the boiler or heat pump to provide heat and also what flow

[7] Samsung EHS Mono ASHP with a heat output of 8kW.

temperature the heat pumps should run at to provide the required temperature setpoint at each time. In most cases, the boiler provides DHW on demand.

Participants only paid part of the installation costs of the technology. The rest of the upfront costs were paid by B-Snug, who recovered them through the domestic Renewable Heat Incentive (RHI) payments. The RHI is a financial incentive created by the UK government and launched in 2014 to promote the installation of renewable heating technologies in England, Scotland, and Wales (Ofgem, 2023). The company promoting the project, in this case, B-Snug, on behalf of the householder, received payments every three months for up to seven years to subsidise the capital costs and maintenance of the technology (Ofgem, 2023). These payments are proportional to the heat generated by the ASHP, with an annual limit of 20,000 kWh (Ofgem, 2023).

The smart heating controls are set to minimise the cost to the householders, assuming a cost ratio of 0.4 between electricity and fossil fuel, which contributes to maximising the operation of the heat pump and the carbon savings while ensuring that the temperature setpoints requested by the householder are always achieved.

Compact hybrid trial[8]

The HyCompact project (referred to as the Compact Hybrid project (CH) in this thesis) was a trial project developed by Wales&West Utilities, UK Power Networks and Passiv UK to test a compact hybrid heating system and its capacity to provide flexibility to the grid (see Passiv UK Ltd, 2022). The technology installed was the Murelle Revolution 30, a hybrid boiler developed by the Italian manufacturer Sime. The heating system is the first in the UK to combine a gas boiler and an ASHP within a single casing. The boiler has a maximum heat output of 30kW, while the heat pump has a maximum heat output of 4kW. The unit is slightly larger than a combi boiler (90x60x39cm). In contrast to stand-alone heat pumps, the

[8] All the information in this subsection is obtained from the report prepared by Passiv UK (2022) on the project.

system is installed indoors and does not need an external unit; two air ducts connect it to the outdoors. As part of the trial, the technology was installed with the smart heating controls developed by Passiv UK. These controls were responsible for choosing when to operate each heating system (or both).

The technology was installed for free in seven homes. The participants were recruited through word-of-mouth by the people involved in the project. To participate, the homes had to be connected to the gas grid and met certain conditions (e.g., have a solid wall to support the unit). The project started in early 2021 and ended in mid-2022. It was developed in two phases: the first one started in March 2021 and involved 4 households, and the second one started in November 2021 and involved all seven households. At the end of the project, participants were offered the option to keep the hybrid system or have their old combi boiler (or a similar one) re-installed. Two participants requested to have the hybrid system removed.

The trial was interested in testing the capacity of the hybrid system to run in heat pump mode while ensuring that the householders' requested temperature setpoint was achieved. The controls operated with a simulated tariff with an artificially high fossil fuel price, which contributed to prioritising the operation of the heat pump and was expected to reflect future energy costs. The assumed prices for the optimisation were 28p/kWh of electricity and 14p/kWh of gas (gas to electricity cost ratio of 0.5). However, during the trial, various short-term interventions (every other week) were carried out looking at other types of incentivisation, including "marginal carbon". In this case, the decision to operate one system or the other was driven by the expected carbon emissions resulting from their operation. That was calculated by comparing the carbon intensity of the worst 5% of the electricity generation mix each hour and the gas carbon intensity (assumed to be 180gCO_2/kWh) and considering both systems' expected efficiency. The system with the lower environmental impact at each time was chosen. Participants in the trial were offered economic compensation if their energy costs increased as a result of testing these alternative optimisation functions.

3.2.2. Recruitment

The recruitment was mainly carried out through the industrial sponsor but was different for each of the projects studied. The hybrid case was not designed as a trial but as a commercial offering in which the householders freely signed up. There was no research planned to be carried out as part of the project. Therefore, the householders in this project were approached individually and asked to participate in the research. The contact with the householders was initially carried out by Passiv UK using a recruitment email prepared by the researcher. Passiv UK provided the contact details of those householders who agreed to participate to the researcher. A total of ten participants were approached and four of them agreed to participate (40% response rate). Three of them had had the new heating system recently installed, and the fourth one was waiting for it to be installed. Unfortunately, the technologies were never installed in the fourth case, and this case was dropped out of the sample. A £20 voucher was offered to those who participated. The amount is small and practically oriented (Braun & Clarke, 2013): it aimed to cover costs associated with participation (to make the research more inclusive), and it is unlikely that it tempted participants to do things they would not otherwise do.

The compact hybrid project was, as explained before, a demonstration project of the technology. The stakeholders involved in it agreed to participate in research activities as part of the project. The author of this thesis was offered the opportunity to design and carry out this research. Therefore, in this case, signing up for the project meant accepting to participate in the research, and there was not a separate recruitment process. All the seven participants in the project took part in the research. The details of the information sheet and the consent form to participate provided to the participants in both projects can be found in Appendices 10.1 and 10.2.

Ten cases were recruited in total: three with hybrid heat pumps and seven with compact hybrid heat pumps. The sample size is in line with some of the studies reviewed in section 2.3 (e.g., Jensen, Kjeldskov & Skov, 2016), but it is at the lower end of the spectrum. However, as Baker and Edwards (2017) explained in their study of samples in qualitative research, there is no right or wrong sample size. It depends on the nature and purpose of the research, practical issues and the judgment of the academic community for this particular field. Regarding the first, the analysis of the case study does not aim to measure the frequency of the issues but to explore a largely understudied topic. Additionally, the findings of the case studies are complemented with the analysis of the CRM dataset. Regarding the second, in contrast to other studies reviewed in section 2.3, this research not only involves social methods, but it also includes technical monitoring. Recruiting a larger sample would have complicated the monitoring process: the installation of the monitoring devices and the analysis of the data. Also, it was not possible to recruit more participants from other projects that could add additional variability to the sample as these are new technologies in the UK, and the existing cases are limited. Finally, the sample size is in line with most interview-based studies on building energy consumption research, according to the review by Galvin (2015) and larger or in line with other mixed-methods building research in the UK (e.g., Love, 2014; Chiu *et al.*, 2014; Few, Shipworth & Elwell, 2024).

The cases studied

The households who volunteered to participate and a summary of the characteristics of their dwelling are shown in Table 3.1. The cases recruited from the Hybrid project have a code starting with H. The ones recruited from the Compact Hybrid project have a code starting with CH. Given the low number of hybrid heat pumps with smart heating controls installed in the UK, all the participants are early adopters of the technologies. All of them volunteered to participate and got the technology for free or at a discounted rate. All of them (at least one person in each case) had previous interest in the technology.

Table 3.1. Summary of the cases studied: the households and their dwellings

Case	Location	Dwelling typology	Size house	EPC	Household	Previous controls[9]	Hydronic system and DHW
H1	East midlands	Detached	$163m^2$	E	Young couple	Timer/Switch	Radiators No DHW tank
H2	West midlands	Detached	$182m^2$	D	Middle aged couple with one child	Programmable thermostat	Radiators No DHW tank
H3	Wales	Detached	$179m^2$	E	Middle aged couple	Timer/Switch	Oversized radiators No DHW tank
CH1	Wales	End-terrace	$180m^2$	-	Semi-retired couple	Programmable thermostat	Oversized radiators No DHW tank
CH2	Wales	Detached	$185m^2$	C	Middle aged couple with one child	Hive thermostat	Slightly oversized radiators No DHW tank
CH3	South-east	Semi-detached	$75m^2$	D	Middle aged couple with one child	Hive thermostat	Radiators No DHW tank
CH4	Wales	Semi-detached	$122m^2$	D	Middle aged couple with two grown-up children	Programmable thermostat	Radiators No DHW tank
CH5	London	Semi-detached	$127m^2$	-	Young couple	Timer/Switch	Underfloor heating and

[9] The information about the existing type of controls was deduced from the participants' description of their heating practices with the new technology and might contain inaccuracies.

							oversized radiators No DHW tank
CH6	South-east	Detached	113m^2	D	Middle aged couple with two children	Timer/Switch	Radiators DHW tank
CH7	South-east	Detached	210m^2	C	Middle aged couple with two ground-up children	Programmable thermostat used as a switch	Radiators DHW tank

Table 3.2 presents some summary statistics of the operation of the heating system in each of the cases studied. It is worth noting that in all cases except one, the room temperature near the thermostat (usually located in the living room) is within 1ºC of the average room temperature in the living room according to EFUS 2011, which was calculated to be 19.3ºC (DECC, 2013). The temperature setpoint chosen by the participants shows variability, which will be studied as part of this research.

Table 3.2. Summary of the cases studied: the heating system

Case	COP HP	Average heating provided per sqm[10]	Percentage of heating provided by the HP[11] [12]	Mean internal temperature (near the thermostat)	Temperature setpoint warmth-requested periods (Min - Max)	Number of warmth-requested periods on Weekdays - Weekends
H1	2.92	91kWh/m^2	81%	19.2°C	19°C – 20°C	1 - 1
H2	3.37	53kWh/m^2	90%	19.9°C	18.5°C – 20.5°C	1 - 1
H3	2.57	-[13]	-	19.5°C	18°C – 20.5°C	1/2 - 1
CH1	3.22	10kWh/m^2	58%	18.6°C	18°C – 19°C	3 - 3
CH2	-[14]	35kWh/m^2	40%	18.6°C	18°C – 19°C	2 - 1
CH3	2.58	57kWh/m^2	33%	18.8°C	16°C – 20°C	2 - 2
CH4	2.7	81kWh/m^2	44%	18.6°C	15°C – 19°C	1/2 – 1/2
CH5	2.28	-	27%	19.5°C	18°C – 20.5°C	1 - 1
CH6	2.57	-	36%	18.8°C	18°C – 21°C	1/2 – 1/2
CH7	2.73	-	25%	21.3°C	19°C – 22°C	1/2 – 1/2

[10] In CH5, CH6 and CH7, the data available did not include the whole heating season because the systems were installed half-way through the heating season. Therefore, it was not possible to calculate the total heating demand per year.

[11] It is important to consider that this is not only affected by the physical characteristics of the building but by the actions of the householders (e.g., temperature settings) and their requirements (e.g., heat pump overnight suppression).

[12] The boiler size in H1 was 40kW and in H2 30kW.

[13] Due to a fault with the boiler heat meter, it was not possible to calculate the heat demand and the percentage of the heating provided by each system.

[14] Due to a fault with the electricity data meter, the COP was not calculated.

3.2.3. Social research

As explained before, exploring the householders' experience and heating practices once the new technology was installed was one of the main aims of this research. Therefore, it is critical to include methods to capture the subjective experience of the users. In this case, the approach to collect this data was a series of semi-structured interviews with all the adults in the house. Kvale (2007:p.7) defines semi-structured interviews as a "conversation that has a structure and a purpose determined by the one party – The interviewer". This type of interview combines predefined and non-predefined topics to discuss, ensuring that some topics are covered but allowing for new themes to emerge as the conversation flows. Interviews are the most common method of qualitative data collection and are particularly useful to capture participants' experiences and perspectives and their language and concepts (Braun & Clarke, 2013), which is one of the objectives of this research. Unsurprisingly, it is also the most common approach used in the studies reviewed (see section 2.3), which is consistent with Bryman (2006) who, in his content analysis of mixed-methods studies found that semi-structured interviews were the most used method.

Semi-structured interviews were chosen instead of other qualitative methods for various reasons. First, they are useful to study in depth how householders experience and understand their world (Kvale, 2007) and, in contrast to other qualitative methods, they are particularly useful when participants have some personal stake in the topic studied (Braun & Clarke, 2013), as it is the case. Second, in contrast to other qualitative methods, such as focus groups, each interview can be linked to one case, which is useful to triangulate the results of the technical and social analysis. Third, they require a low level of commitment from householders: they can be scheduled whenever works better for the participant (Bryman, 2012).

However, as Hitchings (2012) explained, some academics have suggested that interviews are not useful to study social practices. Social practices, as explained in section 2.4, are "a routinised type of behaviour" (Reckwitz, 2002:p.249). According to Hitchings (2012), as the actions that constitute these practices are habitual, embodied and often do not require active reflection or will to be reproduced, some academics suggest that householders might be unable to discuss them. However, Hitchings (2012) showed that people can often talk about mundane actions even when these are performed unthinkingly. While he suggests that that can vary from practice to practice, previous research has shown that householders can talk about heating practices (e.g., Gram-Hanssen, 2010a).

Serial interviewing

The semi-structured interviews were designed as a series of interviews with each of the adults in the house. The interest of speaking with all the adults in the house was to capture the different experiences of the technologies. That was decided because, during one of the pilot projects of the research (see section 3.4), it was found that, in some cases, those adults in the house who signed up to get the technology often had a more positive experience of the changes in indoor conditions. Interviewing other adults living in the same house was an opportunity to capture other experiences. However, that was not always possible (see Table 3.2 for a summary of the interviews carried out). Children were not invited to participate because they were not the focus of the study and getting access to them would have required a much more complicated and lengthy ethics application process.

Each of the participants was interviewed two times (see table 3.3) (serial interviewing). There were two reasons why that was decided. First, as several researchers have shown (e.g., Hitchings, 2012; Read, 2018), interviewing participants multiple times helps to build familiarity and trust with the researcher and helps them be more comfortable sharing information. Second, in contrast with one-shot interviews, this approach is particularly useful for exploring evolution and variation over time (Read, 2018). In those cases where the technology had already been installed by the time when the participants signed the consent form to participate, the first interview was used to capture their initial experience with the technology, and the second interview assessed the evolution of the heating practices over time. In those cases where the technology had not been installed, the first interview explored the practices with the existing technologies, and the second one explored their heating practices with the new technologies. However, during the analysis, it was found that it was more useful to discuss heating practices with the old technologies once the new technologies were installed than before. This is because householders found it easier to discuss the differences between heating practices with one and the other technologies than to talk about heating practices without something to compare them, which is consistent with Few (2021). That suggests that moments of disruption in the practice are particularly useful to discuss these practices, as they make householders more aware of the mundane and routine. All the interviews were carried out in winter, as it was thought it would be easier for householders to discuss the heating practices.

Due to the COVID pandemic and strict lockdowns, the research was designed to minimize the risks for the interviewer and participants. As a result, participants were given the option to carry out the interviews either online, using MS Teams, or in person. Most of them decided to participate online and only two interviews were carried out in person in the participants' house. In some cases, virtual interviews are often seen as poor substitutes for face-to-face interviews (Braun & Clarke, 2013). However, Bryman (2012) suggests that the concerns are not as great as sometimes feared as virtual interviews still allow the participants to see each other (non-verbal communication), and there is no evidence that they affect the capacity of the interviewer to secure rapport. The few interviews that were carried out in person included a home tour which was particularly useful for the interviewer to understand the physical arrangement of the technology and some of its problematics (e.g., the noise of the system).

Table 3.3. Summary of interviews with participants.
The pseudonyms of the participants in each case start with the same letter.

Pseudonym	Case	1st interview	Means	2nd interview	Means
Barry	H1	22/04/2021	Video call	27/04/2022	Video call
Richard	H2	16/04/2021	Video call	29/03/2022	Video call
Greig	H3	15/04/2021	Video call	01/04/2022	Video call
Grace	H3			08/04/2022	Video call
Nelson	CH1	22/11/2021	Video call	31/03/2022	Video call
Nicole	CH1	22/11/2021	Video call	31/03/2022	Video call

Laurence	CH2	09/12/2021	Video call	25/04/2022	Video call
Simon	CH3	23/11/2021	In person	31/03/2022	Video call
Susan	CH3	01/12/2021	Phone call		
Clare	CH4	29/11/2021	Video call	22/03/2022	Video call
Corinna	CH4	10/12/2021	Video call		
Jim	CH5	22/11/2021	Video call	21/04/2022	Video call
Jessica	CH5	22/11/2021	Video call	28/04/2022	Phone call
Dorothy	CH6	22/12/2021	Video call	11/04/2022	Video call
Daniel	CH6	22/12/2021	Video call	11/04/2022	Video call
Molly	CH7	09/12/2021	In person	24/04/2022	Video call
Matthew	CH7			24/04/2022	Video call

Interview guide

The interviews were structured using an interview guide with some questions and themes (see Appendices 10.3) that was kept open to adapt it to the flow of the conversation during the interview (Kvale, 1996). As suggested by White (1981), the topics were organised following a funnel structure; starting with general questions and moving to more detailed ones. This type of structure is particularly useful when the participant knows the topic, as was the case. This is because it helps to avoid missing any relevant information while giving room to the participants to elicit other issues that they might consider relevant (White, 1981). Care was put in place to avoid leading and closed questions.

Three interview guides were developed (see Appendices 10.3). Two for the first round of interviews and one for the second one. One of the interview guides for the first round was directed to participants who did not have the new heating system installed (Cases CH5, CH6 and CH7) and the other one to those who already had it (Cases H1-H3 and CH1-CH4). The interview guides were influenced by the literature review of the topic, the pilot interviews with the customer service team (see section 3.4) and the pilot project developed in parallel and reported in Martin-Vilaseca et al. (2022) (see section 3.4). The interview guides were tested with colleagues, and, as suggested by Braun and Clarke (2013), they were improved during the project as new issues arose, or it became necessary to clarify or reframe some questions.

The interviews covered different topics including the background context (e.g., number of people living in the home), the installation process, and the heating practices with the new technologies. The latter was analysed through questions about the participants' experience with the technologies (including thermal comfort), how they used them, and which conflicts arose after its adoption. Each of the questions was linked to one or more of the elements that, according to Shove et al. (2012), constitute heating practices: meanings, competences and materials. In addition, the participants were asked about their specific experience with the technology the day of the interview or the day before. That was done to encourage participants to discuss their actions and experience more specifically, avoiding potential biases.

Analysis

The interviews lasted between 35 and 75 minutes. Prior to any interview starting, participants were asked for permission to audio-record the interviews. All granted this permission, so interview recordings were transcribed, coded and analysed. The recordings were only used for transcription and were deleted at the end of the project to minimise potential data protection breaches. All transcriptions were pseudonymised. The transcriptions focused on the words spoken rather than on capturing non-verbal utterances as well; the latter was unnecessary given that this research used thematic analysis rather than discourse analysis. The transcriptions were coded using NVivo.

<u>Thematic analysis</u>

The data from the interviews was analysed using thematic analysis as described by Braun and Clarke (2006). Thematic analysis is a method for identifying and analysing themes arising in the data and is widely used in qualitative research (Braun & Clarke, 2006). Unlike some other approaches to qualitative data analysis, it is not theoretically bounded (Braun & Clarke, 2006). The analysis of the interview data aimed to go further than simply describing what the participants explained that it was happening. Instead, it tried to gain a deeper understanding, unpicking the different elements that contribute to the experience of the householders and the heating practices with the new technologies.

The analysis followed the approach developed by Braun and Clarke (2006) and comprised several stages: familiarisation with the data, generating initial codes, searching for themes, reviewing themes, analysing each of the themes and writing up.

- Familiarisation: The analysis of the qualitative data started during the interviews and the transcription of the recordings. These stages were critical in the process of familiarisation. The researcher took notes to summarise the most important elements in each of the cases. Issues like the problems with the noise of the system and its running costs became obvious at this stage.
- Generating initial codes: The transcriptions were extensively analysed to identify different codes (the different features in the data). That process generated an initial list of 324 detailed codes, although some of them were very similar or repeated. The codes covered issues like the householders' reactions to the new technologies, how they controlled these heating technologies or the previous ones, their expectations of the system, etc. The process of coding was not approached with specific questions other than the research questions presented in section 1.1.
- Searching for themes: The list of codes was then reviewed, and some of the codes were collated. Through that process, it was possible to identify different themes discussed in the interviews. Four main themes were identified: Installation process, Achieving comfort, Waste (including economic and environmental costs), and Trust-Control. Each of the themes had various subthemes.
- Reviewing themes: The initial themes were reviewed, refined and discussed with the supervisors. That process reduced the main themes studied to two: Achieving comfort and reducing waste, with several subthemes.
- Analysing the themes: Once the main themes were identified, all the transcriptions were re-coded for each of these themes, paying particular attention to the role of

social practices in them, and trying to identify the elements that constitute the practice. The comfort-related sections were also coded to identify the different changes in the indoor conditions (e.g., temperature radiators) as described in section 2.2. This second process of coding was more theory-driven. A summary of these codes can be found in Appendices 10.4.

As this summary shows, the analysis process took a more inductive approach at the beginning and a more deductive approach later on. The themes studied emerged from the data and were not theory-driven. Once they were identified, they were analysed top-down using an SPT framework.

Flyvbjerg (2006) explained that some academics have criticised qualitative methods for contributing to a bias towards verification of the preconceived notions of the researcher. While he suggests that they do not contain more bias than other methods and the closeness to the subject of enquiry might help the researcher be more aware when that happens, this is still a threat for the research reported here. Given that this research was theory-informed and the author was already aware of some of the problems arising from the adoption of the technology, there was a risk that the data was forced to fit the chosen theory, as Sandelowski and Barrosso (2002) caution. There is also the risk that some of the highlighted problems received more attention than others. The approach taken to the analysis should have helped to mitigate these risks. Additionally, the triangulation of the findings using other methods (Silverman, 2013), as done in this research, should also contribute to further minimise them.

3.2.4. Technical research

In addition to the analysis of social data, this research also studied the experience of the householders through technical data obtained through monitoring. The ETI (2018) and Foulds et al. (2013) make a strong case for combining qualitative methods and monitoring data. The first suggests that monitoring data can help better understand what people actually do. However, it is not only relevant to understand what they do but also to explore the outcomes of their actions and to better understand their experiences. In this case, the monitoring data is used to provide context to the analysis of the interview data, and it is key to understanding what householders expect and do. The interest of the analysis was in three areas: the heating operation, the indoor conditions and the householders' manual overrides of the temperature schedules.

Collecting data

In this research, two different sets of data were analysed: the information collected by the smart heating controls about the heating operation and the temperature setpoints and the indoor temperatures in different locations of the house collected through dedicated monitoring devices. Hereafter, the first dataset will be called smart heating controls dataset, and the second will be referred to as monitoring dataset.

Smart heating controls dataset

The smart heating controls have a series of monitoring devices that collect information about the operating conditions of the system. The sponsoring company had remote access to this dataset, which is stored for analysis. Access to this dataset was granted by the monitoring company to analyse the technical aspects of the project. The dataset includes, among others:

- Boiler call for heat (0/1): signal to the boiler to provide heating.
- Heat pump firing status (0/1): signal to the heat pump to provide heating.
- Flow temperature (ºC)
- Return temperature (ºC)
- Flow rate (l/h)
- Heat output of the system (kW)
- External temperature (ºC): external temperature from the nearest Met Office weather station.
- Indoor temperature (ºC): temperature measured at the thermostat.
- User temperature setpoint (ºC): requested temperature setpoint, including manual changes.

- User scheduled temperature setpoint (ºC): requested temperature setpoint according to the temperature schedule.

The data was recorded at 5-minute intervals (288 values per day for each variable) since the new heating system was installed. In those compact hybrid cases where the technologies were removed at the end of the trial, the data does not continue after the end of April 2022. In those cases in which the system was not removed, the smart heating controls continued to collect information. However, due to some connectivity problems in the compact hybrid project, the quality of the data for the winter 2022/2023 was very low, with many missing values. Therefore, no analysis of this dataset was performed for this period, and the technical analysis was limited to winter 2021/2022 (see Table 3.3).

<u>Monitoring dataset</u>

In addition to the dataset supplied by the industry sponsor, the indoor temperature was also measured with dedicated monitoring devices in all the cases studied. In the hybrid cases, the temperature was monitored in four different rooms (main bedroom, near the thermostat, widely used room 1, widely used room 2), while in the compact hybrid cases, the temperature was monitored in six rooms (main bedroom, second bedroom, near the thermostat, kitchen, living room, widely used room). As the research was designed during the pandemic, it was decided that to minimise the risks for the participants and the researcher, the monitoring should not require the researcher to visit the properties, and the monitoring devices would be posted to the participants. Therefore, it was decided that only the indoor temperature would be measured as the monitoring devices needed to measure other parameters, such as the radiant heat or the noise, would be more invasive and would require access to the participants' houses to install them.

The need to monitor the indoor temperatures was presented in the information sheet and was one of the conditions included in the consent form to accept to participate (see Appendices 10.2). The monitoring devices were posted to the participants' homes, and they were asked to place them following the instructions provided (see Appendices 10.5.1). Additionally, each device had a label with the name of the room where it should be placed (e.g., main bedroom). At the end of the monitoring period, the participants received a prepaid envelope that they could use to return the devices to the researcher. In addition to the instructions provided, to ensure that the devices were used correctly, the researcher requested participants to send pictures of the devices in place, and at the end of the monitoring period, they were asked to complete a short survey for each of the devices indicating its exact location, to try to identify potential problems (see Appendices 10.5.2).

A battery-powered Hobo U12-012 temp/RH logger was used (Temperature range of -20° to 70°C and accuracy ± 0.35°C from 0° to 50°C). The monitoring started between November 2021 and December 2021 for all the cases except CH5 and ended the last week of April 2022. In CH5, the new heating system was installed as part of a house refurbishment, and the monitoring did not start until 08/02/2022.

Data cleaning and preparation

The monitored dataset and the smart heating controls dataset supplied by the industry sponsor were checked to see if there were missing data or errors that could affect the validity of the results. That was done through visual inspection of the datasets and some basic analysis. It was done independently for each dataset and then jointly.

Smart heating controls dataset

The cleaning process, in this case, involved two tasks. First, the instances in which the data presented "unexpected" patterns or values were identified and discussed with the supervisor at the industry sponsor. In most cases, that had to do with problems in the import process and new datasets were provided to address these limitations. Second, identifying periods of missing data. In this case, those days with data missing for one or more values were removed from the dataset. The only exception was when data for the external temperature was missing. In this case, a minimum of 12 hours of data per day (144 timestamps) were required. This was because the external temperature data was only used to calculate the average external temperature, and as it was only stored when the temperature changed, there were more missing values. At that point, it was discovered that the heat meter in H3 did not work properly and did not record any data. Therefore, the analysis of this case was limited as it was not possible to check when the heating system was running.

In addition to the visual inspection of the dataset, a new indicator indicating whether the heating was on or not was created to prepare the data for the analysis. Acknowledging when the system is heating is critical for some of the indicators studied. However, after performing the first calculations, it was noticed that the data was noisy, and using the heat output or the heating system call for heat to define when the heating was running could be misleading. For example, there were some instances in which the boiler or the heat pump call for heat was 1, but the heat output was close to 0 or even negative. Assuming that the heating was on in these cases would be wrong as the heating system was not providing any heat to the radiators. In the new variable, heating was assumed to be on if the following conditions were met:

- Boiler or heat pump call for heat = 1
- Flow rate >150 l/h
- Heat output from the heating system >1 kW

These thresholds were defined after visually inspecting the data.

Monitoring dataset

The temperature dataset measured through the monitoring devices was explored visually to find outliers or unexpected patterns. Additionally, the survey data collected at the end of the monitoring campaign was used to ensure the devices were installed properly. In those cases in which the temperature showed repetitive and unexpected peaks (e.g., temperatures above 25ºC in winter every afternoon) or the participants indicated in the survey that the device was set incorrectly (e.g., too close to a heat source), the data collected from these temperature loggers was not used. As a result of that, not all the cases had the same number of rooms with valid data (see Table 3.3). In a few cases, the participants were contacted during the analysis to clarify the results, but they were not always able to help.

Comparing the data from the smart heating controls and monitoring

The final stage of the data cleaning process involved analysing the quality of the temperature data recorded by the smart heating controls. To do that, as part of the research, the participants were asked to place one of the temperature sensors in the same room as the wall-mounted heating controls (that include the indoor temperature sensor used by the smart heating controls). To ensure that both the data collected by the thermostat and the monitoring devices were comparable, the correlation between the two temperatures was calculated. In all the cases, the relationship between the two parameters was close to 1 (>0.9), which suggests that the temperature measured by the thermostat was similar to that measured by the temperature data loggers (see Table 3.4).

Table 3.4. Summary of the technical data analysed

Case	Period analysed smart heating controls dataset	Period analysed monitoring dataset	Number of rooms with valid monitoring data	Correlation temperature smart controls and monitoring
H1	01/10/2021 – 30/04/2022	01/10/2021 – 26/04/2022	3	0.93
H2	01/10/2021 – 30/04/2022	01/10/2021 – 26/04/2022	4	0.98
H3	01/10/2021 – 30/04/2022	01/10/2021 – 26/04/2022	4	0.99
CH1	01/10/2021 – 30/04/2022	01/10/2021 – 26/04/2022	6	0.98
CH2	01/10/2021 – 30/04/2022	01/10/2021 – 26/04/2022	6	0.96
CH3	01/10/2021 – 30/04/2022	01/10/2021 – 26/04/2022	6	0.90
CH4	01/10/2021 – 30/04/2022	01/10/2021 – 26/04/2022	5	0.96
CH5	08/02/2022 – 30/04/2022	08/02/2022 – 26/04/2022	6	0.90
CH6	22/12/2022 – 30/04/2022	22/12/2022 – 26/04/2022	6	0.95
CH7	16/12/2021 – 30/04/2022	16/12/2021 – 26/04/2022	6	0.99

Development of new indicators

As summarised in the first research question (see Section 1.1), one of the aims of the research reported here was to better understand the heating operation and the indoor conditions in the house, once the new heating system was installed. As explained in section 2.2, the addition of the heat pump and the smart heating controls was expected to affect a wide range of characteristics related to the heating system activity and the indoor conditions. However, as explained before, measuring some of these characteristics requires specific monitoring devices that are very invasive and require the researcher to access the property. As it was decided that the monitoring should be carried out without needing to visit the participants' houses, the characteristics studied are those that were found to be more relevant for the householders' experience and that could be measured using the monitoring dataset or the smart heating controls dataset. The decision on the exact characteristics to be analysed was not only driven by theory or the available data. It was also informed by an initial analysis of the interview data, and therefore, the analysis of the technical data reflects the experiences of the participants and makes it easier to compare the findings. By doing that, the study intends to bridge the incommensurability of technical and social data, which is one of the challenges of combining social and technical approaches, according to Love and Cooper (2015).

Seven different characteristics of the indoor conditions and the heating operation were analysed: the flow temperature, the heat output, the heating duration and times, the temperature oscillation in the evening, the temperature drop at night, the temperature gradient across the building and the manual changes in the temperature schedule. Different indicators were created to analyse each of them. The details of the indicators can be found in the following subsections.

The absence of pre and post-installation data made it impossible to measure how much these characteristics changed with the adoption of the new technology. The study developed two ways to overcome this limitation. First, the results were compared with the existing literature on combi gas boilers. Second, in those cases in which there was no literature on the topic, the characteristics studied were analysed under different conditions. As the new heating technology installed was a hybrid system, the characteristics studied were measured in those cases in which the system operated like a combi boiler and compared to those situations in which the system operated like a heat pump. While that approach cannot substitute a pre and post-installation analysis, it provides interesting insights into how the parameters evolved after the adoption of the new system.

Flow temperature

The flow temperature was analysed using the flow temperature data recorded by the smart heating controls after removing all these values recorded during periods in which the heating was not on. Three indicators were studied:

- Average daily flow temperature when the heating was on.
- Flow temperature when the heating was on per 5-minute period.
- Flow temperature when the heating was on per 5-minute period for each heating mode (boiler mode, heat pump mode or mixed mode).

Heat output

The heat output was analysed using the heat output data recorded by the smart heating controls after removing all these values recorded during periods in which the heating was not on. Three indicators were studied:

- Average daily heat output when the heating was on.
- Flow temperature when the heating was on per 5-minute period.
- Flow temperature when the heating was on per 5-minute period for each heating mode (boiler mode, heat pump mode or mixed mode).

Heating duration and heating times

The heating duration was calculated by adding up all the 5-minute periods when the system was heating. Three indicators were studied:

- Average daily heating duration: number of hours the heating was on per day.
- Correlation between the heat output and the heating duration: Correlation between the average heat output per day and the time the heating was on this day. Only data for the days in which the average external temperature was between 3ºC and 7ºC was used. That was done to minimise the effect of the external temperature on the results.
- Probability of the heating being on per each 5-minutes period: Percentage of the days the heating is on per each 5-minutes period.

Temperature oscillation when warmth is requested

The temperature oscillation was calculated for the period compressed between 5pm and 11pm. This period was chosen as it is a period in which householders often requested heat; they were more likely to be at home and awake (according to what they explained in the interviews) and fall within the times BREDEM (Building Research Establishment Domestic Energy Model) assumes that the heating is on (Huebner et al., 2013a). The temperature oscillation was measured as the standard deviation (SD) of the indoor temperature measured by the thermostat during this period. Only those days in which there was heating demand were included. The standard deviation has previously been used to calculate temperature variations in domestic buildings (see Huebner *et al.*, 2013b, 2015; Teli *et al.*, 2018, 2021). The new parameter was called Standard Deviation of the Temperature in the Evening - SD(TE). Two indicators were studied:

- Average Standard Deviation of the Temperature in the Evening – SD(TE) per day.
- Correlation between the heating duration and the SD(TE): Correlation between the heating duration and the SD(TE) per day. Only data for the days in which the average external temperature was between 3ºC and 7ºC was used. That was done to minimise the effect of the external temperature on the results.

Temperatures during periods that used to be cold

The temperature during periods that used to be cold was calculated as the temperature difference between 8pm and 4am (the following day). The exact times were chosen because at 8pm most householders were at home (as explained during the interview) and it was more likely that the house was at temperature (warmth-requested period temperature). At 4am all the participants were sleeping, there were no solar gains, and it was well before any participant requested warmth so it was unlikely that the system would be preheating if operating on boiler mode. While there is not much literature on the temperature drop at night when using combi boilers, several researchers have analysed the temperature pattern over the day before (see Huebner *et al.*, 2013b, 2015; Hanmer *et al.*, 2019a; Pullinger *et al.*, 2022). From these temperature profiles, it was easy to calculate the temperature drop at night. The new parameter was called temperature drop at night - TD(N). Two indicators were studied:

- Average Temperature drop at night per day – TD(N) per day.
- Correlation between the heating duration and the TD(N): Correlation between the heating duration and the TD(N) per day. Only data for the days in which the average external temperature was between 3ºC and 7ºC was used. That was done to minimise the effect of the external temperature on the results.

Temperature differences across rooms

The temperature differences across rooms were calculated using the data monitored with the temperature data loggers. To calculate the temperature differences, the standard deviation of the temperature across the monitored rooms was calculated for every day for each timestamp. Then, the average value per day was calculated. The parameter studied is the average Standard Deviation of the Room Temperatures SD(RT). It is important to point out that the standard deviation is affected by the number of values included. Therefore, the results of the analysis are affected by the number of rooms with valid data included in each case. As not all the cases had the same number of rooms analysed, the results might be affected by that. Therefore, comparing the results obtained across the sample might be misleading. Two indicators were studied:

- Average Standard deviation of the Room Temperatures – SD(RT) per day.
- Correlation between the heating duration and the SD(RT): Correlation between the heating duration and the SD(RT) per day. Only data for the days in which the average external temperature was between 3ºC and 7ºC were used. That was done to minimise the effect of the external temperature on the results.

Un-scheduled interactions with the controls

The number of manual changes to the scheduled temperatures is one of the most relevant parameters analysed. This is because it directly affects the capacity of the system to forecast the heating demand, and therefore, the efficiency of the system. Previous research has focused on understanding the times of the day when these un-scheduled changes occur

(Hanmer, 2020), whether they occurred during warm-requested periods or not (Hanmer, 2020), or the amount of time the heating runs on un-scheduled temperature setpoints (Morton, 2016). However, the interest, in this study, was on whether participants overrode the scheduled temperature or not. Therefore, a simpler analysis of the days with manual changes in the scheduled temperature setpoint was sufficient. That was calculated by comparing the scheduled temperature setpoint and the real temperature setpoint of the system for each 5-minute period. In those cases in which there was a difference between the two values, that was recorded as a manual change, and it was indicated whether it was an increase in temperature or a decrease. This information was used to calculate four different indicators:

- Number of days with manual changes in the scheduled temperature during the heating season.
- Number of days with manual increases in the scheduled temperature during the heating season.
- Number of days with manual decreases in the scheduled temperature during the heating season.
- Number of days with manual changes in the scheduled temperature per month.

3.2.5. Combining social and technical data

Energy research in domestic buildings is often characterised by a division between social and technical analyses (Love & Cooper, 2015). The combination of both approaches is less common, and Love and Cooper (2015) suggest that it presents various challenges. First, each of the approaches is often underpinned by different philosophical assumptions and theoretical models that are incompatible. Second, the social and the technical data often report on different things. For example, the temperature sensors measure the internal air temperature while what people experience and report as temperature is a combination of many factors, such as radiant temperature, air temperature, temperature gradient, etc. Third, the technical and the social data have different temporal resolutions which renders them difficult to compare. While technical data is often monitored almost continuously over extended periods of time, social data is collected at occasional intervals and the experiences at specific dates and times that may not be accurately recalled, or may not even be reported. Foulds et al. (2013) add an additional challenge to the list. They explain that, while the indoor conditions monitored are the result of social practices, many different practices are involved (e.g., ventilation practices, heating practices, cooking practices, etc.) and it is often complex to disentangle this complexity.

The analysis of the social and technical data collected in this study was designed to overcome some of these limitations. First, the research took a social practice theory approach that acknowledges the important role of the technical and the social. While the new technologies installed have certain intrinsic characteristics that make them different from the combi boilers that they replace, the indoor conditions monitored result not only from these differences. They are, as suggested by Foulds et al. (2013), the outcome of social practices. Second, the analysis of the social data paid attention to unpicking the elements that shape the experience of the householders so that the findings of the social data can be triangulated with those of the technical data. That was especially true of the analysis of thermal comfort data. For example, when participants reported being warmer with the new technologies, they were asked to discuss it in detail, to better understand the physical changes underpinning their experience. Third, when possible, the actions described by the interviewees were linked to the specific times when they happened and later triangulated with the technical data. That was done with the participants description of their interactions with the heating controls.

Despite that, this research is not socio-technical as defined by Love and Cooper (2015). While the project produced social and technical data, the generation and analysis of this data were not always integrated (e.g., the technical data was not presented to the participants), and the two data sources were not of equal importance. This is a social and technical project in which the social data led the analysis. Although there was a back-and-forth process when analysing the two data streams, the role of the social data was more central, mainly because of the extensive data available. The social data was analysed before the technical data.

3.3. Content analysis of the CRM dataset

The last piece of analysis included in this thesis is the content analysis of the data stored through the Customer Relationship Management (CRM) software, which includes all the communications between the Customer Service Team (CST) at Passiv UK and participants in a large-scale project where hybrid heat pumps with smart heating controls were installed. Content analysis is a widely used approach to the analysis of texts or documents (Bryman, 2012). Previous research on energy and heating has analysed the content of magazines and online articles (e.g., Strengers & Nicholls, 2018), online forums (e.g., Royston, 2014), statistical data, advertisements and newspaper articles (e.g., Heidenstrøm *et al.*, 2013), factsheets and online advice (e.g., Nicholls & Strengers, 2018), etc. However, to the author's knowledge, no previous energy research has analysed CRM data of any type.

While content analysis has been used as the primary research method (e.g., Royston, 2014), in this case, it is used in combination with the analysis of the case studies presented in the previous sections. The CRM data is used to cross-validate (triangulate) the findings of the case studies and to provide guestimates[15] of the scale of some of the issues observed in these cases. This type of analysis is particularly useful for cross-validation as it provides access householder's experiences and practices minimising the influence of the researcher on their responses (Braun & Clarke, 2013; Bryman, 2012). Additionally, the analysis of the CRM data is extremely useful because it gives access to a large sample without the complexity or the resources necessary to approach them using other methods (e.g., interviews or surveys).

However, Coffey (2014) warns of the risk of seeing the documents or text analysed as portraits of the social reality of the people or organisations that generate them. She explained that documents are social artefacts "that are created for a particular purpose, crafted according to social convention to serve a function of sorts" (Coffey, 2014:p.369).

[15] Due to the intrinsic characteristics of the dataset studied and its limitations, the dataset cannot be used as a representative sample of the population who have these technologies at home.

Therefore, they cannot be treated as exactly the same as empirical evidence of what they report. In this case, they have to be understood in relation to the aims of the database creators and the aims of the householders included in the database due to contacting the CST. Moreover, any consideration of this database must bear in mind the absence of householders who did not contact the customer service team; absence from the database does not imply the absence of an issue.

The CRM data analysed is obtained from a database that contains information on all interactions between the customer service team and a group of householders for a specific project. The customer service team at Passiv UK was in charge of maintaining and updating the database. Every time that a participant in the project got in touch with the company (in person, by phone or by e-mail), a summary of the conversation was stored in the database. In those cases in which the communication was through e-mail, the content of the e-mail was also uploaded to the system. For each issue discussed, a ticket was opened, which included all the communications with one participant regarding one topic. It is important to note that the database is biased as it almost only contains negative experiences. This is because participants usually only contact the customer service team to complain about issues that they are unable to solve. Additionally, not all the participants might contact them when facing a problem. Finally, it is important to consider that in those cases in which the communication was on the phone, the employee summarises the conversation in the database, and this summary is likely affected by their own view of the problem or their understanding of the technology.

3.3.1. Introducing the case studied

The CRM dataset analysed includes all the communications for a large project with 130 participants. As part of the project, all of them had an air source heat pump installed on top of an existing oil or LPG boiler. The hybrid system was controlled through the smart heating controls developed by Passiv UK. All the properties were located in the UK in off-gas grid areas. The dataset analysed was provided by the industrial sponsor, and it was already fully anonymised. It contains all the communications with the householders happening during the three years prior to the analysis (06/2020 to 04/2023).

3.3.2. Analysis

Bryman (2012) suggests that content analysis is not a research method in itself but an approach to analysing documents and texts. It is a very flexible approach that can give access to any type of unstructured textual information. Depending on the emphasis of the analysis, it might be used in quantitative and qualitative research. Therefore, Kracauer (1952) distinguishes between approaches interested in measuring the frequency of certain words or themes in the document (manifest content) and those that focus on the underlying "latent" content. However, he warns about some of the limitations of quantitative analysis as often researchers assume that the texts and documents analysed have clear and manifest content that can be analysed quantitatively, and they often overlook the multiple connotations that they hide.

The analysis reported here is mainly quantitative but incorporates some qualitative analysis to ensure that it captures all the complexity of the analysed data. The analysis builds on the findings of the case studies. First, all the tickets of the dataset were classified according to the two main themes identified in the social data analysis: comfort and waste. Later, they were coded according to the conflicts/issues identified in the case studies (e.g., noisy heat pump). However, the code guide was kept open, and new codes were incorporated as new themes arose. Once all the tickets were coded, they were grouped to measure the number of households that discussed each topic. A total of 979 tickets from 130 different households were analysed. Each ticket contains an average of six messages. All the participants in the project contacted the customer service team at least once.

3.4. Pilot projects and unfollowed paths

The research design outlined in the previous sections was not set in stone from the beginning of the PhD. It evolved over time, and it is the result of several tests and failed attempts. Three main pilot projects or lines of research were tested.

The first one was carried out during the early stages of the research to identify the issues that generated more complaints and conflicts for the householders when using the technology. As part of this study, several customer service employees at the sponsoring company or associated with it were interviewed (n=6). The interviews were transcribed, coded and analysed together with a small set of data from the CRM software following the same approach as discussed in sections 3.2.3 and 3.3.2. The analysis was useful in identifying priority areas for research.

The second pilot project was used to test the specifics of the methods used in the case study and the integration of technical and social data. The project was developed by a researcher at the UCL Energy Institute, and the collection and analysis of the social data (including the design of social research) was led by the author of this thesis. The study aimed to analyse how demand response was experienced by a small group of householders living in houses equipped with stand-alone heat pumps (n=3). The social research involved interviews with all the adults in the house and a comfort questionnaire during demand response events. The pilot project showed the importance of interviewing various adults in the house. This is because it was found that the experience of the person who volunteered to participate in the project, was the one usually in charge of the technology and his or her experience differed from those of other people in the house. At the same time, the project was also useful in deciding that a comfort questionnaire would not provide additional information. A detailed description of the research carried out and the findings obtained has been published as a peer-reviewed conference paper (see Martin-Vilaseca *et al.*, 2022) and in a peer-reviewed journal paper (see Crawley *et al.*, 2023).

Finally, while not designed as a pilot project, it was useful for the research to carry out an initial observation of the installation and the handover process of the technology. This was initially planned to be part of the data included in this thesis. However, the difficulties of attending a reasonable number of installations meant that that aspect of the research was not reported here. One installation (CH7) and one handover process (CH5) were observed. The observations highlighted the importance of the installation and the communication between the installation team and the householders regarding how the technology was used. For this reason, specific questions about the installation process were included in the second round of interviews, which were particularly useful in understanding the impact of the installation experience on heating practices with the new technologies.

3.5. Ethics in research

This research followed the UCL Barlett School of Environment, Energy and Resources (BSEER) procedures for low-risk ethics approval. A first application was approved during the first year of the PhD, which covered the analysis of the CRM dataset. A second application was submitted and approved before starting the main data collection (before upgrade). A third application was submitted and approved to cover the changes in the research half-way through the project (new sample). The project was compliant with the General Data Protection Regulations (registration number: Z6364106/2021/01/80). Additionally, a Non-Disclosure Agreement (NDA) was signed between the researcher and the industrial sponsor (Passiv UK) to share the data needed for the research.

All the information was pseudonymised before the analysis and any information that could identify the participant has been removed. The personal information required for the interviews (address, email address and contact number) was stored in a password-protected file and was deleted at the end of the research. The recordings of the interviews were also deleted at the end of the project. All the participants received an information sheet (see Appendices 10.1) before starting the project. They were asked to sign a consent form (see Appendices 10.2) to participate. The form included giving consent to receive and use the data collected by the smart heating controls in the participants’ homes regarding the operation of their heating system and the temperature setpoints requested.

3.6. Impact of COVID and the cost-of-living crisis on the research

As mentioned throughout this document, the research presented here was partially developed during the COVID-19 outbreak and the cost-of-living crisis (see Figure 3.1). Both events indubitably affected the research and the context in which it was developed. However, each of the events had a different impact.

This PhD started only 6 months before the COVID-19 outbreak. At this time, only an initial pilot project had been planned, which had to be re-designed, considering the new situation. The rest of the research that constitutes this thesis was mainly designed during the COVID lockdowns. Given the uncertainty of these periods, the research was planned to be very robust and require as little interaction with the participants as possible. As explained in sections 3.2.3 and 3.2.4, the interviews were designed to be carried out online, and only those monitoring devices that could be posted to the participants and placed in the correct location by them were used. However, the situation worldwide improved quickly, and most of the data was collected after the lockdowns. Because the research was already designed by that time and there was still uncertainty about potential future COVID outbreaks, the research was carried out mainly as designed. The researcher offered the participants the option to conduct in-person interviews at their house. However, only a few of them accepted (see Table 3.3). The COVID lockdowns also affected some of the companies involved in the trials of the technology. As explained in section 3.2.1, the Hybrid project was cancelled after one of the companies behind it went into administration. This event required the researcher to recruit new participants, which is why the Compact Hybrid project became part of this research.

In contrast, the cost-of-living crisis did not affect the researcher directly. By that time, the research was already designed and the data was being collected. However, it had a more notorious effect on the participants' lives and their experience of the technologies tested. Between the first and the second rounds of interviews, the energy prices escalated quickly, and energy became the focus of much public debate. Heating practices were probably affected by that situation. To assess that, during the second interview, the researcher asked the participants if their heating practices had changed because of the cost-of-living crisis. As shown in Section 6.3.1, most explained that they did not alter their practices. However, it is likely that not all the changes were mentioned by the participants, or there might be changes that they were not aware of. This is, as explained in section 7.2, one of the potential limitations of this research. Despite that, it is important to point out that the fuel prices used in the optimisation (smart controls), did not change during the whole trial (see section 3.2.1).

Figure 3.1. Timeline of the research in relation to COVID and the cost-of-living crisis.

3.7. In conclusion

The previous Chapter 2 has explained that hybrid heat pumps with smart heating controls are adopted in a socio-technical system, the home, that combines physical, emotional and behavioural dimensions and suggested that the analysis of the adoption and use of these technologies has to acknowledge this complexity. This Chapter has outlined a research design that takes that into account by studying the technologies in real settings using a social practice theory approach. The research design integrates a detailed analysis of a series of case studies and a dataset with interactions between the customer service team and a group of householders who had the technologies recently installed. The case studies include social and technical research methods and the findings of each are triangulated. The next three chapters (4-6) present the findings obtained with this research design. First, the findings of the analysis of the technical data are presented (Chapter 4). Later on, the findings of the analysis of the social data are introduced focusing on those related to comfort first (Chapter 5) and those related to waste later (Chapter 6).

4. Measuring indoor conditions and heating operation

The literature analysis on hybrid heat pumps with smart heating controls suggests that adopting these technologies has physical and social consequences. The tested heating technologies are more than substitutes for the existing heating systems. They operate in a completely different way (e.g., low flow temperature instead of high flow temperature), and they offer different opportunities for householders to engage with them. The literature reviewed in section 2.2 suggests that the indoor conditions and the heating operation achieved with the new technologies and those provided with combi boilers are not the same. However, in most cases, the physical changes reviewed were calculated using modelling approaches or measured in climate chamber studies, and there is a lack of empirical studies in real settings. The heating operation and the indoor conditions are the outcome of the performance of heating practices. Therefore, they are determined not only by the specifics of the technology but also by the materials (including the physical form of the home), competences, and meanings involved in these practices. For that reason, analysing them in field studies is critical to understanding the physical conditions that householders experience and contribute to creating after the adoption of new technologies.

This chapter explores the conditions experienced and the operation of the heating system through the analysis of the technical data. That aims to enable deeper insights from later chapters, which can then be based on a knowledge of these two things. Therefore, it enables complementary sources of information to be brought together. The analysis is divided into two main parts. First, some of the changes in the indoor conditions and the operation of the heating system are introduced. Second, the householders' interactions with the controls are presented. The analysis aims to answer the following research questions:

- How does the heating system operate as part of the heating practices with the new technologies?
- What indoor conditions are achieved as part of the heating practices with the new technologies?
- How do people interact with the heating controls?

The present chapter uses the technical data collected from the case studies to explore this topic. More specifically, the findings rely on the temperature data monitored in multiple locations within each case study and the data collected by the smart heating controls regarding some of the parameters that define the heating system's operation: the temperatures requested by the householders and the indoor conditions.

The chapter is organised as follows: First, the observed changes in the monitoring data are presented and compared with the literature, focusing first on the operational parameters and later on the indoor conditions. Second, the householders' changes in the requested temperature setpoints are measured. Finally, a brief summary of the findings is presented.

4.1. Measuring the operation of the new technologies

As explained in section 2.2, the way heat pumps or hybrid heat pumps operate significantly deviates from the operation of conventional heating systems (e.g., a combi boiler). These differences can affect the indoor conditions in the home and the householders' experience with the technology. However, the changes described in section 2.2 are based on the findings of modelling studies or physics first principles. Therefore, it is necessary to assess whether these changes can also be observed in real settings. As explained in section 2.2, the changes in the operation of the heating system can be summarised in changes in the flow temperature and the heat output and changes in the duration the heating is on. In this section, these parameters will be measured for each participating household (except H3, for the reasons explained in section 3.2.4). Figure 4.1 shows the parameters studied in relation to all the expected physical changes after the adoption of the new technology.

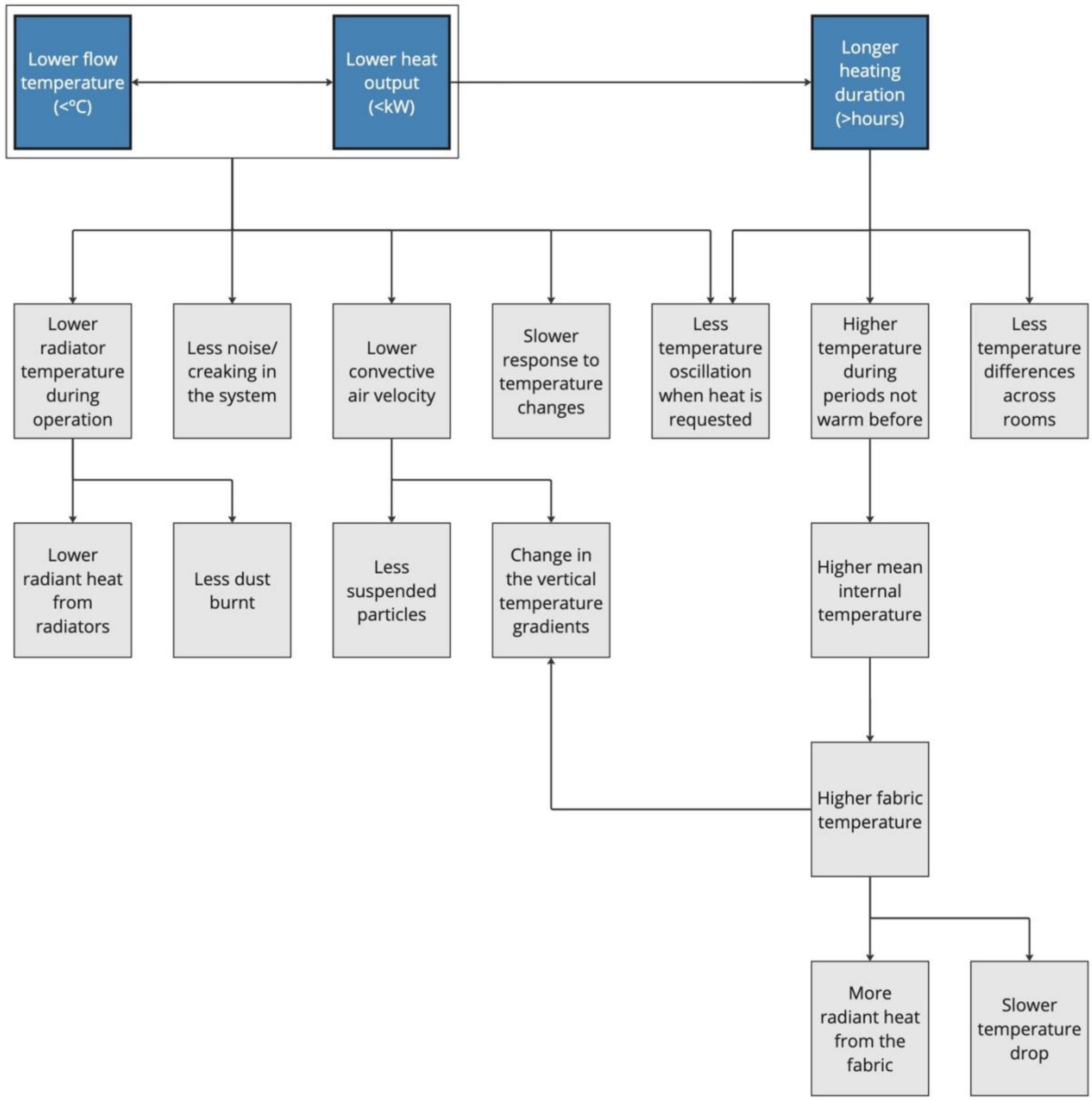

Figure 4.1. Summary of the operational parameters studied (in blue) in relation to the other expected physical changes after the adoption of the new technologies.

However, before presenting the analysis, it is important to note that to measure the true change experienced in each property in the heating operation, it would be necessary to measure it before and after installing the technology. But, as explained in section 3.2.4 that was not possible, and only post-installation data was available. However, other researchers have analysed some of these operation parameters in heating systems with combi boilers. Therefore, the analysis compares the findings obtained with this body of literature. While that does not help measure the change in each home, this provides insights into the potential effects, and it is useful to better understand the householders' experience (Chapters 5 and 6).

4.1.1. Flow temperatures and heat output

A summary of the daily average flow temperatures when the heating was on is presented in Figure 4.2 and a summary of the daily average heat output when the heating is on is presented in Figure 4.3. Both indicators have been calculated according to the method described in section 3.2.4. The average flow temperature across all the cases is 45.6ºC[16] and the average heat output when the heating is on across all the cases is 5.7kW. However, the analysis shows significant differences between cases with an average flow temperature between 30.6ºC in CH1 and 55.7ºC in CH4 and an average heat output ranging from 2.8kW in CH1 to 9.8kW in CH7. Multiple, well-established factors contribute to this, including the thermal efficiency of the building fabric, ventilation practices, the size of the home, the temperature setpoints chosen, etc. CH1, for example, is a well-insulated house with oversized radiators and a low number of manual overrides, in which the system can run at low flow temperatures most of the time. In contrast, CH7 is a large house with a high heating demand, which cannot be heated if the heat output is low. However, within this research, the

[16]As shown in Figure 4.2, the flow temperatures are not normally distributed in many cases. Despite that, the mean is used to characterise the results because it enables comparison to the existing literature.

causes for the discrepancies in heating demand are not analysed in detail, and it is too complex to unpack the effect of each of the factors affecting them here.

Most combi boilers in the UK operate with a flow temperature between 60ºC and 88ºC (Rossi & Bennett, 2024)[17][18], which is above the mean temperatures recorded in most cases. CH4 is the main exception because, as Figure 4.2 shows, the system runs often at temperatures closer to those of a combi boiler. However, even in this case, the system has mean flow temperatures lower than 60ºC on 56% of the days the heating is on. Therefore, while with the available data, it is not possible to confirm that the flow temperature was reduced after the installation of the heating system in the cases studied, the flow temperatures recorded are not common when heating with combi boilers. Therefore, it is highly likely that there was a reduction in this temperature. That will be further investigated in the next chapters with the findings of the social data.

The changes in the heat output after the adoption of the new technologies are more difficult to confirm. This is because there is a lack of information on the average heat output of boilers in the UK, which makes it difficult to compare the findings of this analysis with data at a national level. Bennett et al. (2022) suggest that the typical combi boiler in the UK is sized at 5-28kW (minimum-maximum heat output)[19], which implies a modulation range of 1:6 (which is the current state of the art according to Bennett et al. (2019)). Therefore, the

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[17] For example, radiators are tested according to standard BS EN 442-2 (2014) with an inlet temperature of 75ºC and boiler manufacturers suggest setting the temperature between 60ºC and 68ºC when they provide recommendations for that (Reguis, Vand & Currie, 2021).

[18] In recent years, several organisations (see Energy Saving Trust, 2024b, for example) have encouraged householders to reduce the flow temperatures in their combi boilers. However, they usually do not recommend setting it below 60ºC, to minimise the risk of legionella (NESTA, 2022) and Rossi and Bennett (2024) have shown that despite this advice most combi boilers in the UK have flow temperatures between 60ºC and 88ºC.

[19] CH2, which is the only case in which data about the previous boiler was available, the heating load of the boiler was 28kW (37kW for the hot water load).

measured average heat output when the heating is on is similar to the minimum heat output of combi boilers. However, the analysis of the heat output in 5-minute periods (Figure 4.5) shows that the new heating technologies were often heating below this value. Therefore while with the available data it is not possible to confirm that the heat output was reduced after the adoption of the new technologies, it is likely that there was a reduction in it for at least some periods, as in most cases the heat output is lower than the minimum heat output of most combi boilers (see The heating hub, 2020).

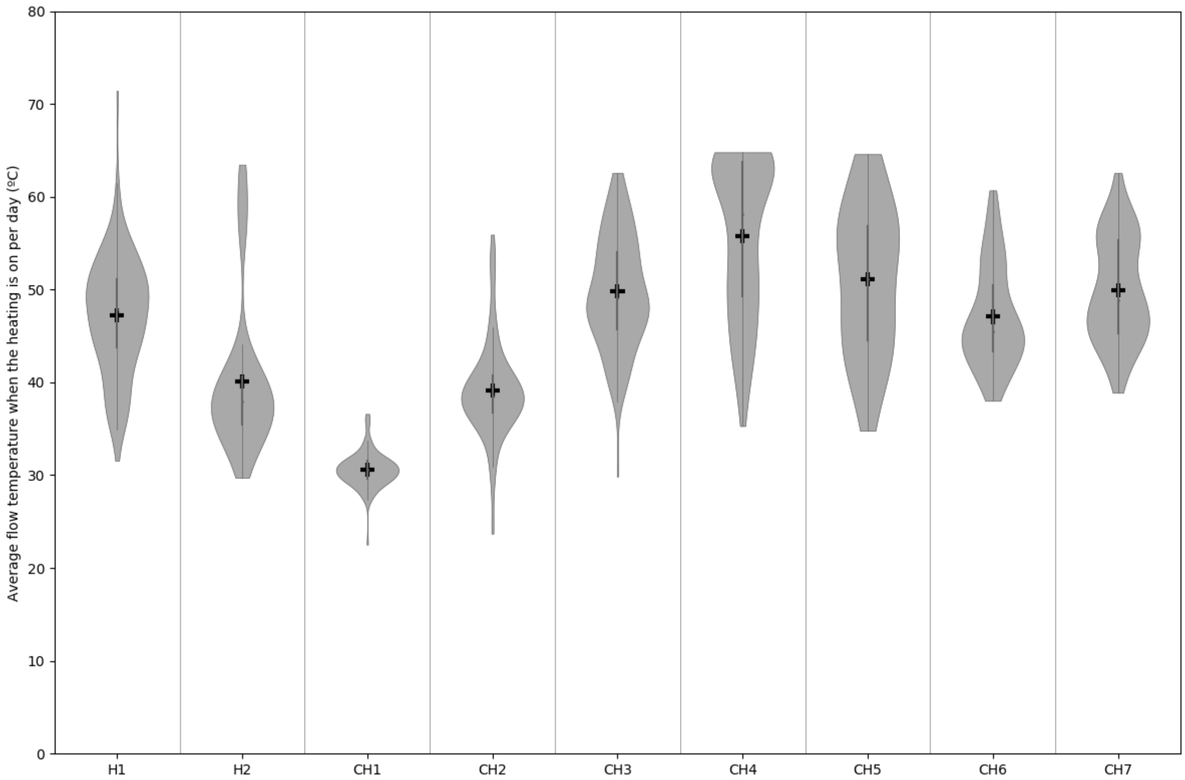

Figure 4.2. Daily Average flow temperature during periods when the heating was on, as measured near the heating device[20].
The + marker indicates the mean value in each case.

[20] It is important to note that the range over which the Kernel Density Estimation (KDE) is plotted for the violin plots is the range of input values. Therefore, the plot might get truncated at the extremes in some cases. This applies to all the violin plots in this Chapter.

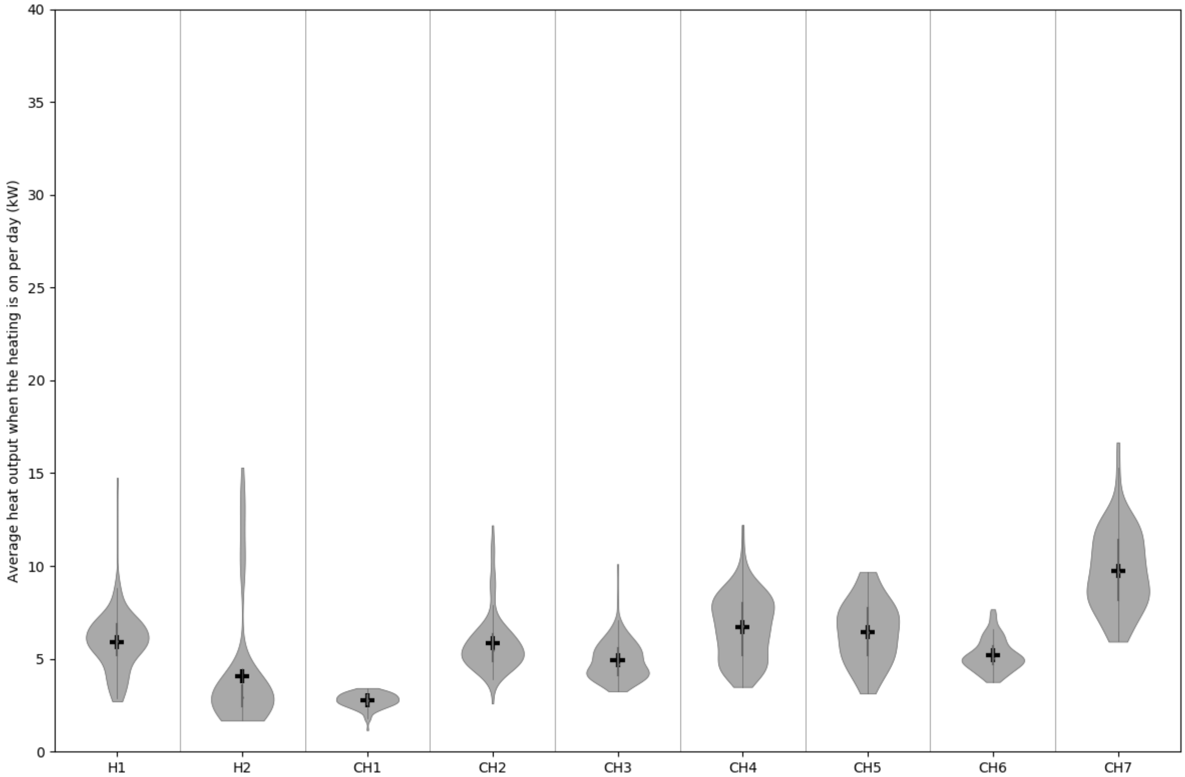

Figure 4.3. Daily average heat output when the heating was on.
The + marker indicates the mean value in each case.

Within each case, the flow temperature and the heat output varied across the heating season. In some cases, the flow temperature shows differences of more than 35ºC, that are not normally distributed. To better understand these differences, an analysis of the flow temperature and heat output per each 5-minute period in which the heating is on is presented in Figure 4.4 and Figure 4.5, respectively. The analysis evidenced important differences between cases. Cases H2, CH1 and CH2 showed a small range of flow temperatures. Additionally, they are, together with CH3, the cases that show lower heat outputs and the only ones with distributions with just one peak (between 2.5kW and 3.5kW). In these cases, the system ran mostly at a constant low flow temperature and provided a low average heat output. The rest of the cases show more variability in the flow temperatures and the heat output. In cases H1 and CH3, this variability has a broadly flat and wide peak between 30ºC and 65ºC (30-75ºC in H1). In contrast, in CH4 to CH7, the analysis shows two distinguishable concentrations of values (35ºC and 65ºC). Those peaks can also be found in the analysis of the heat output: H1, CH4, CH5, CH6 and CH7 showed a multimodal distribution with two peaks. In most cases, those two peaks correspond with the two modes of operation of the system (boiler mode and heat pump mode), as can be seen in Figure 4.6 and Figure 4.7.

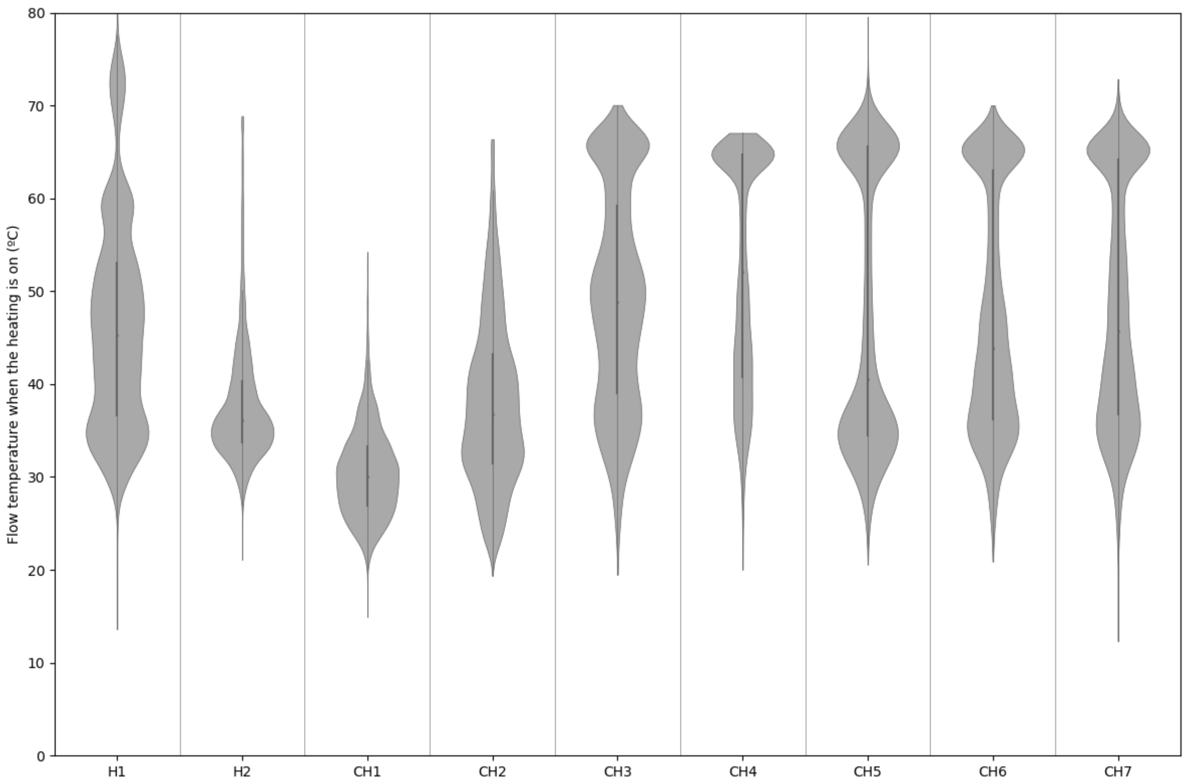

Figure 4.4. Flow temperatures for each 5-minute period when the heating was on, as measured near the heating device for each case.

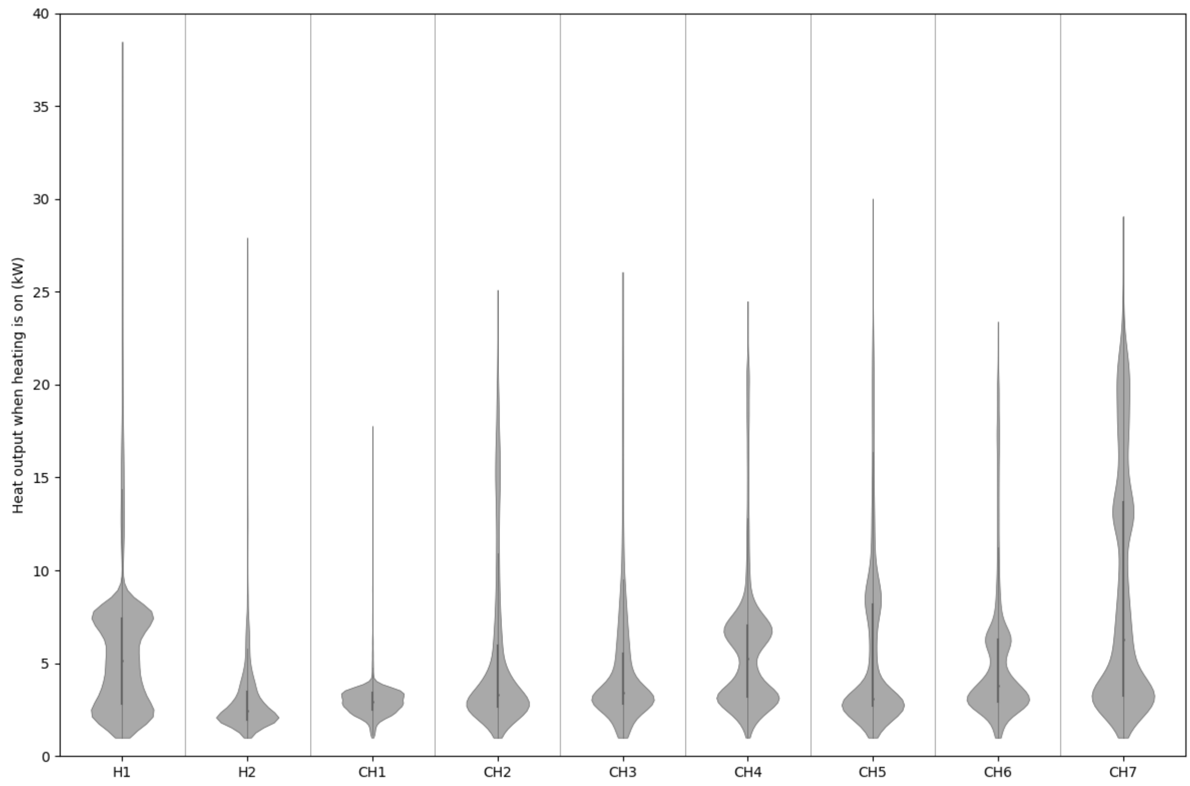

Figure 4.5. Heat output for each 5-minute period when the heating was on.

As shown in Figure 4.6, in all the cases, the flow temperature is higher when the system is in boiler mode than in heat pump mode, with an average flow temperature across the sample of 39.4ºC, 54.8ºC and 40.6ºC when on heat pump mode, boiler mode and mixed mode, respectively. This is consistent with the findings of the analysis of the heat output: in all the cases except CH1, the average heat output when the system was in boiler mode is higher than when it was in heat pump mode. The low heat output in CH1 when on boiler mode is likely to be explained by the small sample of boiler-dominant periods, as the system ran almost all the time in heat pump mode or mixed mode. The lower flow temperatures and heat output when on heat pump mode are consistent with the expected changes described in section 2.2. These results are, in some cases, the consequence of a higher heating power demand that cannot be provided by the heat pump alone, which may be caused by the set points, the controlling algorithm, the heating schedule and lower external temperatures, and it is likely affected by the size of the heat pump installed. As explained in section 3.2.1, the size of the heat pumps was limited by the size of the unit (compact hybrids) or the limitations of the RHI scheme[21] (hybrid units).

The sizing and characteristics of the different components of the system can also explain the differences between the hybrid and the compact hybrid cases. For example, the heat pump in the hybrid cases shows a broader distribution of heat outputs. This can be explained by the fact that the heat pump in these cases is bigger than in the compact hybrid cases and it has an inverter compressor that can modulate its output. In the compact hybrid cases, the average heat output when the system was in heat pump mode was between 2kW and 4kW. This is because the heat pump was designed to have a 4-kW heat output, and it had a single-speed compressor. That means that it was not able to modulate output, and the variation is due to changes in the thermal performance of the heat pump. So, it is entirely expected that heat output is usually much less than 4kW in non-ideal conditions. The data also shows the capacity of the boiler in the compact hybrid cases to modulate the heat output. In CH6, for example, two different peaks can be identified at 3kW and 6kW.

The flow temperatures in heat pump mode are similar to those found in the literature for heat pumps (38.8ºC in the Electrification of Heat project[22] (Energy Systems Catapult, 2023) and 35-40ºC in the RHPP trial[23] (Love *et al.*, 2017b)). However, the average flow temperatures in boiler mode are lower than those commonly found in combi boilers (see Rossi & Bennett, 2024) (which should improve the efficiency of gas boilers, particularly, condensing boilers).

The analysis showed that while the average flow temperature and heat output is smaller when the system is in heat pump mode, there are cases in which the boiler operates at a lower flow temperature and heat output than the heat pump. This is because the control algorithm calculated that it was better for achieving its objective to provide a low heat

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[21] The RHI does not allow claims for more than 20,000kWh of heat per year for ASHP (Ofgem, 2023), and project promoters figured out that installing a heat pump bigger than 8kW was not cost-effective.

[22] The data includes HP and hybrid heat pumps in heat pump mode, but it is not disaggregated.

[23] Heat pumps only (GSHP and ASHP).

output with the boiler. Therefore, it is important to be cautious if using the heating mode to assess other variables (e.g., to measure the impact on indoor conditions) because the mode of operation does not always determine the flow temperature or the heat output.

The analysis allows us to analyse the dominant heating mode in each case and shows the important differences between the compact hybrid cases (CH) and the hybrid cases (H). The hybrid cases run primarily on heat pump mode, and the boiler rarely intervenes. Among other reasons, this might be explained because the heat pump is sized to be able to provide all the heating demand of the building: typically, additional heating from the gas boiler should not be required to meet heating demand (but that would depend on the heating controller). On the contrary, the compact hybrid cases only include a small heat pump that is often unable to provide all the required heat and the boiler needs to intervene more often. In those cases, the mixed mode is also frequent to stop the heat pump from frosting up (Carter, 2024).

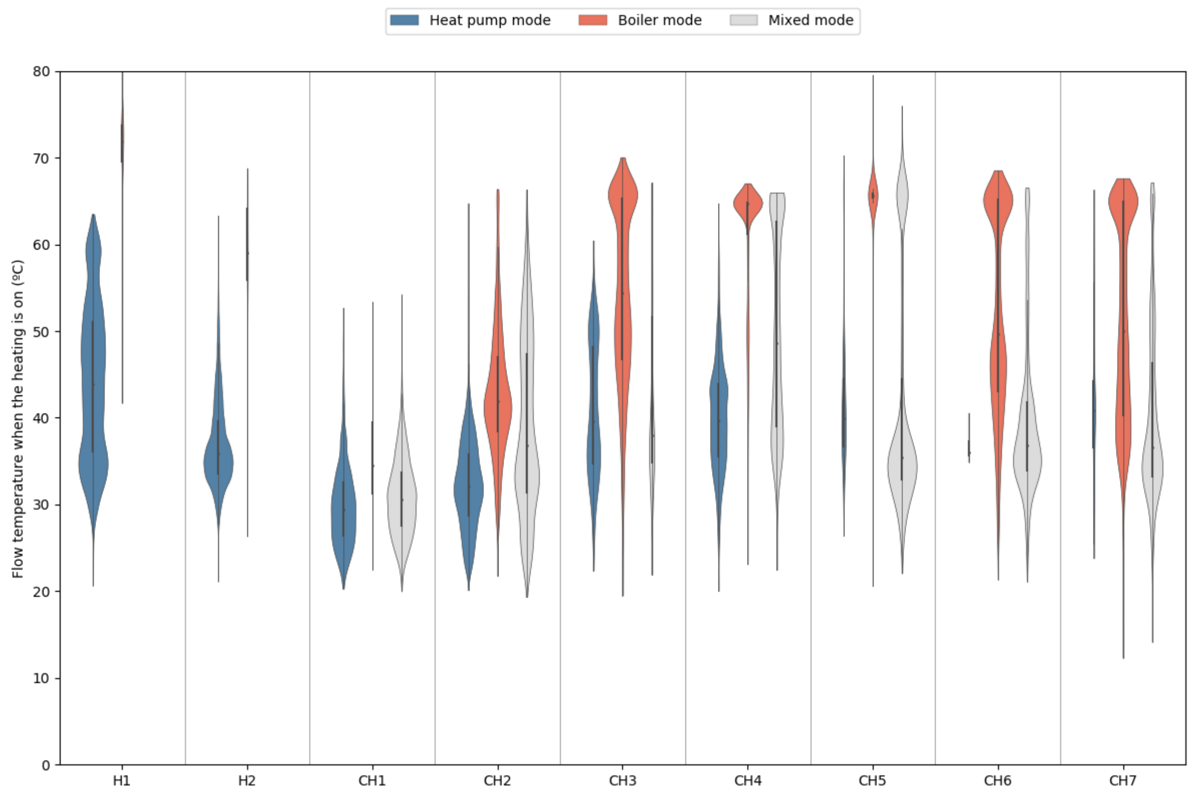


Figure 4.6. Flow temperatures for each 5-minute period when the heating was on for each heating mode (heat pump, boiler and mixed), as measured near the heating device for each case.

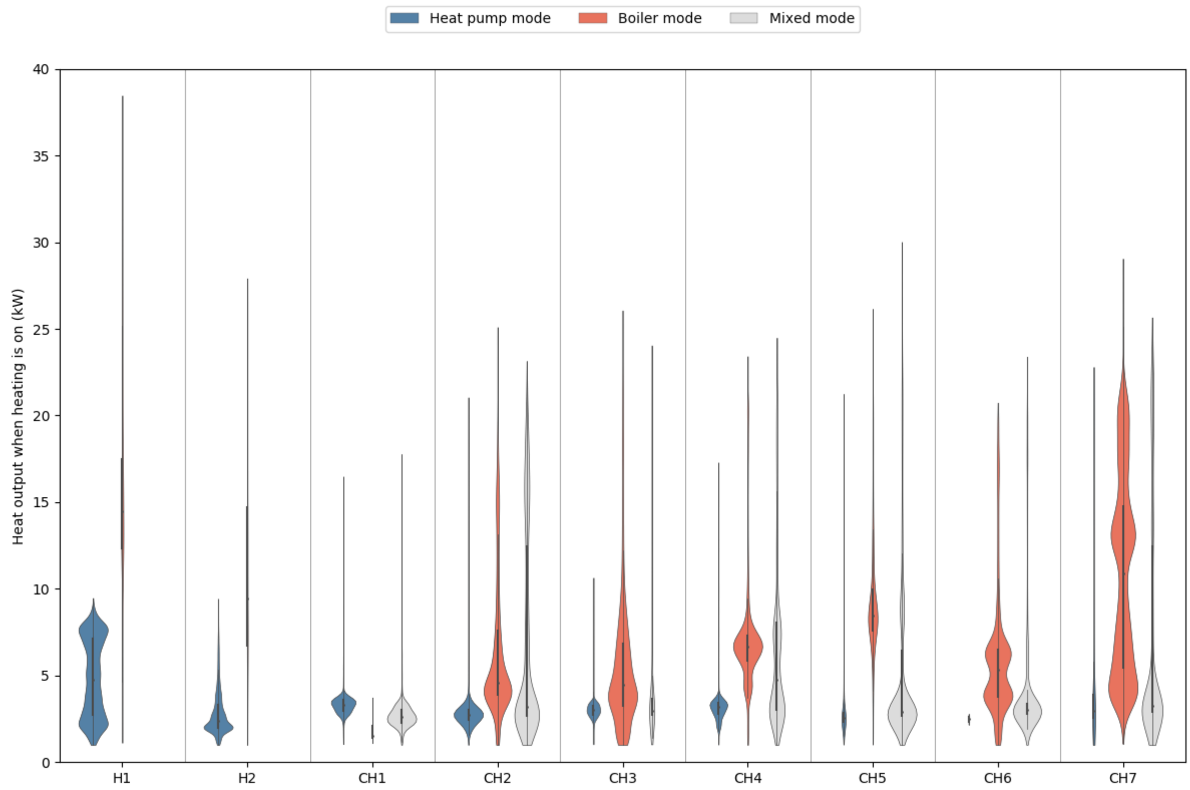


Figure 4.7. Heat output for each 5-minute period when the heating was on for each heating mode (heat pump, boiler and mixed).

As explained in section 2.2, a reduction in flow temperature and heat output can have significant impacts on the temperature of the radiators, which affects the radiant heat from them and the dust burnt on their surfaces. Unfortunately, none of these parameters were measured. However, while heating losses and the position of TRVs or the radiator controls might contribute to a difference between the radiator temperature and the flow temperature, the overall temperature of the heating system has to be lower if the flow temperature is lower, so that includes the pipes and the radiators. That means it is very likely that the radiators were, on average, colder after installing the new technologies, most notably in H2, CH1 and CH2. That is consistent with the expected changes, as described in section 2.2. Additionally, it is likely that, because of the diversity in flow temperatures observed, the temperature of the radiators experienced significant oscillations, most notably in H1, CH3-CH7. Among other things, the expected consequence of the change in radiators' temperature might be an average reduction in the radiant heat from the radiators, with important variations over the heating season. Further research might be needed to better understand the causes and the temporality of these changes.

4.1.2. Duration the heating is on

As introduced in section 2.2, the low heat output and low flow temperatures of the heat pump make it necessary to heat for more extended periods or continuously (Watson, Lomas & Buswell, 2021). A summary of the daily duration the heating is on is presented in Figure 4.8. The duration the heating is on has been calculated according to the method described in section 3.2.4. The average heating duration per day across all the cases is 10.8 hours (45% of the time). However, the analysis evidences significant differences between cases with an average heating duration per day that ranges from 3.7 hours in CH1 to 18.0 hours in H2 (with several days with 24 hours of heating). The results for the hybrid and the compact hybrid cases are clearly different. The former achieved an average heating duration per day of 17.2 hours (72% of the time). The latter achieved an average heating duration per day of 9.0 hours (38% of the time), which is almost twice that of the hybrid cases. Several factors can contribute to these differences, such as the size of the heat pump (greater in the hybrid cases), the heating demand of the building and the size of the radiators.

The literature on heating duration in the UK is extensive, but the results are heterogenic and always rely on indirect methods to measure the heating operation (Kane *et al.*, 2017). The studies reported by Kane et al. (2017) indicate that there are marginal differences in the duration of heating between weekdays and weekends and great heterogeneity across households. The length of heating time calculated in the studies reviewed varies significantly, ranging from 8.3 hours (SD 1.5) in Shipworth et al. (2010) (gas and oil boilers with timer control or manual operation) to 12.6 hours (SD 3.5) in Kane et al. (2015) (mainly gas boilers, no information on the heating controls). The more recent study by Pullinger et al. (2022) of a non-representational group of gas-fired homes in Scotland (no information on the type of heating controls) reported an average heat duration of 6.1-6.0 hours. The differences are probably driven by differences in the heat demand of the building studied and the methods used to measure the heating duration. Kane et al. (2017) found that radiator methods (as in

Pullinger *et al.*, 2022) are more accurate for measuring the time the heating is on. They also explained that room temperature methods (as in Shipworth *et al.*, 2010; and Kane, Firth & Lomas, 2015) tend to overestimate the heating duration by 0.5 to 2.9 hours compared to radiator methods during winter (more in shoulder seasons). The methods used in this research, because they are based on the data recorded by the sensors in the heating system, are likely to be even more exact than the radiator methods and the temperature methods used previously. Therefore, it is difficult to compare the results obtained in this study with the literature and pre-installation data might be needed to measure the exact changes in the heating duration. However, the lower heat output and flow temperatures mean that unless the duration is longer, the houses would be colder.

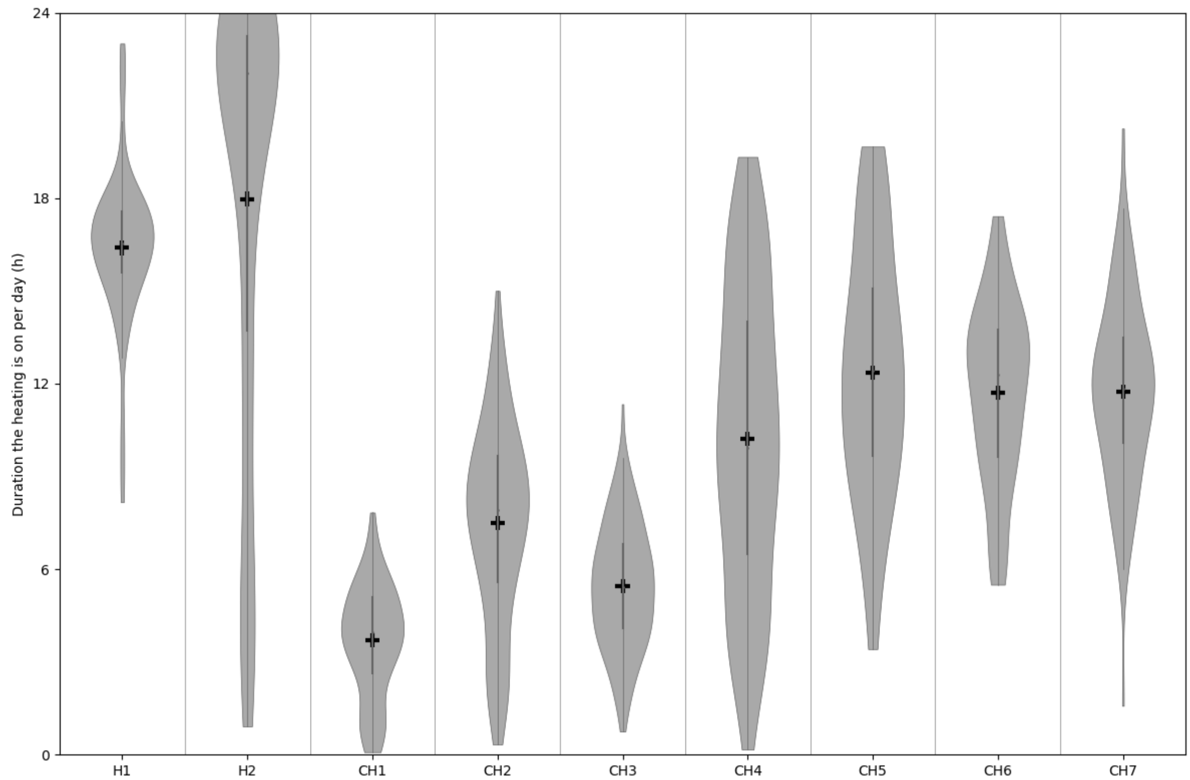
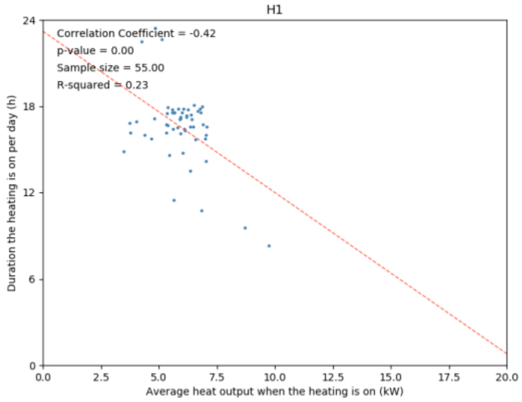
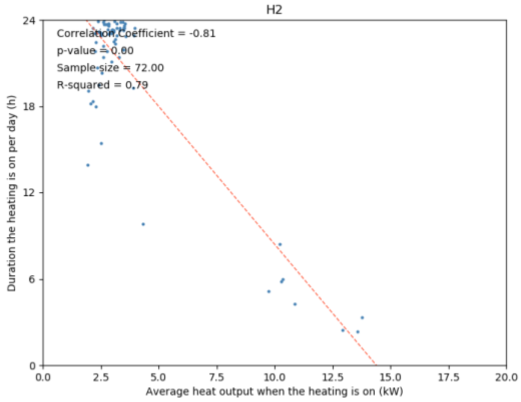


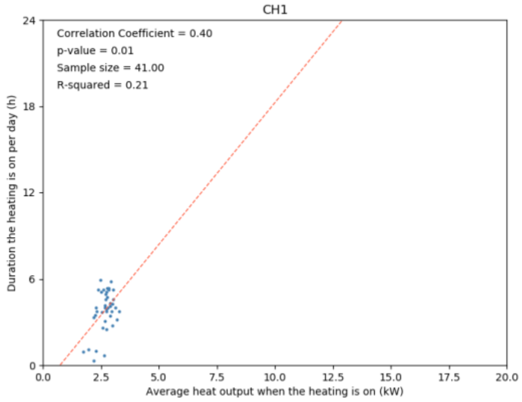
Figure 4.8. Daily average heating duration.
The + marker indicates the mean value in each case.

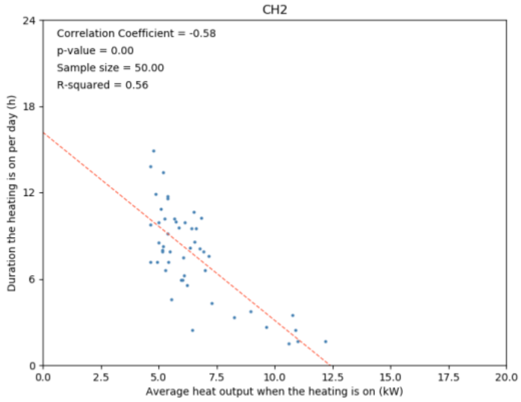
The heating duration in the cases studied varies within each home. As is evident in Figure 4.8, in most of the cases, the values are very spread, and the range of heating durations varies between 7.5 hours (CH1) and 23 hours (H2). Because the analysis includes all the days of the heating season, some of these differences are likely to be affected by differences in the outdoor temperature (the colder it is, the longer the heating system needs to run). However, it is also possible that the different modes of operation of the hybrid system affect the variance. In section 2.2 it was explained that the low heat output of the new heating system contributes to longer operating hours or even continuous heating. If that relationship exists, with similar external conditions the days in which the system runs at higher heat output will likely require shorter heating durations. The results of the analysis of this relationship are presented for each case individually in Figure 4.9[24]. Seven of the cases have statistically significant results ($p<0.05$). In six out of these seven cases, there is a negative correlation between the average heat output when the heating is on and the heating duration per day. So, the higher the average heat output (when the heating was on) is, the shorter the time the heating system is running. This reflects the physical explanation that higher heat output achieves set point temperature quicker than low heat output. In CH1, this relationship is positive, but the results in this case and in CH3 are calculated from a very small range of heat outputs. Therefore, the results for these two cases are not very meaningful, and the calculated r-squared is the lowest of all the cases with statistically significant results. The findings of this analysis could help better understand the changes experienced in the heating periods before and after the adoption of the technology.

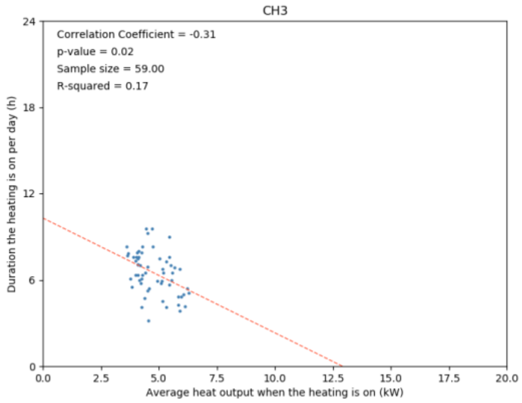
[24] As explained in section 3.2.4, to minimise the effect of the changes in the external temperature on the results, only days with an average outdoor temperature between 3ºC and 7ºC are included in the analysis.

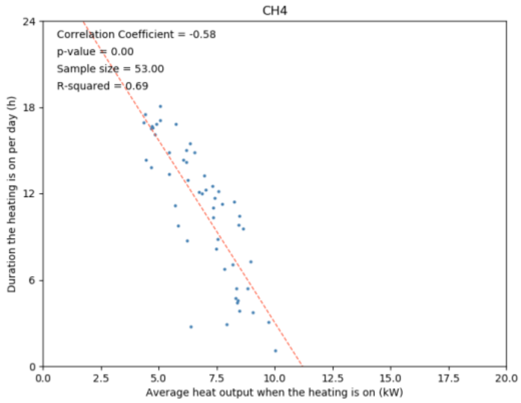

H1
Correlation Coefficient = -0.42
p-value = 0.00
Sample size = 55.00
R-squared = 0.23
Duration the heating is on per day (h)
Average heat output when the heating is on (kW)


H2
Correlation Coefficient = -0.81
p-value = 0.00
Sample size = 72.00
R-squared = 0.79
Duration the heating is on per day (h)
Average heat output when the heating is on (kW)


CH1
Correlation Coefficient = 0.40
p-value = 0.01
Sample size = 41.00
R-squared = 0.21
Duration the heating is on per day (h)
Average heat output when the heating is on (kW)


CH2
Correlation Coefficient = -0.58
p-value = 0.00
Sample size = 50.00
R-squared = 0.56
Duration the heating is on per day (h)
Average heat output when the heating is on (kW)


CH3
Correlation Coefficient = -0.31
p-value = 0.02
Sample size = 59.00
R-squared = 0.17
Duration the heating is on per day (h)
Average heat output when the heating is on (kW)


CH4
Correlation Coefficient = -0.58
p-value = 0.00
Sample size = 53.00
R-squared = 0.69
Duration the heating is on per day (h)
Average heat output when the heating is on (kW)

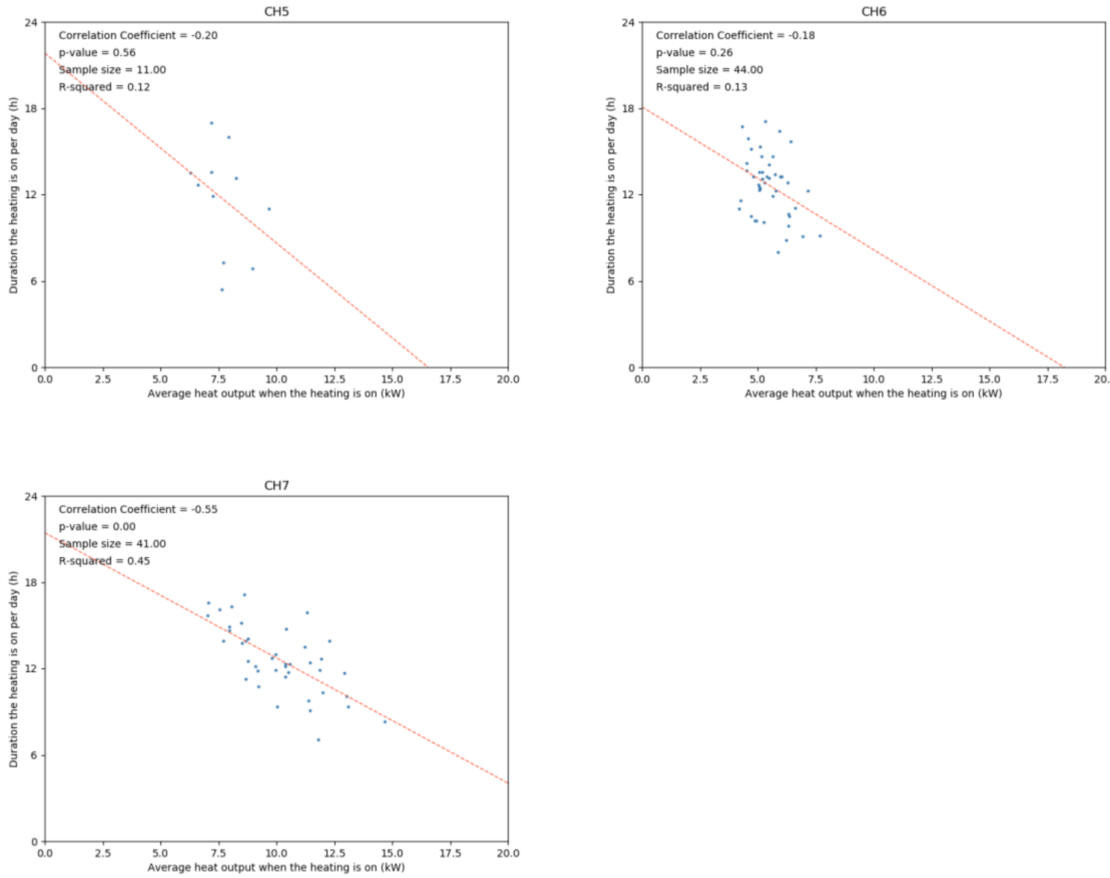


Figure 4.9. Heating duration as a function of the average heat output per day when the heating was on.

However, as explained in section 2.2, the impact of the new heating technologies does not only affect the total amount of time the heating is on but also the times when the heating is on. Figure 4.10 summarises the frequency of the heating being on at each 5-minutes period during the day for each of the cases analysed. The results for the hybrid and compact hybrid cases are clearly distinguishable. The hybrid cases (H1 and H2) show a more constant frequency of the heating being on throughout the day. The only exception is the night period in H1 (11pm to 7am) when the heat pump was forced not to work. In contrast, the compact hybrid cases show a heating probability with one (CH5) or two peaks (all the other compact hybrid cases). Part of the differences are explained by the different sizes of the heat pump in each project and the strategy pursued by the algorithmic controls in each case. In the compact hybrid cases, the heat pump is smaller, and the controls might decide to operate the boiler more often. However, the temperature settings and the householders' interactions with the system are also likely to affect the shape of the frequency curve, as it will be analysed in the next chapters.

Huebner et al. (2013a) analysed the probability of the heating being on for a large sample of boiler-heated households (n=248 dwellings). While their exact percentages cannot be directly compared with the analysis reported here due to the methodological differences (this thesis analysed the heating data at 5-minute intervals while Huebner et al. (2013a) worked with temperature data at 45-minute intervals), the shapes of the plots are comparable. On weekdays, they identified a heating probability with two clear peaks: in the morning (7am-7.45am) and evening (6pm). These patterns are clearly different from the constant frequency calculated in the hybrid cases but more similar to the results of compact hybrid cases. However, the peak times measured for the compact hybrid cases are always earlier than those calculated by Huebner et al. (2013a), particularly for the morning peak. For example, in CH1 and CH2 the highest frequency of the heating being on is at 4am, which is clearly different to how combi boilers are usually operated. The timing of the peaks is also different from that calculated by Love et al. (2017a) for a large sample of heat pumps (n>400), as they found that the timing of the peaks when heating with heat pumps was similar to that of combi boilers. Surprisingly, the load profile of heat pumps measured by Love et al. (2017a) also does not correspond to that of the hybrid cases. All these differences might be explained by the role of the optimisation algorithm: the need to achieve the temperature setpoint at the beginning of the warmth-requested period (which is not common with combi boilers (Bennett & Elwell, 2020)) and the objective of the optimisation (e.g., reduce costs and avoid using electricity during peak periods).


H1
H2
CH1
CH2
CH3
CH4
Probability of the heating system being on (%)
0
20
40
60
80
100
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
24:00

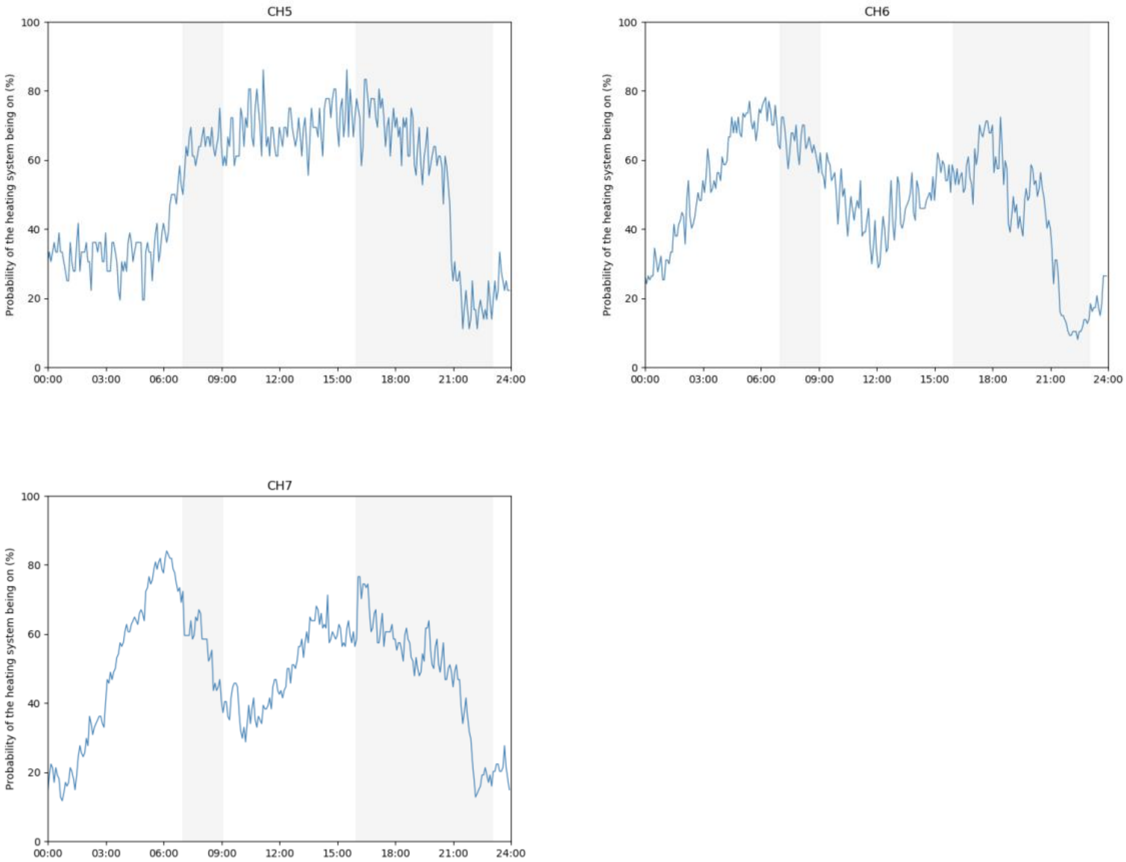


Figure 4.10. The frequency of the heating system being on for each 5-minute period. The grey bands indicate the times BREDEM (Huebner *et al.*, 2013a) *would assume the heating is on (weekdays).*

4.2. Measuring the indoor conditions with the new technologies

The previous section measured some parameters related to the heating system's operation and compared the results obtained with the existing literature for domestic buildings with combi boilers. As explained in section 2.2 and summarised in Figure 4.11, these changes in the operation of the heating system are expected to affect the indoor conditions in the participating homes in different ways. In this section, some of these parameters are analysed: the temperature oscillation when warmth is requested, the temperatures during periods when warmth is not requested and the homogeneity of temperatures across the house (see Figure 4.11). As explained in section 2.2, the range of parameters that are likely to be affected by the adoption of the new technologies is broader. However, it was not possible to measure all of them without specific and often very intrusive equipment. For that reason, the analysis is limited to three parameters.

As discussed above, no pre-installation technical data was collected. Therefore, the change in indoor conditions with the new technologies cannot be calculated from direct measurement. Instead, insights are inferred from the available data. In the previous section, that is done using the available information in the literature. However, the literature for the three measured indoor conditions parameters is scarce, and it was not possible to compare the results obtained with existing studies on combi boilers. To overcome that limitation, the analysis takes advantage of the hybrid and variable operation of the heating system and compares how these three parameters evolve under different heating patterns (exemplified by changes in the heating duration). In that way, it is possible to compare indoor conditions during periods in which the system's operation was more similar to the operation of a combi boiler and periods in which it was more similar to the operation of a stand-alone heat pump.

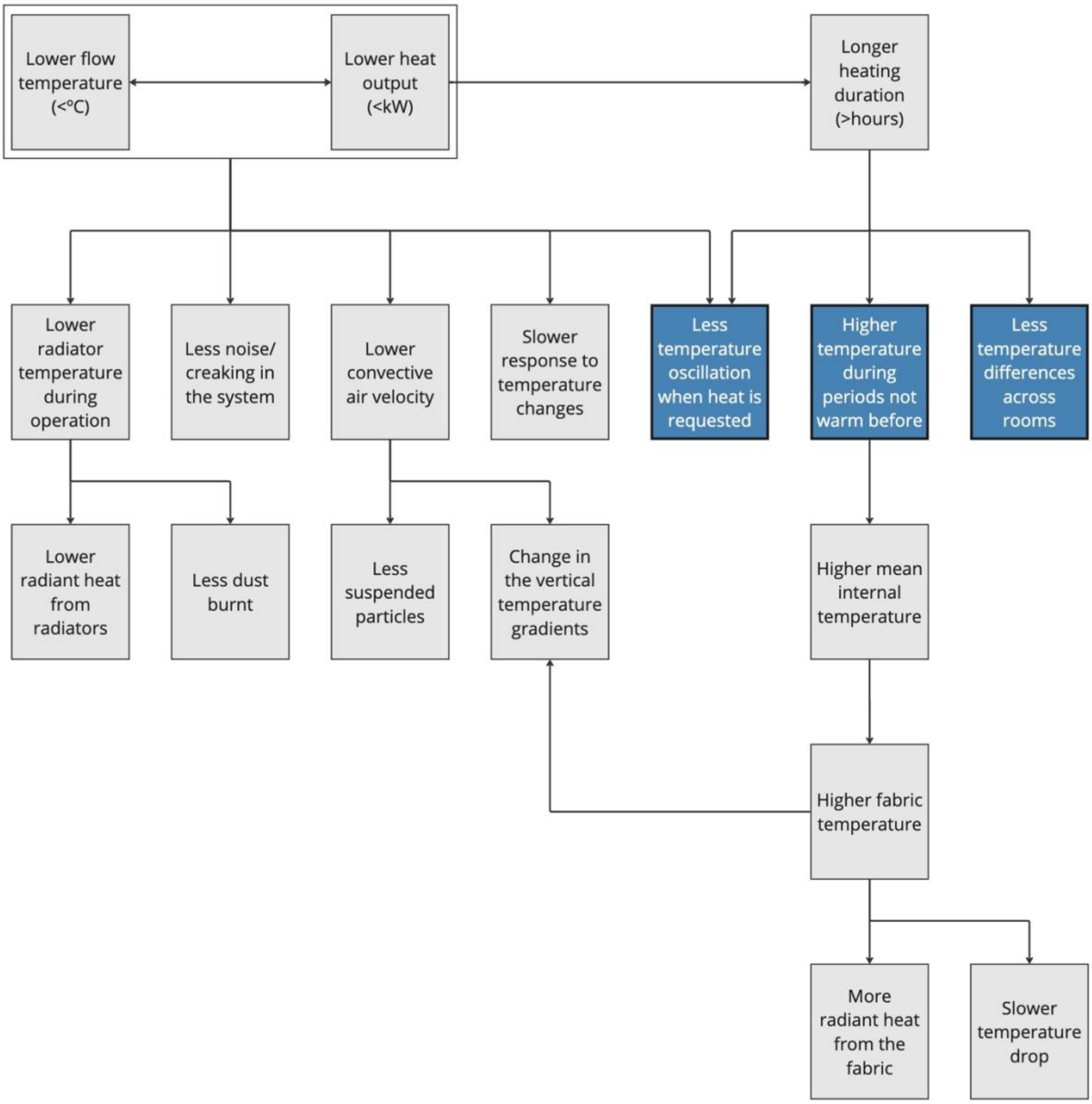


Figure 4.11. Summary of the characteristics of the indoor conditions studied (in blue) in relation to the other expected physical changes after the adoption of the new technologies.

4.2.1. Temperature oscillation when warmth is requested

As explained in section 2.2, one of the expected consequences of the change in the heating duration and the flow temperature is a reduction in the temperature oscillations during warmth-requested periods. The change has been analysed according to the method described in section 3.2.4, measuring the standard deviation of the indoor temperature as recorded by the thermostat during the 5pm to 11pm period[25] for those days in which the heating system operated. The metric is defined as the Standard Deviation of the Temperature in the Evening – SD(TE). A summary of the daily SD(TE) is presented in Figure 4.12. The median of the SD(TE) in all the cases was below 0.4ºC (average 0.22ºC). No significant differences can be seen between Compact Hybrids and Hybrid cases other than a broader spread in cases CH3 to CH7, which could be explained by the important role that the boiler played in these cases. Unfortunately, the data available is insufficient to confirm that.

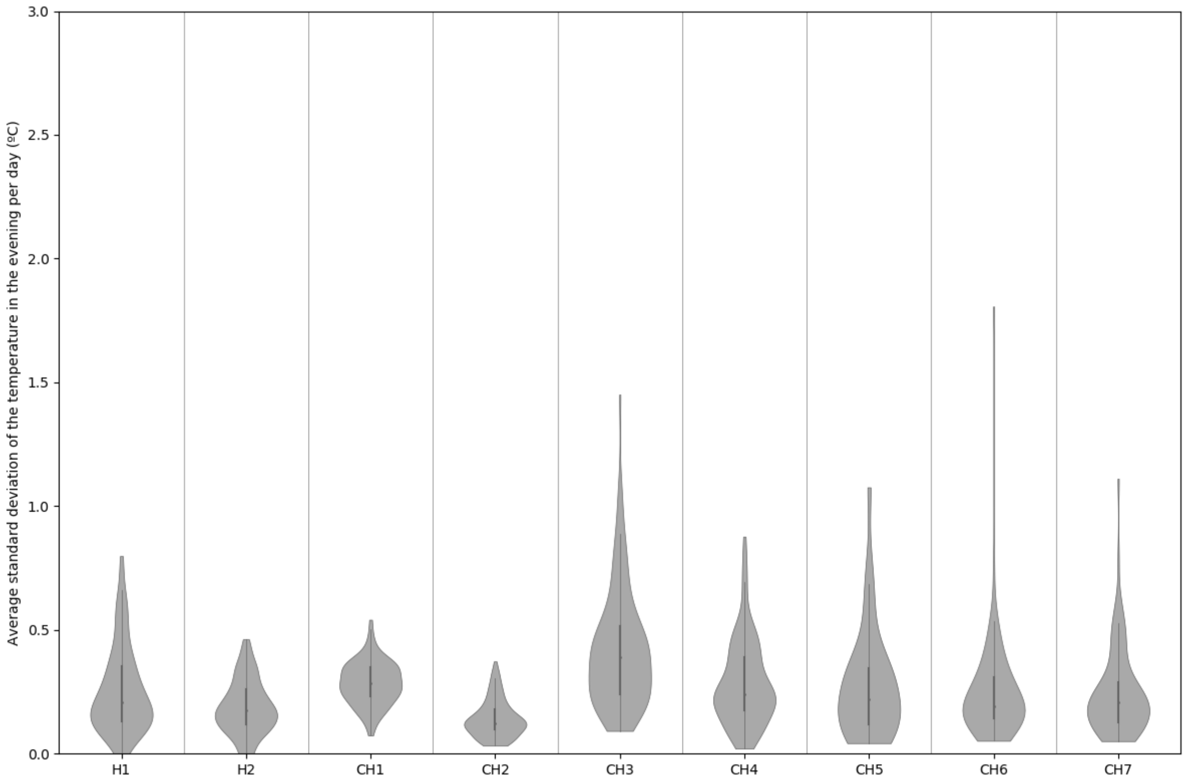


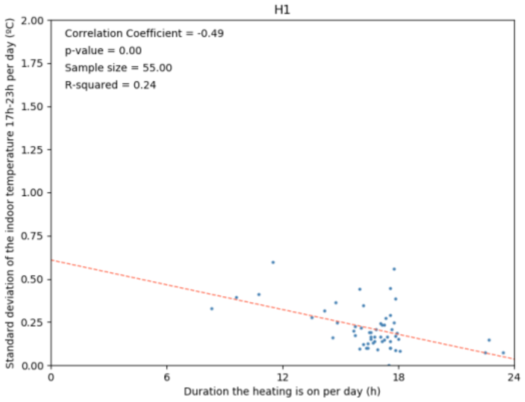
Figure 4.12. Daily average standard deviation of the indoor temperature in the evening (5pm to 11pm)

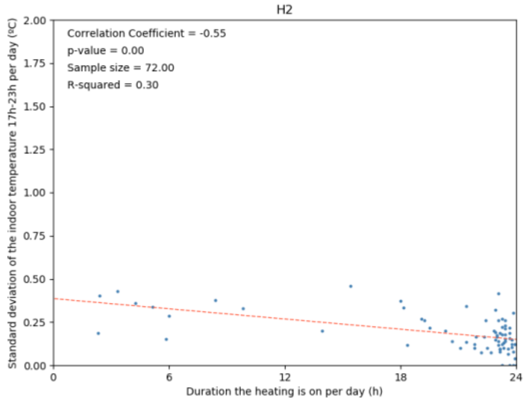
Contrary to the three operation parameters analysed previously, there is a lack of literature on temperature oscillation during periods where heat is requested with combi boilers. Therefore, it is not possible to compare the results obtained with existing studies. To assess

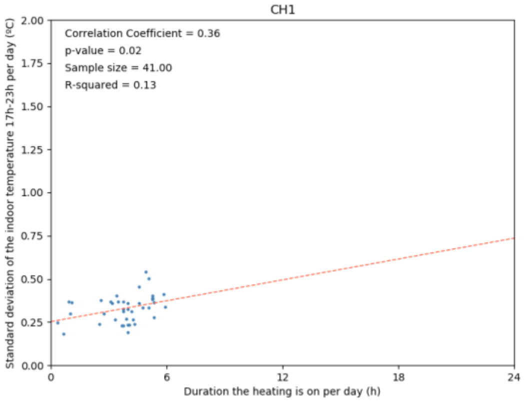
[25] Note that this period was chosen because it is when it is more likely that people were at home.

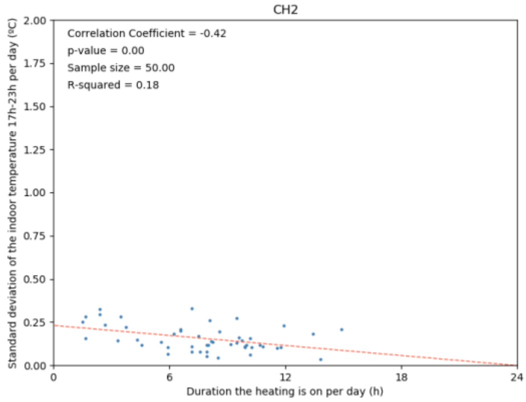
the potential change in the SD(TE) after adopting the technology, the analysis follows the approach described in section 3.2.4. It compares the changes in the SD(TE) to the heating duration each day. The data from the days with shorter heating periods is closer to intermittent heating, as is common in the UK (Huebner *et al.*, 2013a), while those with longer durations are more similar to how heat pumps work (Crawley, Wade & de Wilde, 2023). Therefore, comparing these situations tells us about the potential of the new technologies to affect the temperature oscillation.

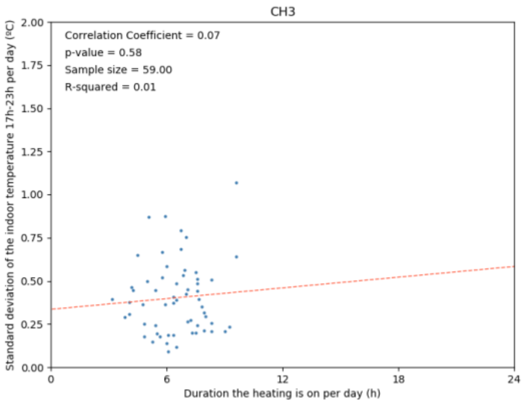
The relationship between the heating duration per day and the SD(TE) is presented, for each of the cases individually, in Figure 4.13. The results are not statistically significant in four of the nine cases analysed ($p>0.05$). However, the sample is small, and the independent variable (heating duration) has a low variability. For example, in the days studied in case CH3, the heating duration only varies from 3 hours to 9.5 hours. In the majority (80%) of the cases in which the results are statistically significant ($p<0.05$), there is a negative correlation between the heating duration per day and the SD(TE). That means that in those cases, the greater the time the heating is on, the more homogeneous the indoor temperature from 5pm to 11pm. The coefficient of determination in those cases ranges from 0.18 to 0.30. In CH1, the results are statistically significant, but the correlation between the heating duration and the SD(TE) is positive, which means that the longer the heating is on, the higher the temperature oscillation. However, in this case, the heating duration only varies from 0 hours to 6 hours (6 hours in total), and the r-squared is the lowest of all the statistically significant cases. It is unclear if the positive correlation would still hold if the system had operated more continuously.

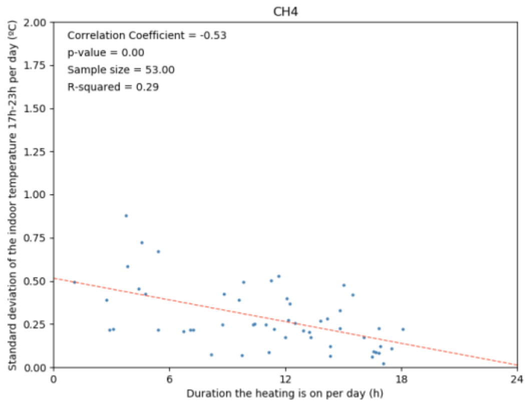

H1
Correlation Coefficient = -0.49
p-value = 0.00
Sample size = 55.00
R-squared = 0.24
Standard deviation of the indoor temperature 17h-23h per day (ºC)
Duration the heating is on per day (h)


H2
Correlation Coefficient = -0.55
p-value = 0.00
Sample size = 72.00
R-squared = 0.30
Standard deviation of the indoor temperature 17h-23h per day (ºC)
Duration the heating is on per day (h)


CH1
Correlation Coefficient = 0.36
p-value = 0.02
Sample size = 41.00
R-squared = 0.13
Standard deviation of the indoor temperature 17h-23h per day (ºC)
Duration the heating is on per day (h)


CH2
Correlation Coefficient = -0.42
p-value = 0.00
Sample size = 50.00
R-squared = 0.18
Standard deviation of the indoor temperature 17h-23h per day (ºC)
Duration the heating is on per day (h)


CH3
Correlation Coefficient = 0.07
p-value = 0.58
Sample size = 59.00
R-squared = 0.01
Standard deviation of the indoor temperature 17h-23h per day (ºC)
Duration the heating is on per day (h)


CH4
Correlation Coefficient = -0.53
p-value = 0.00
Sample size = 53.00
R-squared = 0.29
Standard deviation of the indoor temperature 17h-23h per day (ºC)
Duration the heating is on per day (h)

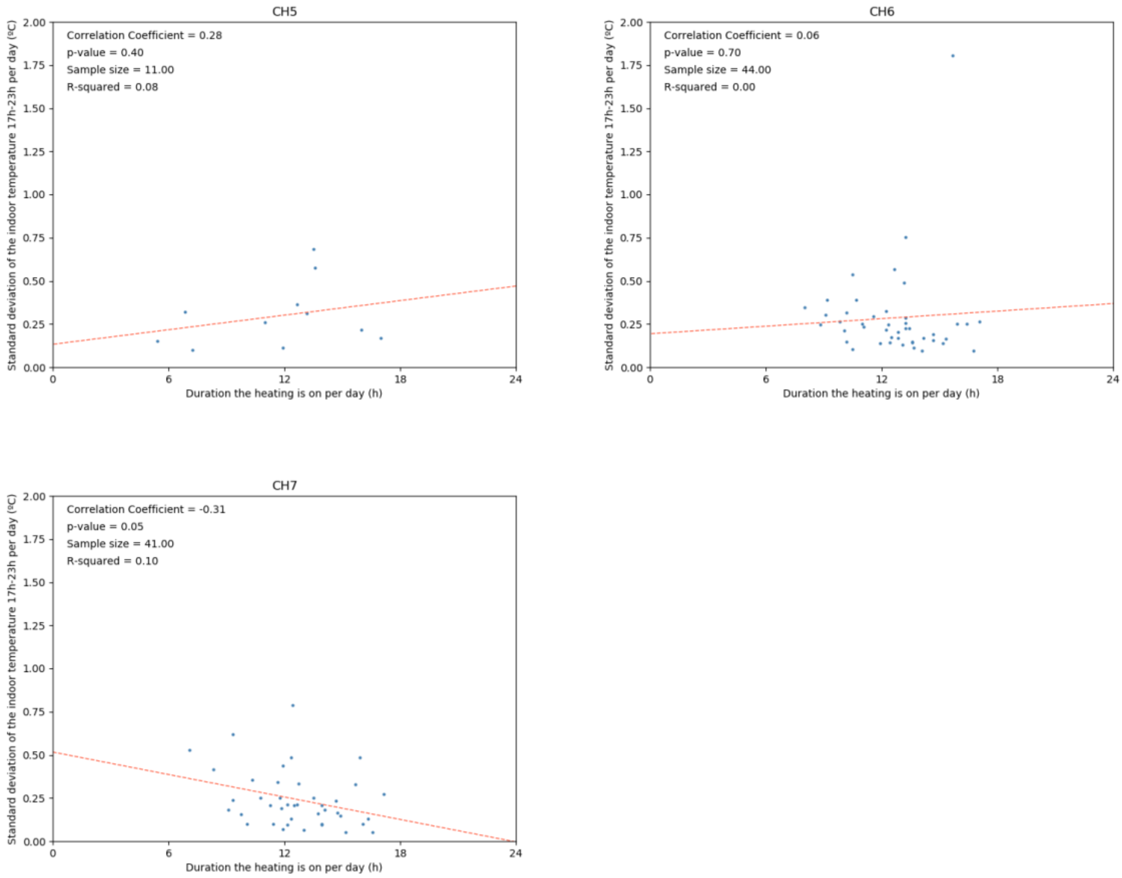


Figure 4.13. Daily standard deviation of the indoor temperature in the evening (5pm to 11pm) as a function of the heating duration.

However, the correlations explored are relatively weak and arise as a combination of multiple factors: the controls, heating system and occupants. The former is particularly relevant as it defines the heating times and the thermostat hysteresis. As the evidence from the technical data is limited, it is unclear if householders will notice the changes. The analysis of the social data in the next Chapters should help to better understand these changes.

4.2.2. Temperatures when warmth is not requested

The increased duration of the heating period and the changes in the heating patterns (see Section 4.1.3) are expected to affect the indoor temperatures during periods in which heat is not requested, as explained in section 2.2. The expected change has been analysed using the monitored data by measuring the indoor temperature drop from 8pm (when heat was requested) to 4am (when heat was not requested), according to the methods described in section 3.2.4. A summary of this metric is presented in Figure 4.14. The mean temperature drop across cases is 1.2ºC; in most cases, there was a slight temperature reduction over this period (temperature drop per hour: 0.14ºC/h).

The results show differences across cases. Some of these differences can be explained by the suppression of the overnight operation of the heat pump to reduce the system's noise, which happened in H1, CH3, and CH7. This is the case in H1 and CH3, which show larger temperature drops than the rest of the cases. However, CH7 also requested the heat pump not to heat during the monitored period, but the average temperature drop is much lower than H1 and CH3. The differences between these cases might have to do with the thermal characteristics of the building as well as the temperature requested by the householders.

The analysis also evidences significant heterogeneity in the results obtained in each case, with a range of temperature drops between 2ºC (CH1) and 5ºC (CH6). Also, in a small number of cases, there are days in which the temperature at 4am was higher than the temperature at 8pm (temperature rises). The increase in the temperature at night is likely driven by the heating system trying to maintain the temperature or preheating (although internal heat gains might also contribute). The findings show the variability in the heating pattern provided by the algorithm.

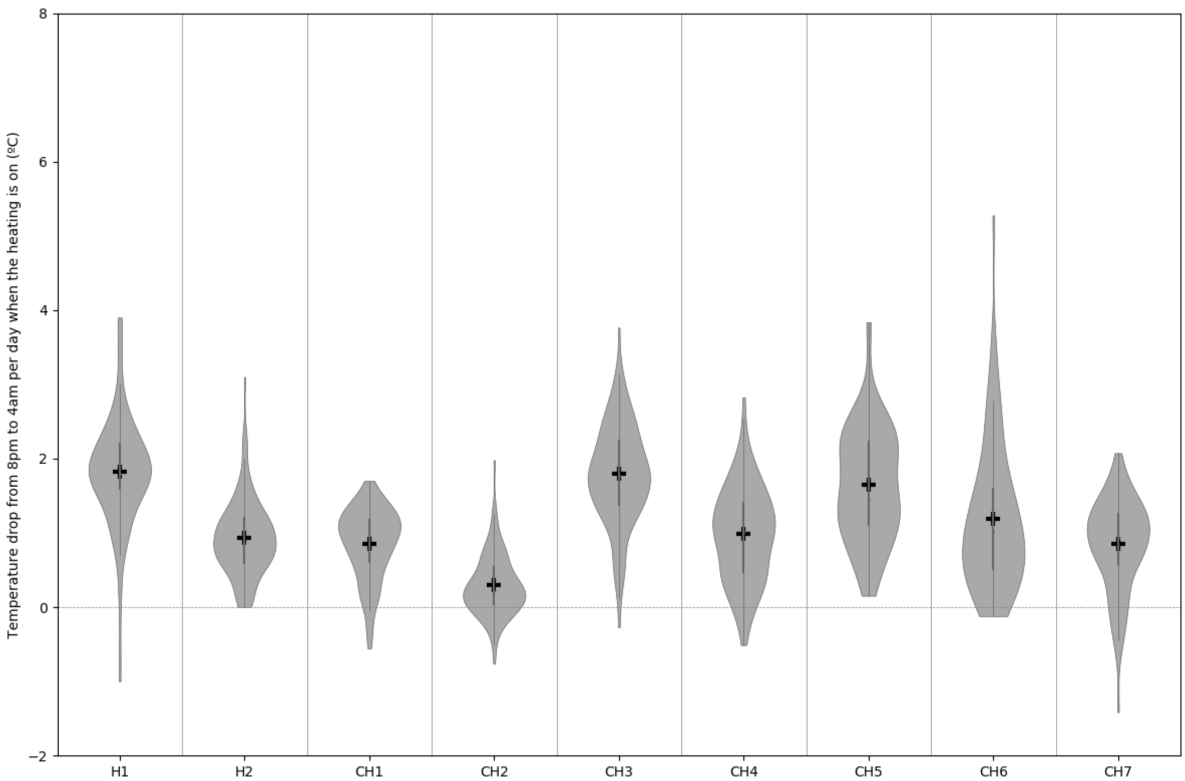
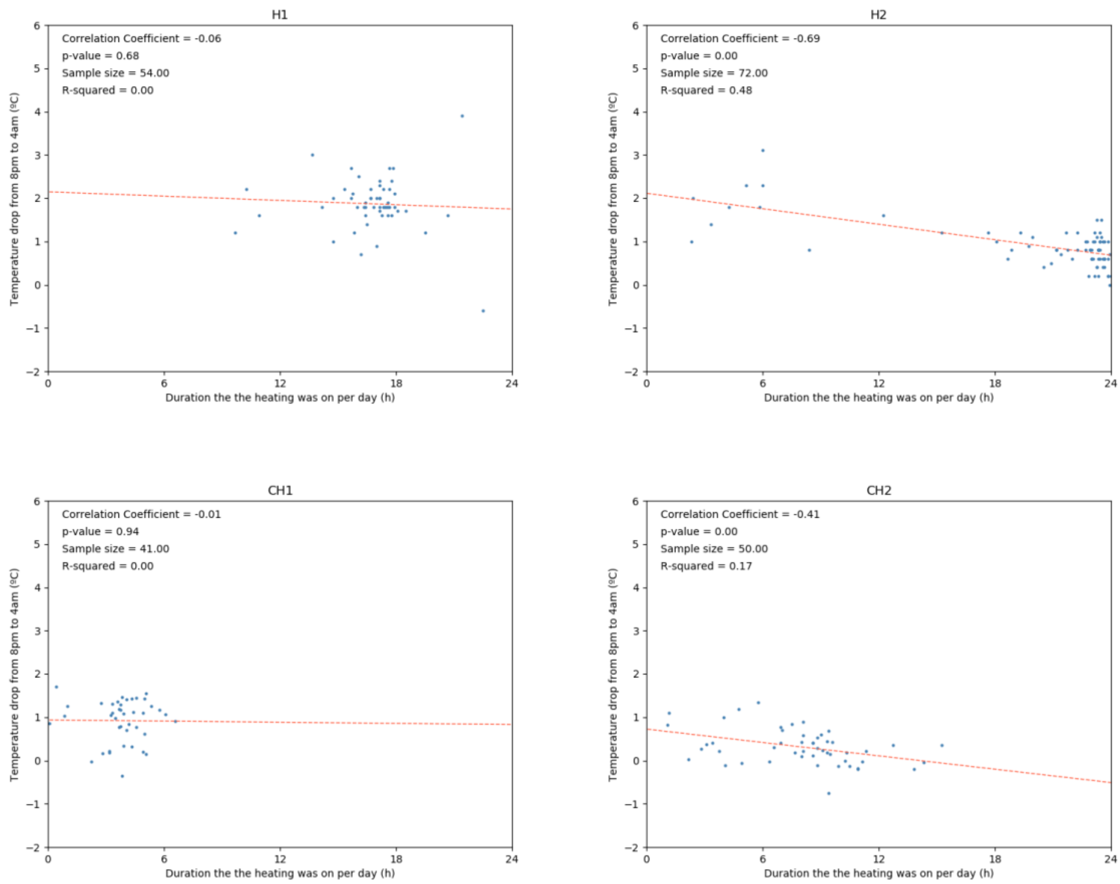


Figure 4.14. Daily temperature drop from 8pm to 4am.
The + marker indicates the mean value in each case.

While no other studies have reported the specific metric tested here, there is some literature on temperature patterns with conventional heating systems that is useful to compare the results obtained here. From the existing literature for UK domestic buildings (Huebner *et al.*, 2013b, 2015; Hanmer *et al.*, 2019a; Pullinger *et al.*, 2022), it can be calculated that the temperature drops between 1.5ºC and 3.25ºC from 8pm to 4am in the homes reported in these studies. Therefore, despite a few exceptions identified by Huebner et al. (2015), most of these studies found an average temperature drop smaller than the measured average in this research. While that may suggest that the temperature drop at night was reduced when adopting the heat pump, it is important to note that the cases studied here and in the literature differ, and factors such as the thermal performance of the buildings analysed and the temperature setpoints might affect the results.

To overcome some of these limitations, the relationship between the temperature drop and the heating duration is presented individually for each case in Figure 4.15. The results are not statistically significant in six of the nine cases analysed (p>0.05). However, the sample is small and/or there is low variability of the independent variable (heating duration). In all the cases where the results are statistically significant (33%), there is a negative correlation between the heating duration per day and the temperature drop. This means that as the heating duration increases, the temperature drop is smaller, and the house is maintained at a more constant temperature, which is consistent with the expected changes. These cases have a wider spread of heating durations than most other cases, which may explain why these relationships have been identified. The coefficient of determination in those cases ranges from 0.17 to 0.48.



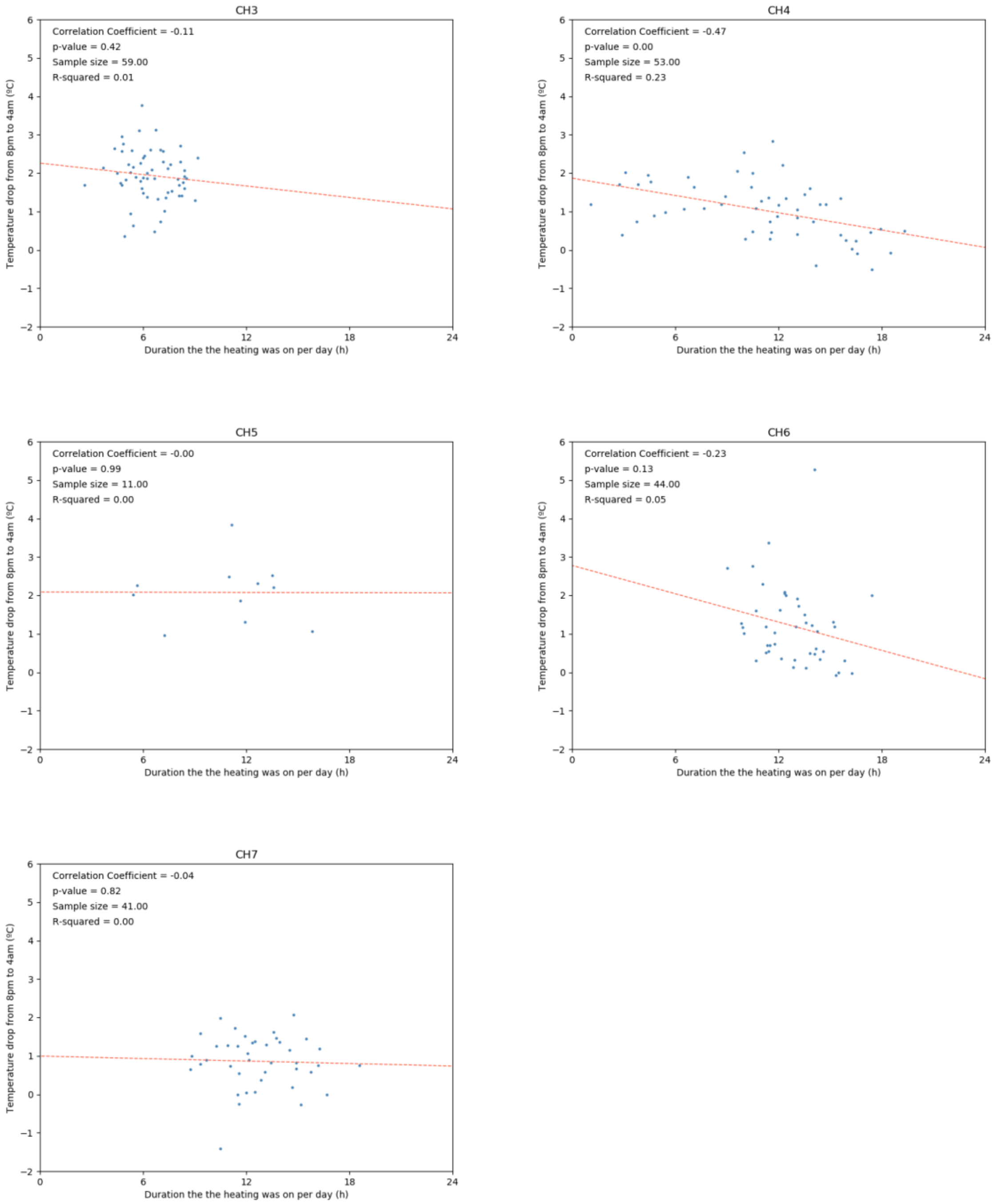


Figure 4.15. Daily temperature drop from 8pm to 4am as a function of the heating duration.

The limited available data (variability in heating duration) has limited the study of the temperature drop. However, the findings point out that in the cases studied, the temperature at night drops less than in other studies and that the relationship between duration and drop for some of the houses suggests that this could be a factor. At the same time, the variability in the temperature drop measured in this study suggests that this might vary importantly from day to day.

4.2.3. Temperature differences across rooms

As explained in section 2.2, one of the expected consequences of the change in the heating duration and the heat output is a reduction in the temperature differences across rooms. When heating operates for longer (less discontinuously) the different rooms continue exchanging heat while the heating is on until they reach a thermal equilibrium. This issue has been analysed using the method described in section 3.2.4. The metric used is defined as the Average Standard Deviation of the Room Temperatures – SD(RT). A summary of the SD(RT) for each of the cases is presented in Figure 4.16. The average SD(RT) across cases is 0.94ºC. The differences between cases are not analysed because the different number of rooms analysed per case[26] have important effects in the standard deviation.

The results show a wide spread of SD(RT) values in all the cases except H1, which evidences that the differences in temperature across rooms vary. The reasons behind this variability might have to do with variations in the heating patterns as well as differences in the internal gains or the outdoor temperature, which affect the cooling rate of the building. In all the cases except H1, the range of SD(RT) values was greater than 1ºC, but it is unclear why in H1, the variability is lower. The cause of this cannot be determined without a forensic building physics investigation, which is not the focus of this work.

[26] In H1 only 3 rooms had valid data, in H2 only 4 rooms, and in CH4 only 5 rooms.

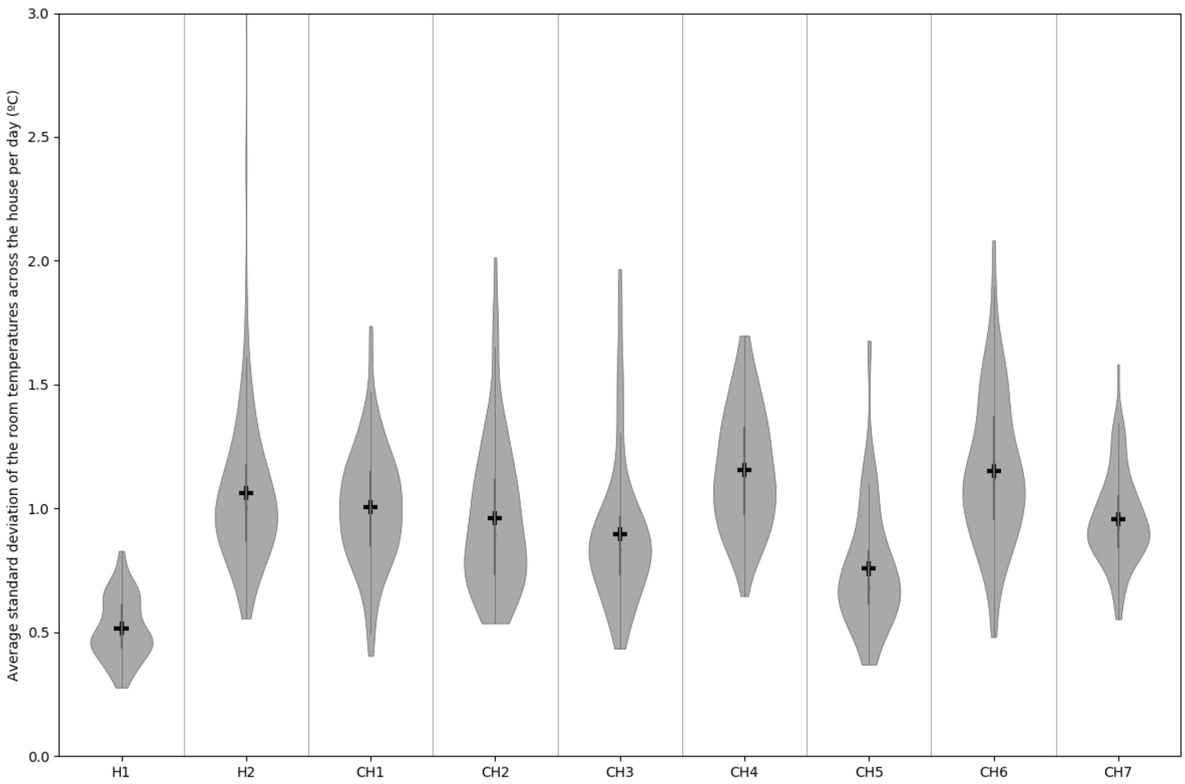
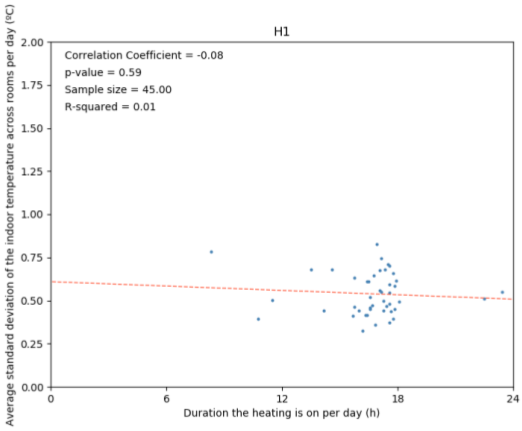
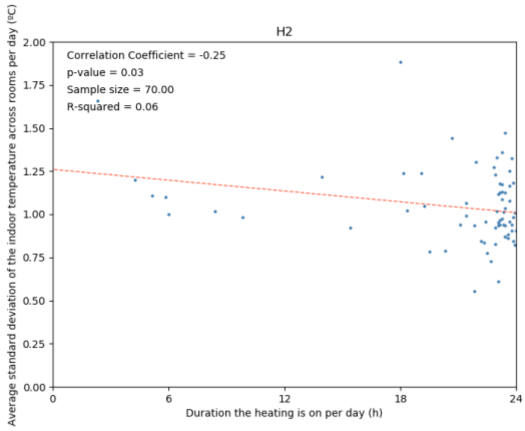
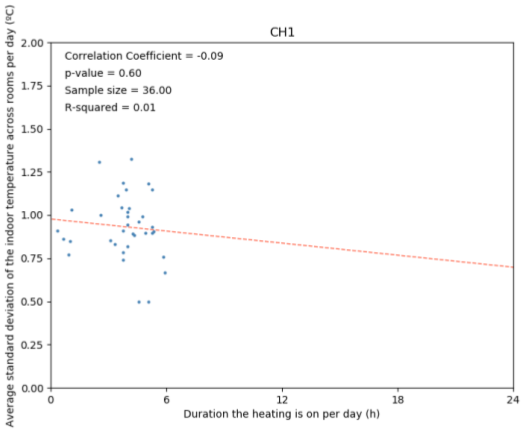


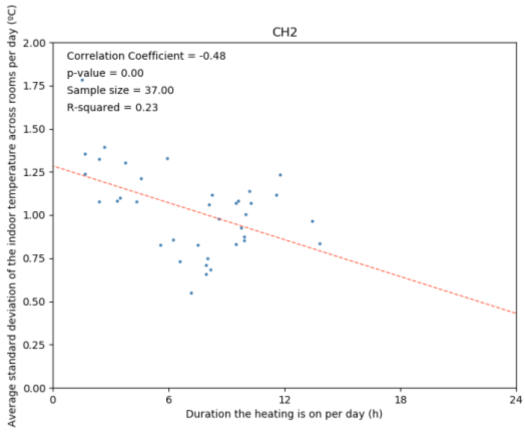
Figure 4.16. Average Standard deviation of the Room temperatures per day.
The + marker indicates the mean value in each case.

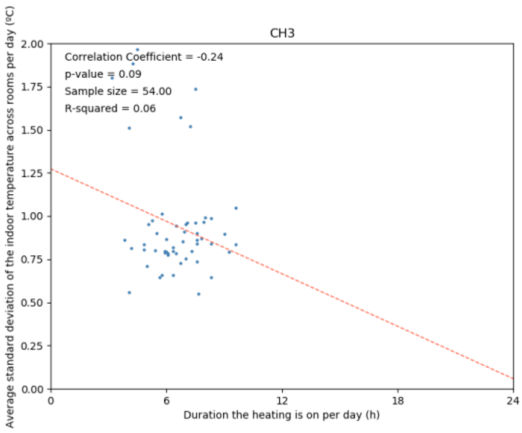
To assess the potential change in the SD(RT) after adopting the technology, the analysis follows the approach described in section 3.2.4, which compares the SD(RT) to the heating duration each day. The relationship between the heating duration per day and the SD(RT) is presented in Figure 4.17 for each case individually. In six out of the nine cases analysed, the results were not statistically significant ($p>0.05$). However, the sample size is small, and the heating duration is homogeneous in many cases. Two cases (H2 and CH2) in which the results are statistically significant ($p<0.05$) show a negative correlation between the heating duration and the SD(RT). That means that the longer the heating is on, the less diversity there is in the indoor temperatures across rooms. On the contrary, CH4 shows a positive correlation between the two variables with a high coefficient of determination ($r^2=0.47$). The analysis suggests that every case is different and that if the temperature homogeneity is affected by the heating duration, this relationship is weak.

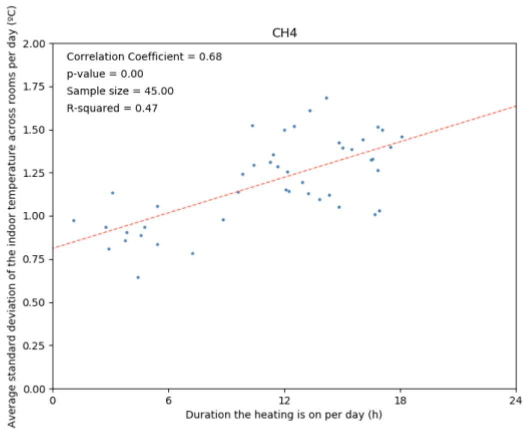

H1
Correlation Coefficient = -0.08
p-value = 0.59
Sample size = 45.00
R-squared = 0.01
Average standard deviation of the indoor temperature across rooms per day (ºC)
Duration the heating is on per day (h)


H2
Correlation Coefficient = -0.25
p-value = 0.03
Sample size = 70.00
R-squared = 0.06
Average standard deviation of the indoor temperature across rooms per day (ºC)
Duration the heating is on per day (h)


CH1
Correlation Coefficient = -0.09
p-value = 0.60
Sample size = 36.00
R-squared = 0.01
Average standard deviation of the indoor temperature across rooms per day (ºC)
Duration the heating is on per day (h)


CH2
Correlation Coefficient = -0.48
p-value = 0.00
Sample size = 37.00
R-squared = 0.23
Average standard deviation of the indoor temperature across rooms per day (ºC)
Duration the heating is on per day (h)


CH3
Correlation Coefficient = -0.24
p-value = 0.09
Sample size = 54.00
R-squared = 0.06
Average standard deviation of the indoor temperature across rooms per day (ºC)
Duration the heating is on per day (h)


CH4
Correlation Coefficient = 0.68
p-value = 0.00
Sample size = 45.00
R-squared = 0.47
Average standard deviation of the indoor temperature across rooms per day (ºC)
Duration the heating is on per day (h)

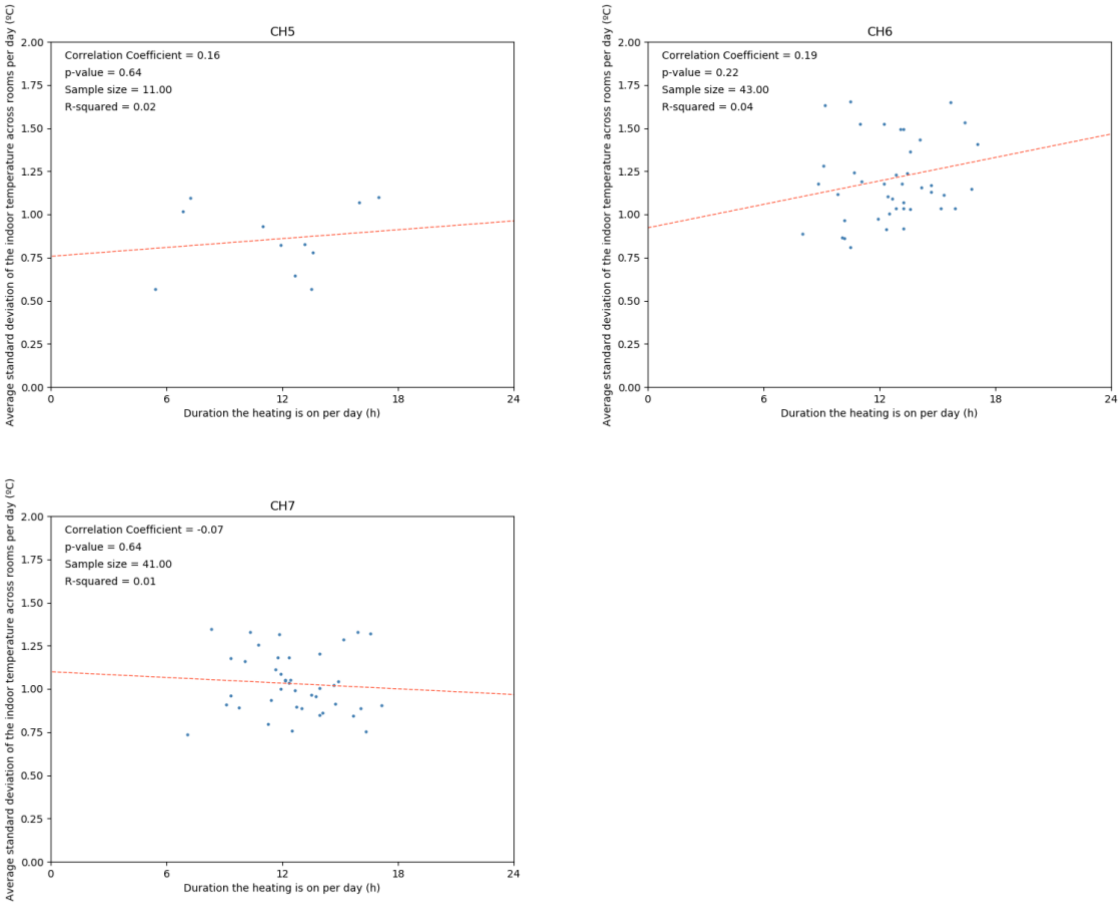


Figure 4.17. Daily average standard deviation of the indoor temperatures across rooms as a function of the heating duration.

The results are inconclusive and do not help to explain if the adoption of the new technologies contributed to an increase in the uniformity of the indoor temperatures across the house. The SD(RT) might be affected by other variables not measured, and the results might vary from case to case. Therefore, there is no clear evidence here of a meaningful effect and the complexity possibly dominates. Further research might be needed if this parameter is found to critically affect the experience of the householders.

4.3. Measuring the unscheduled interactions with the heating controls

The analysis of technical data presented so far has focused on measuring the heating operation and the indoor conditions and has tried to understand how these change after the adoption of the novel heating technologies. As explained in Chapter 2, while the new technologies have intrinsic characteristics that affect these parameters, the indoor conditions and the heating operation are the outcomes of the heating practices with the technology. Therefore, they are the result of the nexus of materials (including technologies), meanings and competences. The technical data presented so far reflects some of these elements, which will be further explored in the next chapters. However, before doing that, it is important to analyse how the householders interacted with the heating controls using the technical data.

As explained in section 1.2, householders have two options to communicate their temperature requirements to the system. Firstly, they can define a temperature schedule for each day of the week. In this schedule, they can define five different temperature setpoints and the times when they want each of them to be met[27]: IN (AM – 0h to 12h), IN (PM – 12h to 24h), OUT, AWAY and ASLEEP[28]. Secondly, they can override the scheduled settings and define a new temperature setpoint "in the moment". This new temperature setpoint will be in place until the next scheduled period. The scheduled temperature setpoint is very relevant for the operation of the new technologies, because it allows the system to plan in advance and calculate the optimal heating pattern depending on the objective of the optimisation algorithm: minimising cost, minimising carbon emissions, etc. In contrast, the manual changes require a rapid response that does not leave room for the algorithm to optimise the operation and can reduce the performance against the optimisation criterion. Therefore, in order to forecast the heating demand and deliver better efficiency outcomes, the tested technologies require a low level of manual interaction.

[27] Note that in contrast to other heating controls, the smart controls tested in this thesis request householders to input the times when they want to be warm, not when they want the heating to be on.

[28] The IN period is more significant in determining when the heating comes on and to what temperature because the others are only used to ensure that the temperature does not fall below these limits.

However, householders do not always act in that way. As previous research has shown (e.g., Sweetnam *et al.*, 2019; Hanmer *et al.*, 2019b; Hanmer, 2020), householders sometimes override the scheduled operation. The reasons behind these actions are multiple and some of them will be analysed in Chapter 5 and 6. This section analysed the householders' changes to the temperature setpoint, as recorded by the heating controls.

4.3.1. Unscheduled temperature setpoint

A summary of the average scheduled changes during the monitoring period is presented in Table 4.1. The scheduled changes have been calculated according to the method described in Section 3.2.4. On average, householders manually overrode the temperature schedule on 41% of the days analysed. However, the variation across homes was high. H1 and CH1 are the cases which had the lowest number of interactions and only overrode the schedule on 12% and 9% of the days, respectively. On the other hand, CH3, CH5 and CH7 manually changed the setpoint on more than 73% of the days. In CH5-CH7 the system was installed halfway during the heating season and the number of days analysed is smaller, which could affect the results. It is important to point out that when householders manually override the scheduled temperatures, they might be trying to achieve different things: from adjustments to comfort levels to forcing the system into a specific heating pattern or to reduce noise. The context for these actions is explored in Chapters 5 and 6.

On average, the householders manually increased the temperature setpoint on 33% of the days and manually reduced it on 19% of the days[29]. Again, there are important differences between the cases analysed. In most cases, upward changes are more common than downward changes. Only in three cases are the reductions more common than the increases

[29] Note that the sum of the days with manual increases (33%) and manual reductions (19%) is greater than the average days with manual changes (41%). This is because there were days which combined manual increases and reductions.

(H1, CH1, and CH2). Those three cases are also the ones with a lower number of manual changes.

Table 4.1. Percentage of all the days of the winter with manual changes in the temperature setpoint.

Case	Days with manual changes (%)	Days with upward changes (%)	Days with downward changes (%)
H1	12%	4%	9%
H2	28%	25%	8%
H3	28%	24%	9%
CH1	9%	4%	5%
CH2	20%	5%	17%
CH3	73%	67%	23%
CH4	40%	36%	5%
CH5	85%	65%	60%
CH6	39%	32%	12%
CH7	74%	65%	46%
Average	**41%**	**33%**	**19%**

The number of days with manual changes did not remain constant during the whole winter. To better understand that, an analysis of the number of days with manual temperature changes per month is presented in Table 4.2. The average number of monthly changes across all the cases does not show important differences over the heating season (the average remains between 30% and 40% for the whole period). However, the results are clearly distinguishable when we analyse each case in detail. In some cases, the percentage of days with interactions remains more or less constant during the whole period of analysis (H1, CH1, CH3, CH5, CH6). In other cases, manual changes are reduced over time (H2, CH2, CH7). Finally, in a small number of cases, the changes increased during the monitoring period (CH4), or they increased and later on decreased (H3).

Table 4.2. Percentage of the days per month with manual changes in the temperature setpoint.

Case	October	November	December	January	February	March	April
H1	10%	30%	10%	10%	0%	13%	13%
H2	48%	77%	19%	10%	32%	10%	0%
H3	0%	17%	35%	48%	75%	26%	0%
CH1	29%	17%	6%	6%	0%	3%	0%
CH2	45%	17%	13%	16%	11%	6%	33%
CH3	87%	93%	74%	84%	46%	65%	57%
CH4	19%	43%	16%	16%	32%	87%	63%
CH5					71%	65%	93%
CH6				32%	25%	26%	57%
CH7			52%	100%	82%	42%	57%
Average	**34%**	**42%**	**28%**	**36%**	**38%**	**34%**	**37%**

The analysis of the manual changes in the temperature setpoint shows important differences between cases and across time. While minimising the number of unscheduled changes to the temperature setpoint is critical for the optimal operation of the heating system, the results suggest this is not always the case. The analysis shows that these actions are not widespread but concentrated in specific times or cases. However, the technical data alone does not help us understand what happened in these households or why some of them changed the way they manually operated the system over time. The next two chapters will analyse the social data collected to understand these actions in the context of heating practices.

4.4. In conclusion

This chapter has explored the technical data collected during the monitoring campaign to try to understand the indoor conditions, the heating operation and the householders' interactions with the controls. These results will be built on in the next two chapters to help understand the social data. The first part of the chapter reported measurements of some parameters related to the indoor conditions and the heating operation to assess how these variables changed after adopting the new heating technologies. The findings for the cases studied confirm some of the expected changes presented in section 2.2 (see Figure 4.18). This suggests that some parameters of the heating operation and the indoor conditions change after adopting the technology. However, it is important to note that no pre-installation data was collected, and the findings presented rely on alternative methods to assess the pre-installation situation (comparison with the literature and the differences in the heating duration). However, the results provide insights that enable a better understanding of the conditions and performance of the system and how it is likely that they contrast to the performance and conditions expected for a home heated with a gas boiler.

The average flow temperature and heat output were calculated to be 45.6ºC and 5.7kW, respectively, which is below the typical values for gas boilers with conventional thermostats or manual controls. The heating duration was found to be 10.8 hours, which is slightly longer than homes with combi boilers. However, what proved to be more different was the time when the heating was on. In contrast to conventional heating systems, the new heating technologies heated during night and in the late morning and afternoon, which is not common with combi boilers. Regarding the parameters of the indoor conditions studied, the temperature oscillations when the heating is on and the temperature drops at night were likely reduced in most cases after the adoption of the new technologies. However, the findings are inconclusive regarding the changes in the temperature homogeneity across the house. The heating practices behind these outcomes are explored in the following two chapters.

The final part of the chapter has analysed the householders' interactions with the heating controls. While the results show a high number of manual interactions with the controls in some cases and during specific times of the year, this type of analysis is too simple to explain what happens inside the homes and why householders override the scheduled temperature setpoints. That suggests that using monitoring data alone is insufficient to capture the complexity behind the householders' interactions with the system, and qualitative data might be needed. However, the results are useful as starting point for the analysis presented in the next two chapters.

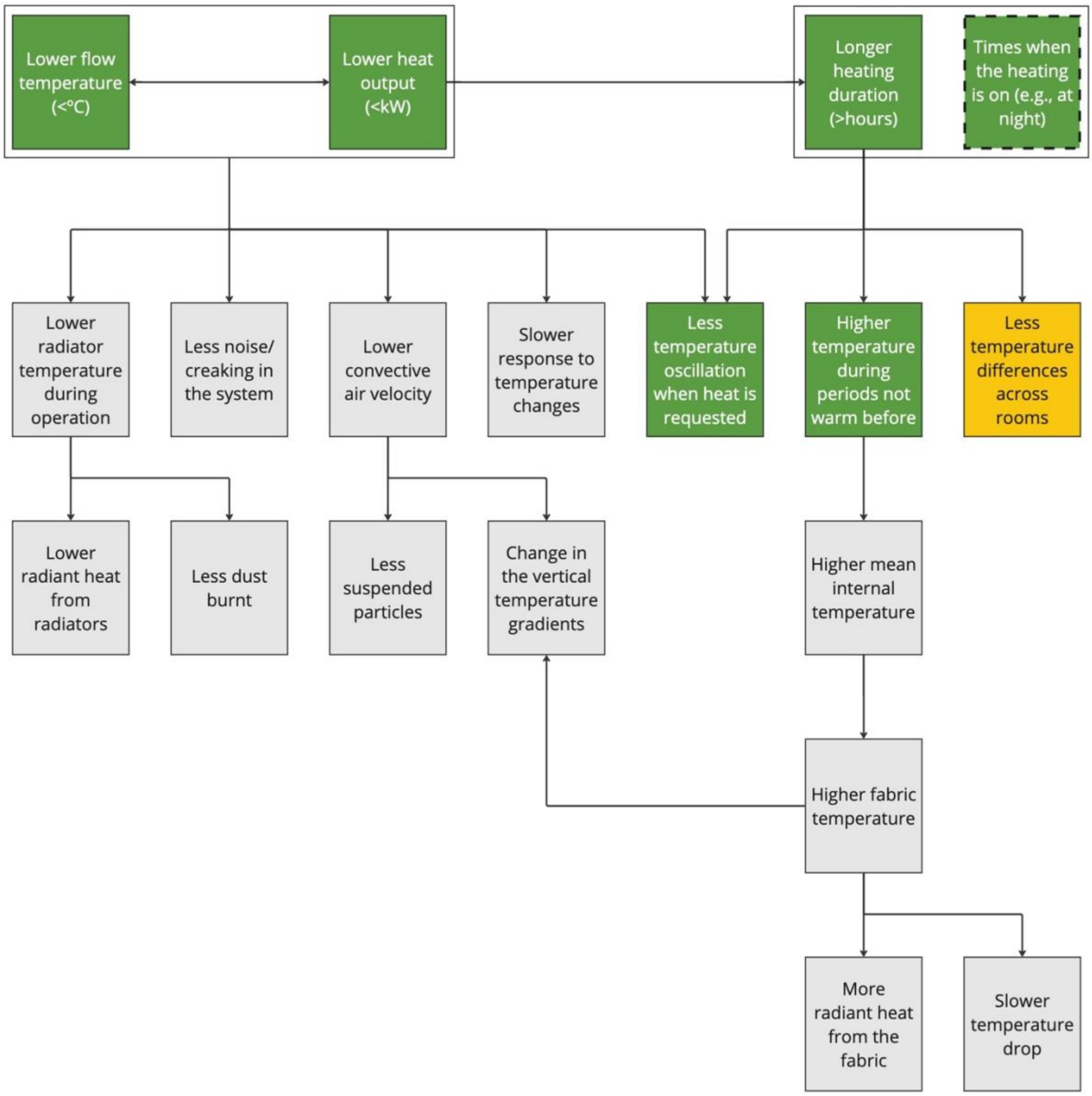


Figure 4.18. Summary of the findings in relation to the other expected physical changes after the adoption of the new technologies.
In green those parameters observed that changed as expected. In orange, those for which there was inconclusive evidence. In red, those that changed in an unexpected way.

5. Exploring comfort-related heating practices

Social practices at home entail expectations for the indoor conditions where they take place. Providing these expected conditions is one of the primary outcomes of domestic heating practices. The heating system plays a critical role in them and, as several authors have explained (see Madsen, 2018, for example) and as it has been shown in section 2.2, the introduction of the new heating technologies can affect these outcomes. Smart hybrid heat pumps, which substitute or supplement gas, LPG or oil boilers, operate differently (e.g., low flow temperature instead of high flow temperature), do not provide the same indoor conditions and do not offer the same opportunities to engage. However, it is unclear how householders experience these changes or whether heating practices evolve after adopting the technologies. Analysing these topics constitutes a critical step to understanding the impact these technologies could have, and it is also a unique opportunity to understand heating practices in domestic settings.

The interest of the research is in the local variations of these heating practices, as they define the dynamics of the practice, and their constant enactment and accumulation could shape the practice-as-entity in the long term. At the same time, the analysis of this variation could contribute to identifying specific performances better aligned with the requirements of the electricity network (performance of the system and/or DSR) and help to design new trajectories for the practice. However, in this chapter, the variations in the performance of the practices are not presented separately (e.g., one section for each household). The elements that constitute these performances are unpacked and analysed separately, and the common elements are grouped. This approach provides a level of detail that would not have been possible by simply describing each of the performances and allows us to explore the links between elements independently, assessing their importance.

The analysis covers two main areas. First, the expectations for indoor conditions are assessed in relation to the indoor conditions provided by the new technologies. Second, the changes in heating practices resulting from the adoption of the new technologies are presented, with a particular emphasis on those changes that diverge from the "expected" heating practices as they might reduce the capacity of the algorithm to forecast the heating demand and minimise the heating costs. The Chapter aims to answer the following research questions:

- How do householders experience the novel heating technologies regarding comfort?
- How do heating practices for comfort evolve after adopting the novel heating technologies?

The findings presented in this chapter rely on the data collected through the interviews with the householders and the analysis of the information stored in the Customer Relationship Management (CRM) database. The analysis of the data should help to explore how the previously analysed indoor conditions (Chapter 4) are experienced and constructed as part of the heating practices.

The chapter is organised as follows. In the first section, the householder-observed changes in indoor conditions and their impacts on thermal comfort are explored using the data from the interviews. The second section discusses how changes in the noise of the system are experienced after adopting the new technologies. In the third section, the findings are triangulated with the data obtained from the CRM database. Finally, the findings of the previous sections are combined and discussed in relation to the literature.

5.1. Experiencing thermal comfort with the new technologies

The findings of the literature review and Chapter 4 evidence that indoor thermal conditions can change when heating with hybrid heat pumps with smart heating controls, compared to conventional boilers. Through the analysis of the interviews with participants in the ten cases studied, this section explores how the changes in the thermal conditions are experienced, analyses whether they conflict with expectations of indoor conditions and studies the changes that the new technologies trigger in heating practices for thermal comfort.

However, while the previous Chapter 4 measured each of the parameters that define the indoor conditions separately, the participants experienced all of them at the same time, and the sensations described might be a consequence of more than one of the expected or monitored changes. Therefore, it is sometimes difficult for participants to link their experiences to each change. Additionally, the feedback loops that shape the dynamics of the practice are often interwoven, and the actions undertaken might respond to several of the described experiences (e.g., reduce the temperature setpoint because the air temperature does not oscillate that much but also because the system is noisy). The analysis has tried to unpick the data and identify all these connections when possible.

The participants' experiences can be linked to three main themes regarding thermal comfort. First, some of the householders explained how, after the installation of the technology, they noticed changes in the radiators and missed their hot temperature, which conflicted with some of the associated meanings. Second, some participants mentioned that the new system provided steady, highly valued warmth, which they often found very appealing, with a few exceptions. Finally, a small group of participants described experiencing feeling too warm (overheating) during specific periods of the year after installing the new technologies. These three topics are explored in more detail in the following subsections. It is important to note that the groups are not exclusive, and the same householder might have experienced these three issues simultaneously or at different times.

5.1.1. The temperature of the radiators

When heating with a conventional boiler, the flow temperature of the system is usually above 60ºC (Rossi & Bennett, 2024), and the system operates in quick bursts. The water flows through the radiators for short periods at high temperatures. As analysed in section 4.1, the flow temperature in most of the studied cases was lower than that. Unsurprisingly, that was a widely discussed topic in the interviews, even when not explicitly mentioned by the interviewer. All interviewees noticed that the radiators were colder after adopting the new heating system and that the heat from the radiators was less noticeable, which is consistent with the measured data. In some cases, participants believed this change was constrained to when the system was on heat pump mode (Greig, Simon, Clare) or was more evident when the heat pump was running (Barry), which, again, is consistent with the analysis in section 4.1. Greig described the surface temperature of the radiators when on heat pump mode as lukewarm and Clare as "not even lukewarm". Simon's case is particularly interesting because despite mentioning differences in the radiators' temperature depending on the heating mode, the monitored data evidenced that often the flow temperatures when on boiler mode and heat pump mode were similar (see Figure 4.6), despite a higher average when on boiler mode.

The cosiness of a hot radiator

The analysis of the interviews showed that this change in the radiators' temperature is not only noticeable but that sometimes the hot temperatures are missed after the adoption of the new technologies. In line with other research on the topic (e.g., Judson *et al.*, 2015), the findings of this analysis evidenced that expectations of indoor conditions at home in some cases include the temperature of the radiators. This is important for two reasons. First, it was common for some participants to touch the radiators when feeling cold and they enjoyed feeling them warm before installing the new technology. After installing it, Greig explained that his wife misses the feeling of putting her hands close to the radiators when they are hot. This is consistent with Clare's experience, who explained that she enjoys standing by a hot radiator when feeling cold, which does not provide any comfort when the system runs at low temperatures.

> *Heat is there all the time. For me, it's really good. I think my wife misses that feeling of putting your hands on the radiator: "Ohhh, (makes a funny face) that's really nice". I think she misses that.*
>
> *Greig – 1st Interview*

Second, because of its effect on radiant heat. When talking about the temperature of the radiators, participants not only referred to the surface temperature of the radiators. Instead, they often mentioned the differences in the heat coming out from the radiators, probably the heat output in the form of radiant heat. As explained in section 4.1, when operating in low-temperature mode, the new system gradually heats, and the flow temperature of the water running through the radiators is lower than with conventional boilers as well as the heat output from them. There is no "heat blast". Greig explained that with the new system, it is difficult to "feel", "smell, or "hear" the heat[30]. With constant low-temperature heat, "you're in the heat"; you get used to it and cannot feel it. On the contrary, the sudden radiant blasts of a high-temperature radiator are noticeable and provide comfort (Greig). The findings are consistent with Crawley et al. (2023) and Madsen and Gram-Hanssen (2017), who showed the importance of the multisensorial dimensions of comfort.

The analysis evidenced that heating practices include meanings associated with this heat output (heat blast) that are sometimes retained after the new technology is installed. Some participants explained that the radiant heat from the radiators contributes to creating a cosy environment, which is an important part of domestic life and is very valued during parts of the day and the year, as several authors have suggested (see Devine-Wright *et al.*, 2014; Judson *et al.*, 2015, for example). For example, Simon explained that his wife enjoys the cosiness of a hot radiator in the late evening before going to sleep when moving from the living room to the bedroom. This environment created by the hot temperature radiators is also important when feeling cold (Clare) or returning home on cold winter evenings (Simon, Susan).

> *So there's benefits to the heat pump for supply in a constantly warm temperature. But when you feel cold, you don't get that satisfaction of the heat being on.*
>
> *Clare – 2nd Interview*

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[30] As explained in section 2.2, in this case, the participant is probably referring to the smell of burnt dust and the noise of the pipes and the radiators cracking due to the sudden change in temperature.

Valuing the sudden heat blast is often not incompatible with enjoying the constant warmth provided by the new system (Greig, Clare), as will be explored in section 5.1.2. Additionally, in a small number of cases, participants explained that the heat boost helped them to feel more comfortable not only because of the change in indoor conditions but also because it reassured them that the heating was doing something (Simon, Susan, Clare) and that they were "getting something from it" (Clare). Simon explained that in some cases, the other householders believed that "if the radiators aren't on" they are "not gonna get hot". These experiences resonate well with Devine-Wright et al. (2014) who identified a few cases in which participants reported how they felt warmer when seeing the glow of a fireplace. In the present study, they did not mention the visible warmth but the surface temperature of the radiators.

Retaining meanings and adopting new know-how to provide the heat blast

The hot radiator temperatures, the heat blast, and the cosiness it provides proved to be a relevant part of the meanings associated with the heating practices with conventional boilers. Some participants retained these meanings after adopting the new technologies and tried to recreate these conditions with the new heating system. They did that mainly in two different ways. On one side, some participants relied on using secondary heating sources to create a cosy environment; on the other, they retained some of the know-how of heating practices with conventional technologies and forced the system to work at high temperatures, which increased the radiators' temperatures and the heat output.

Regarding the first strategy. Simon described how he uses an electric rug in the living room in the evening to provide cosiness and comfort. He believes he uses it less than once a week in winter, but it is unclear if that was already part of the heating practices in the household before the adoption of the technology. Additionally, he placed some blankets in strategic places in the house and encouraged the other people at home to use them to create this feeling of cosiness and not force the heating system to run. Clare also described this dichotomy between using blankets or the heating system, but she ended up settling for the latter, as explained below. The householders in H3 (Greig, Grace) explained that they use a log burner 3 to 5 days a week in winter. Despite using it less than when they had their conventional heating system because the heating system does not need any help to achieve the required indoor conditions, they still use it to provide cosiness because "it's nice to have it on" and as an alternative to forcing the system to run at high temperature (Grace). These two cases suggest that feeling radiant heat on the body is an important part of feeling warm, and while the source of the radiant heat can be replaced, this sensation is critical. However, in one case, heating practices changed in the opposite direction, and the householders stopped using the wood stove to provide cosiness after installing the system because the house would get too hot (Laurence). It was unclear if they found other ways to provide radiant heat, but they did not discuss them or if they developed new meanings of comfort that did not involve feeling the radiant heat. The findings are consistent with Judson et al. (2015) and Tweed et al. (2015), who explained that the role of supplementary heating sources changed after the adoption of heat pumps, with some people retaining them for cosiness or as a backup system and others abandoning them as the new system already provided the expected indoor conditions.

As part of the heating practices to recreate the old comfort conditions previously discussed, three households described know-how that involved unscheduled changes to the temperature setpoint. Common in it was manually increasing the current setpoint to force the system to increase the flow temperature and the heat output of the radiators (Clare, Simon, Greig). The manual operation prevents the system from preheating at a low flow temperature before the warmth-requested period (IN period in the terms used in the app). And requires the system to increase the heat output of the system to increase the air temperature quickly. That usually increases the flow temperature and forces the boiler to operate as it is more powerful than the heat pump.

CH4 (Clare) is the most extreme example of that. As Clare explained in the second interview, during the second winter with the technology and after being unable to achieve the outcome she wanted, she stopped scheduling the temperature setpoints and let the system optimise its operation in advance. She set a low setpoint for the whole day (12ºC) and manually increased the temperature setpoint to 20ºC using the wall thermostat whenever she wanted heat, usually for one hour in the morning and 3-4 hours in the evening (see

Figure 5.1). The change aimed at two different things: controlling the heat output from the radiators and reducing the noise at night, which will be explored later. Additionally, expectations of energy costs linked to certain heating patterns might also have played a small role in that (and will be analysed in Chapter 6). The low-temperature setpoint all day ensured the heating system was not coming on, and the manual increase forced the boiler to kick in when she wanted. This type of operation was repeated almost every day during the winter, according to the participant, and contributed to providing the heat output that she wanted. However, the participant complained that the temperatures in the morning were colder because the system did not have time to preheat and that manually operating the system every day was inconvenient. She manually changed the temperature setpoint using the wall thermostat, which she understood to be more responsive than the app[31]. This type of operation could explain why her average flow temperature was close to that of a conventional boiler (55.7ºC), and it was the higher of all the cases (see Figure 4.2). Additionally, the experience described is consistent with the recorded manual overrides of the scheduled operation. They were low in autumn 2021 and the first two months of 2022 (see Table 4.2) and increased in the following months (27 and 19 days with manual interactions in March 2022 and April 2022, respectively) when Clare decided to start forcing the system to change its output.

[31] The experienced low responsiveness of the app was investigated with the controls manufacturer without finding any plausible explanation for it. While the app might take a few more seconds to update than the wall thermostat, it is unlikely that this delay could explain the experience described.

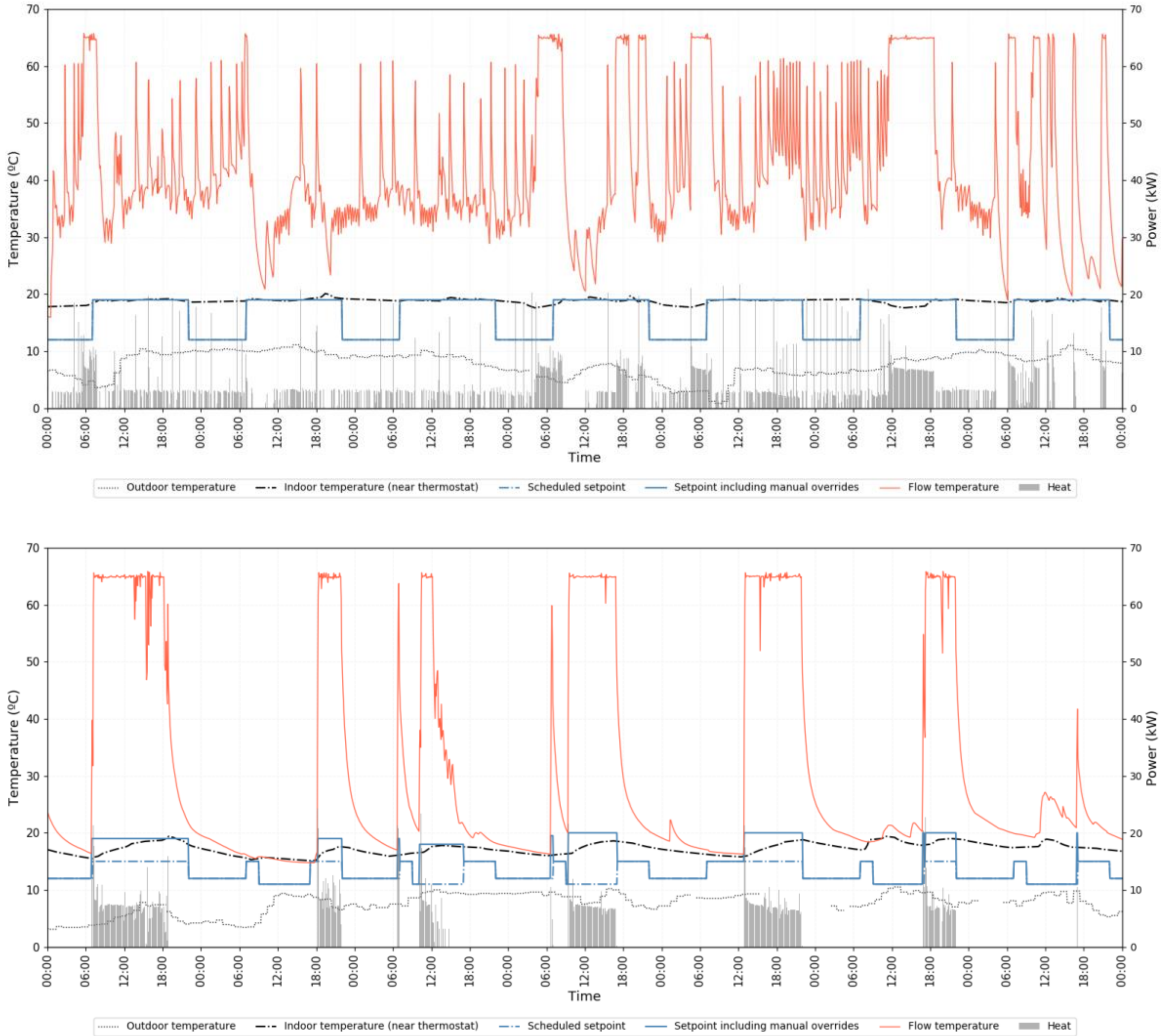

Figure 5.1. Operation of the heating system and indoor temperature near the thermostat in CH4. The plot on the top is from the week commencing the 7/2/22 and the one on the bottom the week commencing the 7/3/22, after adopting the new (manual) way of operating the system.

The other participants who adopted similar know-how did not set such a low setpoint all day. Instead, they set a setpoint that was enough to satisfy their comfort expectations most of the time, and they increased it by 1-2ºC to force the system to provide extra heat and boost the output of the radiators when they wanted. The frequency of this type of operation varied between cases; Simon admitted doing that most days during cold months, and Greig only once or twice per month. In Simon's case, the number of manual interactions is consistently high (>15 days every month) (see Table 4.2), as well as the average flow temperature recorded (49.8ºC). However, that might not only be determined by the actions described in this section, as he mentioned other reasons, which will be explored in Chapter 6. In H2 (Richard), that operation was initially part of the heating practices during the first winter, but it was abandoned later on to try to reduce boiler usage as part of an effort to reduce waste, which will be explored in the following Chapter 6.

This type of operation makes it clear that the thermostat setpoint is sometimes not only used as a temperature setpoint schedule but also as a way to control the heat output of the radiators. This know-how might be inherited from previous heating practices with conventional heating systems (with small variations to adapt it to the new controls), which allowed fine control of the heat output and the radiant heat from the radiators, as Clare explained. In those systems equipped with on-off controls, that was done by simply switching on or off the heating system and, in thermostat-equipped combi boilers, temporarily increasing the temperature setpoint.

> *When you just want some warmth, traditionally, I would press the boost button and I'd get one hour of blast the radiators. And I know that that would be enough. Whereas in this scenario you can't do that. So, how do you then get the warmth that you're looking for when you feel cold?*
>
> *Clare – 2nd Interview*

Developing new meanings more aligned with the cold radiators

The previous subsections explained how meanings of cosiness associated with the heat blast were retained after adopting the new technologies and that new know-how was developed to provide that. However, that was not always the case. In some households, those comfort meanings associated with a high radiator temperature were quickly abandoned. For example, Richard explained that he likes that the radiators are not hot to touch after adopting the technologies and that he does not miss the heat blast from the radiators because it used to wake them up every morning when using their old heating system. This is consistent with Laurence, who also prefers not to notice the heat from the radiators.

5.1.2. The steady warmth

The temperature of the radiators was not the only noticeable change after adopting the new technology. When participants were asked about the indoor conditions with the new heating system, the most common answer was that they felt warmer in their house and that they noticed that the warmth provided with the new heating system was different than that provided with their old boiler, particularly in terms of consistency. Most participants explicitly mentioned how they enjoyed the new thermal environment. However, in some cases, the participants experienced the increased warmth and constant conditions as wasteful, which had consequences for heating practices and will be explored in Chapter 6.

Warmth is an open and broad concept; feeling warm can result from changes in indoor conditions as well as other elements of the practice. Many of the issues discussed in section 2.2 can explain why people might find the house warmer and the indoor conditions more consistent. Therefore, to understand how householders experience the technology as part of their heating practices, it is necessary to unpick their thermal experience.

The new warmth

When participants explained the differences in warmth when engaged in heating practices with the new technology, they not only referred to higher air temperatures. Instead, they identified a wide range of changes in indoor conditions. Molly, for example, described the new warmth in the following terms:

> *I believe that the house was never as warm as it was this winter and it wasn't warm in a way that it was usually warm when- It was very pleasant warmth. More kind of natural rather than having a peak of putting the boiler on and then everybody says: "Oh, put the heating off" and then half an hour later, everything is cold. It was more kind of unified. It was as if you don't notice that the heating is on, but it is warm throughout the house, which was really nice. This was the nicest winter in terms of heating, in my view.*
>
> *Molly – 2nd Interview*

Richard also explained that one of the main differences he noticed was in the low-temperature drop at night, which he believed was caused by differences in the heat stored in the building fabric. He believes the new system heats the fabric rather than just the air, and the temperature does not decay much at night. For that reason, the warmth provided by the new system is completely different from the warmth provided by their old boiler, and the house feels warmer.

> *it is all about the fabric with the heat pump. You know, the building is warm, whereas with a boiler, the building would go cold at night and then the radiators would be hot. So, rather than having- We've now got a warm house; we used to have a cold house at night and hot radiators in the daytime.*
>
> *Richard – 1st Interview*

Both quotes describe the new indoor conditions as warmer and help to identify four elements that participants believed contributed to that. First, the constant temperatures during periods in which warmth is requested (fewer peaks and drops). Second, the changes in the characteristics of the warmth provided, particularly the heat stored in the fabric. Third, the constant and steady warmth during periods in which heat is not usually requested (e.g., at night). Fourth, the homogeneity of the indoor temperatures across the building. While none of the participants explicitly identified those four elements at the same time as the reasons behind the changes in warmth, these elements recurrently appeared in the interviews. For that reason, they will be analysed separately in the next subsections.

More constant warmth during warmth-requested periods

As mentioned before, participants found that with the introduction of the new technology, the air temperatures were less varied, with fewer peaks and drops during the periods in which they requested warmth (IN periods in the language of the app) (Nelson, Nicole, Laurence, Clare, Jessica, Dorothy, Molly, Barry, Richard, Greig, Grace). While the temperature oscillations have already been explored using the measured data in the previous Chapter, the interviews offer a unique opportunity to better understand how they are experienced as part of the heating practices. Participants described the change in the temperature oscillations using different terms that referred to their sensations (e.g., "no extreme too cold or too hot" (Nelson)), to the changes in the air temperature (e.g., "consistent temperature" or “temperature that doesn’t go up and down” (Jessica)) or to the changes in the heat provided (e.g., “constant trickle heat” (Laurence)).

Most participants described the lack of peaks and drops as one of the characteristics of the new heating system in general. However, Clare explained that the constant warmth was only noticeable when the system was on heat pump mode, not boiler mode. She explained that at one point, the heat pump broke down and did not work for over three weeks. During this period, she noticed that the house started to feel colder in the early afternoon despite having scheduled the heated period from 6am to 10pm. The experience described is compatible with the technical analysis (see section 4.2.1) because the heat pump ran longer than the boiler, and, in her case, the negative correlation between temperature homogeneity and heating duration was the largest of all the cases. None of the other participants mentioned a similar experience.

<u>The experience of previous practices regarding temperature oscillations</u>

The experience described by the householders is the consequence of comparing the indoor conditions against the template provided by their memory of previous performances. This template is shaped by the previous technologies installed (oil, gas or LPG boilers), which, as explained in section 4.2.1, might have contributed to more temperature oscillations during warmth-requested periods. However, the analysis of the interview data found that the existence of temperature oscillations cannot only be attributed to the heat output of the previous system. The manual operation of the old heating controls also shaped it. Before installing the new technologies, half of the participants in the study (CH5, CH6, CH7, H1, H3) did not set any temperature schedule, and they turned the heating on when they wanted or felt cold and switched it off when they did not need it anymore. It is likely that because of this type of operation, the temperature experienced relatively large oscillations, with participants feeling cold right before the heating was turned on or overheating before the temperature started dropping. For example, Greig and Jessica explained that the house was constantly overheating and underheating with the previous system, contrasting with the current constant temperature:

If we've set it really high in the morning, then probably late morning, it feels really probably too hot. And then we respond, and we turn it down. And then maybe early afternoon it's too cold. So, it's like a yo-yo. Up and down.

Jessica – 1st Interview

As summarised in Table 3.1, for most of the participants, this was the first time that they did not use the heating controls manually as an on-off switch. There was an evident difference between the old and the new control mode, not only in terms of convenience, as Barry acknowledged, but also in the indoor conditions achieved. Participants moved from the constant peaks and drops in warmth when using the old controls to the thermostatically regulated new indoor conditions. Therefore, the new indoor conditions could represent a bigger disruption than is often acknowledged.

That does not mean that the system's capacity to better modulate down the heat output or heat for longer does not play any role here. For example, Richard, who used a conventional thermostat before installing the new technology, also explained that the old heating system created more temperature peaks than the new heating system. In this case, the results are consistent with the technical data, as this was one of the cases that showed a statistically significant correlation between the heating duration and the temperature homogeneity. Therefore, it is likely that the specific physical characteristics of his house might make changes in the heating duration more noticeable than in other cases, even when switching from a conventional thermostat, not from an on-off control.

Other differences in warmth during warmth-requested periods

While the lack of peaks and drops in temperature was the most commonly described change in warmth during the warmth-requested periods, it was not the only one. For example, Richard noticed that the new heating system better heats the building fabric, which contributes to increasing the radiant heat from it.

it's warmer so you feel that heat is not coming just from the radiators. It's from all around. That might be it. It's just more comfortable.

Richard – 1st Interview

In section 2.2, it has been explained that the adoption of the new technologies is expected to result in mean indoor temperatures increasing; thus, more heat is stored in the building fabric. While only he explicitly mentioned noticing this change, the expected changes are compatible with the experiences of other participants. Molly, for example, described the new indoor conditions as "natural warmth" or "unified warmth", and Nicole described them as "nice and warm". However, it is difficult to link these experiences to specific changes in indoor parameters as these are often not easy to identify or describe by the participants, which shows the difficulties to combine social and technical data, as explained in section 3.2.5.

Other non-described changes might also contribute to the experience of the householders. As Benett and Elwell (2020) explained, participants might have constantly under-achieved the requested temperature setpoint when using conventional boilers (e.g., because the system might not have time to achieve it during short heating periods). Therefore, the indoor air temperatures achieved through heating practices with the new technologies might be higher (and experienced as warmer) than those achieved with the previous technologies despite maintaining the temperature setpoint.

Adapting heating practices to the constant warmth

The findings show that expectations of indoor temperatures as part of the heating practices with conventional boilers were, in most cases, shaped by discontinuous heating and oscillating temperatures. However, the interviews suggest that as part of adopting the new technology, householders could develop new meanings of thermal comfort more aligned with the constant warmth conditions provided by the new system during periods in which heat is requested. Most participants described the new indoor conditions as very pleasant (Nelson, Nicole, Laurence, Clare, Jessica, Dorothy, Molly, Barry, Richard, Greig, Grace). Only Clare did not fully embrace the mentioned changes in the indoor conditions. She was worried that the new operative patterns might increase her energy bill, which will be further analysed in Chapter 6. This quick adoption of the new indoor conditions contrasts with the previously described relationship between heat output (hot radiators) and cosiness, which evidences that some of the changes are easier to adapt than others. The lack of meanings associated with the old oscillating temperatures, other than those of waste (Clare), might explain the absence of conflicts in most cases.

In some instances, the described changes in indoor conditions during warmth-requested periods were accompanied by changes in know-how, other than delegating the control of the heating times to the system. For example, Jessica explained that she stopped using a blanket while working from home because she did not feel cold. This is consistent with Grace, who explained that she no longer needs to change clothes often when at home because after installing the technology, it was never too cold or warm (less temperature oscillations). For the same reason, some participants believed that they interact less to increase the temperature setpoint with their new heating controls than their old boiler controls (Grace, Barry, Laurence) and others that they have reduced the usage of the log fire (Laurence, Richard). In both cases, that contributed to reducing the temperature oscillation.

It is also interesting to note that those participants who already defined temperature setpoints before installing the new technology (those who had and used programmable thermostats) noticed that they reduced the temperature setpoint with the new technologies. That was because, otherwise, it felt too warm in the house (Nelson, Richard, Clare). Nelson lowered the temperature setpoint from 21ºC to 20ºC and turned down the TRVs. Richard lowered the setpoint 0.5ºC compared to the temperature settings with his old boiler. The findings evidence that the temperature setpoint people initially wanted was experienced as too warm once they could achieve it. One potential explanation for that is that with the old heating system because the temperature oscillated more, the temperature setpoint was chosen to ensure comfortable conditions in the colder part of the cycle and with the new system, the temperature fluctuation was smaller, and it was too warm. However, other elements, such as underachieving the temperature setpoint with their old heating system (see Bennett & Elwell, 2020) or changes in other parameters (e.g., radiant heat from the walls), might have also affected the changes in the temperature setpoint.

Warm during periods which used to be cold

As explained before, various participants noticed that, after starting to heat with the new technologies, the house felt warmer than before during periods in which they did not usually request warmth before installing the technology (OUT or ASLEEP periods in the terms of the app) (Nelson, Nicole, Laurence, Clare, Richard, Greig, Grace). The changes were noticed during two main periods, night and late morning/early afternoon. Participants described the changes in two ways: longer preheating and no cooling down outside warmth-requested periods (OUT or ASLEEP periods in the app terms).

Regarding preheating, various participants noticed that the system anticipates the heating needs and warms the house before the periods when heat is requested (Laurence, Grace, Jessica), ensuring that it is always up to temperature at the beginning of these periods (which also affected the temperatures during the warmth-requested periods, as explained before).

> *It's actually quite nice- I tell it is actually better getting up now when it's slightly preheated. Than perhaps when the old gas combi just used to kick in instantaneously at the time you set it, really. It wasn't quite intelligent enough to come on before.*
>
> *Laurence – 1st Interview*

Jessica explained that, before installing the new technologies, they switched on the heating system every morning when they woke up. Because even with a gas boiler, it takes some time to heat the house, they often felt cold in the mornings until the house had warmed up. This is consistent with Laurence, who used a programmable thermostat and also explained that it was cold in the mornings with the old heating system. This is because he had it programmed to start to operate at approximately the time when they woke up, probably to try to reduce energy waste, and the system did not have enough time to bring the spaces up to temperature. This also suggests that householders tolerate colder temperatures in the morning and that achieving the temperature setpoint might not always be required but it is often very welcomed. The noticed changes are consistent with Bennett and Elwell (2020), who have argued that when heating with conventional boilers without heat-up optimisation, the temperature setpoint is often not achieved.

Regarding temperature decay, several participants noticed that with the new heating system, the temperature did drop less during periods when heat was not requested (Nelson, Nicole, Laurence, Clare, Richard, Greig, Grace). Richard explained that after installing the new technology, the temperature did not usually drop below 18ºC in those periods, even when they set a low-temperature setpoint.

> *I'm finding is the way that the profile is that when it drops down at night it's always thinking of the following afternoon. So, it doesn't matter what it's set it to at night or the morning, it's trying to get to 20.5 or 21 at midday the following day. So, I found that a little bit strange, really. And if you ever look at my profile, it hardly drops during the night. My indoor temperature probably only goes down to 19.5 or something like that, normally.*
>
> *Richard – 1st Interview*

The analysis of the technical data recorded in his home (see section 4.2.2) shows that the temperature dropped an average of 1ºC overnight in his house, with only a few days falling more than 2ºC, which is consistent with his explanation. Greig also mentioned that he set a night temperature setpoint of 12ºC, but that the temperature rarely dropped below 19ºC. These differences are consistent with the expected changes described in section 2.2: the lower heat output of the system makes it more efficient to maintain the temperature during periods in which warmth is not requested (heat-up optimisation, which is what the smart thermostat is doing), and the higher temperature of the walls slows down the temperature decay. However, it is also important to note that both participants live in well-insulated buildings, and because of their interest in the technology, they might be monitoring the indoor temperatures in a more detailed way after the adoption of the new system and might be more aware of the temperature patterns. Barry, who lives in an older and less well-insulated building, explained that the temperature in his house still drops at night after adopting the technology, and the temperature drop overnight in his household was the larger of all the cases (see section 4.2.2). However, in his case, the experience was different because he requested the control manufacturers to force the heat pump not to work overnight to reduce the noise (an issue that will be further discussed in section 5.2).

Householders in CH6 and CH7, who also live in poorly insulated buildings, did not refer to this matter, but the temperature drop recorded overnight in these buildings was smaller (1.2ºC and 0.8ºC, respectively).

Adapting heating practices to being warm when not requested

The expectations for indoor conditions before adopting the new technologies were shaped by the characteristics of the existing system: the house is warm during the periods in which warmth is requested, and the temperature drops outside these periods. Heating practices with conventional boilers commonly involve heating intermittently, with the heating being off at night or during working hours (Hanmer *et al.*, 2017), resulting in a pattern of temperature peaks (Huebner *et al.*, 2015). If using programmable thermostats, like CH1, CH2, CH3, CH4 and H2, householders program the system to operate during these periods. If using simpler on-off heating controls, like CH5, CH6, CH7, H1 and H3, the heating system is only switched on during these periods. That means that for the rest of the time, the heating system does not heat, and the building cools down (except in those cases in which there are large internal gains or solar gains).

The research evidenced that this type of discontinuous operation was common before the adoption of the new technologies and was accompanied by expectations of being cold during these periods. For example, some participants explained that despite being at home, they wanted/expected to be cold (or colder) (Nelson, Laurence, Susan, Richard). The literature has extensively explained how maintaining cold temperatures at night is an important part of sleeping practices in the UK (Kuijer & Watson, 2017), which was also mentioned by the participants (e.g., Richard explained that they "like it a bit cooler in the room" when they sleep). However, the analysis also evidenced that there are other times in which people chose to be cooler, which is consistent with Hanmer et al. (2019b). For example, the previous subsection has identified an expectation for cooler temperatures in the morning. Also, Nicole explained that Nelson prefers not to heat when working from home, and he simply wears more clothes than at other times. Nelson believes that "it needs to be reasonably cool to work, but not cold", and he seemed to suggest that that was a strategy to cut down energy waste, which will be further explored in the next chapter.

Richard explained that he used to schedule the heating to be off from 9am to 3pm with the previous heating system, despite working from home, and he boosted the heating system if it was too cold. Simon and Susan also described a similar situation.

The adoption of the new technologies contributed to more constant temperatures all day. However, adjusting some of the abovementioned expectations to the new indoor conditions during the day was, in some cases, quick. Some participants explained that these new conditions were more comfortable and better suited to their lifestyle because they work from home (Nelson, Laurence, Richard, Grace, Clare) or are at home for other reasons (Nicole). Richard explained that he would like to keep these indoor conditions even if he was not working from home. In contrast, Clare explained that she would not want them if she returned to the office because of the perceived associated costs, which will be further explored in the next chapter.

These changes in indoor conditions during the day triggered small changes in know-how. For example, Laurence explained that because the house is warmer when he works from home, he does not need to boost the system anymore because he never feels cold. In other cases, the know-how was retained. For example, Susan and Laurence explained that they set the new heating controls to no heat requested (OUT) during the day despite working from home. As explained in section 5.1.1, participants often do not use the heating periods according to the house occupancy. The lack of a clear link between the settings chosen and the outcome of the heating system might reinforce this. For example, Richard explained that it does not matter what settings he chose for the non-heat requested periods (OUT or ASLEEP) because the system will always try to achieve the temperatures for the next period in which heat is requested (IN period).

However, not all the changes were that easy to adopt. The night warmth was more difficult to accept despite being fundamental to minimise costs, carbon or achieve the objective set by the smart heating controls. None of the participants described the new indoor conditions at night as more comfortable. Instead, they often retained the expectations of cold bedrooms and tried to reduce the temperatures provided by the new heating system at night to bring them to acceptable levels. For example, Clare explained that they delayed the period when heat was requested to reduce preheating at night, which was suggested by the customer service team when they complained about the night temperatures.

> *So, it's about adjusting the time that it comes on in the morning, whereas I was operating it under the traditional boiler where I would have it coming on at 6.20am in the morning and then I'd have it going off at 7-7.30am and off for the whole day until I came back from work in the evening. So, I think what they suggested was to make the 6.20am a later time to stop it from coming on so early. To try and regulate the temperature and the heat.*
>
> *Clare – 2nd interview*

Richard also initially felt too warm in the bedroom, and he decided to turn the TRVs in the bedroom down. During the winter months, he set a routine of turning down the bedroom TRVs every day before going to sleep. He believes that if he does not do that, he does not sleep well. When enquired about other options, like using a thin duvet, he answered that it was easier to change the TRV every day because some nights are still cold, even after installing the new technology, and the duvet might be needed. That is probably because, in certain cases, the system runs on boiler mode and does not need long preheating, and the temperature drops more at night (the temperature data recorded in his household shows a statistically significant correlation between the temperature drop at night and the heating duration, which is consistent with this explanation). The use of thick duvets might likely have contributed to the need to maintain low night temperatures. Richard believes that the temperature at night in the bedroom should always be below 21ºC, which is what he has set for the day, and probably around 18ºC.

Nelson explained that he set the TRVs in the bedrooms permanently low. Still, it is unclear if that was defined after adopting the technology or was already part of the heating practices with conventional heating systems. His wife, Nicole, explained that she noticed the increase in temperature at night but did not change her practices because the new indoor conditions did not affect her sleep, which suggests that some increase in the night temperature might still be acceptable in some cases.

Spatial differences

One of the quotes introducing this section explained that adopting the new technologies contributed to more homogeneous temperatures across the building. The analysis of the expected changes in indoor conditions (section 2.2) suggests that the building will be heated for longer, which should contribute to less spatial temperature differences as the heat exchange between rooms will continue for longer. However, the participants' experience is more complex. This is consistent with the results of the technical analysis (section 4.2.3), which were inconclusive as not many cases had statistically significant results, and there were significant differences between them.

Homogeneous warmth across rooms

Regarding the changes in the thermal differences across the house, four participants (Nicole, Dorothy, Molly, Greig) noticed that the indoor temperatures were more homogeneous after installing the new heating system. They acknowledged that there used to be cold and warm spots in the house, and with the new technologies, these differences were reduced. The four of them found these new conditions more comfortable, and in one of the cases, the change in indoor conditions contributed to reducing the usage of secondary heating systems (electric heaters) in cold rooms (Molly). Greig also mentioned that because of the homogeneity of indoor temperatures, he changed the TRV settings less. The results of the technical analysis were not statistically significant in any of these three cases, and it is not possible to know how the indoor conditions in these buildings changed with the adoption of a continuous and low-heat output heating system. None of the participants mentioned a change in the spatial warmth distribution within rooms, as Tweed et al. (2015) suggested that should happen. However, the warmth consistency described in the previous subsections by some participants might already include that.

Increased temperature differences across the house

In contrast to these three cases, Barry and Jim explained that after adopting the system, they noticed more cold spots across the building. They believed this was because the system was not correctly balanced during the installation process, and the radiators were not sized equally in the house (e.g., Barry believed that the radiator in the kitchen was too small). In Jim's case, the issue was addressed quickly through rebalancing the system. However, as the installation of the technology did not involve changes in the radiators and the new operation patterns do not affect the balancing of the heat distribution system, it is likely the hydronic system was already unbalanced before the installation of the new technology, but that remained unnoticed. This is consistent with Richard's words: He noticed more cold spots after adopting the technology but believed that they were already there before the adoption of the new system, but they were not noticing them because they were overheating the house. Adopting the new technology also affected the differences in indoor temperatures across the house in CH3 (Simon and Susan). In this case, new radiators were installed simultaneously with the new heating system, which unbalanced the heat distribution system. While in all the cases, the non-homogeneity of indoor temperatures conflicted with the expectations of indoor conditions, it is unclear whether these expectations concerned the temperature differences across rooms or the minimum temperature in the worst room.

Temperature homogeneity and heating practices

In most cases, increases in the homogeneity of the indoor temperatures across the home were positively experienced. However, it is important to note that, in some cases, the non-homogeneous temperatures were not the consequence of the limitations of the previous heating technology. Householders actively sought to create differences in temperature across the house when heating with combi boilers. For example, Laurence explained that they choose the temperature setpoints to ensure different temperatures in the different areas: colder on the ground floor, where the bedrooms are, and warmer on the upper floor of the house, where all the common areas are. This is consistent with Nicole, who explained that they keep the ground floor cooler because they do not use these rooms often, and when they use them, they are usually active. In this case, it is likely that meanings associated with waste, which will be explored in the following chapter, also shaped the temperature expectations. The findings are consistent with Tweed et al. (2015), who found that householders have a detailed, complex and nuanced understanding of the thermal behaviour of the building, which often informs their actions.

5.1.3. Seasonal conflicts: Overheating

The previous two sections have explored changes in indoor conditions and heating practices throughout the heating season. However, participants did not always discuss their experience in general terms. A few described specific issues that only occurred during parts of the year. Among those issues, overheating on specific days during the shoulder season was commonly mentioned by a few participants. Clare was one of the participants who was more vocal about this problem when she complained about overheating during the shoulder months of the first season after installing the system.

> *When we got to around probably March-April last year the outside temperature was really odd because one day it was freezing and the next day it was really warm and inside the house was just unbearable. It was so hot, and I couldn't get control of the temperature at all. It was just constantly running to the point where I rang the guys at Passiv 'cause my butter turned into liquid. It was so hot. And you were stuck because if you open the windows to get air in to cool down then it just make it fire even more because it was thinking: "Oh there's cold coming in".*
>
> *Clare – 1st interview*

Surprisingly, the technical data does not show any temperature peaks during these periods. If we accept that the experience described by Clare results from a high air temperature, several reasons might explain why the technical data does not capture the situation. For example, the problem might be located in certain rooms of the house where the thermostat was not located (unfortunately, the monitoring campaign did not start until the following winter season, so only the thermostat data is available), or the thermostat was in a location with a lower temperature than the rest of the house (e.g., they might have removed the thermostat from the wall and put it on a shelf which meant that it never gets warm, resulting in house being overheated). The householder did not experience these problems the next season, but that might be because she moved to a more "manual" operation of the heating system, as explained in section 5.1.2.

The problems of overheating in certain rooms during sunny days were not unusual. While this was the most extreme case, Jessica, Richard and Simon also described similar situations.

Richard and Simon explained that on sunny days, the south-facing rooms of the house tended to overheat as the heating system did not stop if the thermostat was in colder areas. Richard blamed the heating controls for not balancing the house automatically and Jessica for not being sensitive enough. Two factors might explain these conflicts. First, the new technology might have been adopted with increasing expectations for thermal comfort and automatisation and be expected to provide homogeneous conditions even under unbalanced solar gains. Second, heating with conventional technologies might have involved dealing with these situations through changes in the heating operation, for example, by planning, not heating on these days and accepting lower temperatures in certain rooms. The delegation of the control of the heating running times to the smart thermostat made those actions impossible, and the smart controls could not automatically perform them.

Controlling the heating running times seems to be particularly important during the shoulder season. Several householders explained that during these periods, they switched off the new heating system on certain days (Nelson, Jim, Jessica). Other participants explained that they switch off or lower the thermostat when they decide that they do not need heat until next winter (Clare, Dorothy, Richard). This is because "the thermostat is still trying to warm the house, but actually, it doesn't need it. The solar gain is enough" (Nelson – Int 2). It is important to note that because the heating system is thermostatically controlled, it would not operate if the indoor temperature were above the temperature setpoint and, in theory, there is no need to switch off the system. Several factors might explain why these actions are still performed. First, participants might not know how a thermostat works or might retain the know-how of practices with conventional technologies. Second, they might not have fixed thermal expectations during the year, with lower temperatures expected during the shoulder season, which would be consistent with the literature on adaptive comfort (see Brager & De Dear, 1998, for example). Finally, the lower air temperatures might be acceptable because of the changes in other parameters, such as the radiant heat from the sun, the temperature differences between inside and outside, etc.

5.1.4. Connected practices

As several authors have noted, practices at home are often interconnected, and these practice *bundles* can become co-dependent (Shove, Pantzar & Watson, 2012). Heating practices provide the indoor conditions for other practices at home, and therefore, they are linked to a wide range of other practices. While the previous sections have explored its links with sleeping or home-working practices, as these practices are often associated with very specific indoor conditions, other practices are also connected. For example, the heating system is critical in the practice of drying clothes at home, and changes in the radiator temperature, air temperature and radiant heat affect the capacity to dry clothes using the radiators, as several participants noted. However, there was no agreement regarding the direction of this effect. One participant, Nicole, explained that clothes dry more evenly with the new technology because the house has a more constant temperature, which is more similar to what happens outdoors. In the first interview, she explained that clothes dried quicker and in the second that they dried slower, but in both cases, she believed that they dried better than with the previous heating system, which is consistent with Judson et al. (2015). Other participants saw the technology as a limitation for drying clothes. Laurence explained that it takes longer to dry clothes, and Simon and Clare thought that the low temperature of the radiators meant that they could not be used to dry clothes.

5.2. Other comfort issues: Noise

While thermal comfort is often the focus of the literature on heating and comfort, the noise of the heating system was probably one of the most discussed topics by the participants and was one of the issues that created more conflicts. This is not surprising, as the noise of the heating system is often a source of concern, and it is often associated with failures of the system (Royston, 2014). However, it is important to note that the problem was not equally experienced by participants using Compact Hybrid heat pumps and participants using Hybrid heat pumps. One of the main differences between the two technologies is the location of the main heat pump components. The CH heating system is a compact technology in which the heat pump compressor and fan are installed inside the building, while in H systems, these components are located outdoors. These two components are the main sources of noise (Torjussen *et al.*, 2023), and having them inside the building (CH cases) can make the noise more noticeable indoors. Unsurprisingly, CH participants discussed this topic in more detail. For that reason, both projects will be analysed separately.

5.2.1. Outdoor heat pump (Hybrid heat pumps)

All the participants interviewed explained that at some point or another, they heard the noise of the heating system. However, in most cases, the noise did not affect their daily activities, and they did not experience it negatively. For example, Greig explained that he could hear the system running at night, but the noise did not wake him despite having the outdoor unit near the bedroom façade. Richard described the noise of the outdoor unit as less problematic than other system components like the circulation pump installed inside and common in most hydronic heating systems. He believed that this was because the system had an inverter compressor. While modulating the heat output, the compressor also modulated the system's noise making it less disruptive than a single-speed compressor (which either runs at a fixed speed or is stopped). It is unclear if, in these two cases, the increase in noise was still within the expected noise levels for domestic practices or if new and more relaxed expectations for noise levels were adopted.

In the other case (H1), Barry explained that the noise was only noticeable when he was outside and was not problematic when indoors. He explained that when outdoors, the unit was noisier than an air conditioning system, and it was difficult to maintain a conversation near the outdoor fan. While that was tolerable for him, it was not acceptable for his neighbour, which created a conflict between the two people. Barry recently moved into the house, which was located in a quiet rural village. According to him, the neighbour, who had been living in the village for years, found the noise of the new system completely unacceptable and in some cases, he jumped the fence of his garden to disconnect the outdoor unit.

> *I actually got into a dispute with my neighbour about the noise the heat pump was generating. So, to the extent that he was jumping over my wall and switching off the*

heat pump on the outside switch, which was not a good situation. So, a compromise I got the controllers manufacturer to reprogram it so it switches off at night and it switches back on again during the day. I'm not particularly happy about the situation. That's not how you're suppose to run heat pumps but it's better than having a big argument with your neighbour.

Barry – 1st interview

The heat pump was correctly fitted (passed its sound assessment) and was located 25 meters away from the neighbour's façade (usually a sufficient distance to reduce any noise problem), but it still was a problem for the neighbour. Barry believed this was reinforced by the neighbour's practice of keeping the windows open at night in winter for ventilation and the lack of double-glazing in his windows. While this is an extreme situation, it evidences that for the Hybrid heat pumps installed, the problem is mainly located outdoors and that the tolerable noise levels might be determined by the noise context (quiet area), which is consistent with Torjussen et al. (2023), and other heating practices (e.g., neighbour's ventilation practices). This type of conflict with neighbours has previously been identified by Owen et al. (2013). To overcome this problem, the participant requested the control manufacturer to force the heat pump to not work at night. That change contributed to more extended use of the oil boiler. The participant plans to build a noise enclosure around the outdoor unit in the future and resume the night operation of the heat pump, as he believes it is more efficient.

5.2.2. Indoor heat pump (Compact Hybrid heat pumps)

For most of the compact hybrid participants, the noise of the heating system, and in particular the noise of the heat pump, was one of the negative aspects of the new technologies installed (Simon, Nicole, Nelson, Laurence, Clare). That was the case even among participants who were satisfied with the technology. Nelson, for example, explained that he would not recommend the technologies tested to other people simply because of how loud they are. The documents that were shared with participants at the beginning of the trial introduced some of the potential differences in noise. Despite that, some participants were surprised by how loud the technologies were (Susan, Simon, Jim, Matthew). They explained that they were told that the new heating system would be as loud as a fridge (Susan, Simon), but they believed it was louder, more similar to a tumble dryer (Simon) or a walk-in fridge (Laurence). However, all the participants did not equally experience that, and Dorothy described it as quieter than a dishwasher, and Nelson explained that it was as noisy as the previous boiler, but it ran for longer.

Noticing the noise

When discussing the system's noise, participants identified diverse factors that affected the noise levels and their characteristics. Those were the location of the heating device within the home and the discontinuity of the noise. Regarding the first, several participants believed that the location of the heating device often determined the disruption caused by the noise. For example, the householders in CH3, who were the ones more concerned about the noise, had their heating device installed in the kitchen, which was part of an open plan area that included the dining room and the living room. The noise, in their case, was noticeable in all these areas of the house and was very problematic. Other participants noticed more problems in the bedroom because the heating system was installed below this room (Jim, Matthew). Even participants who did not have problems with the system's noise believed it was because it was located in utility rooms, away from bedrooms and common areas (Dorothy, Laurence).

Regarding the discontinuity of the noise, Molly and the CH3 householders (Simon, Susan) explained that the noise was particularly annoying for them because it was constantly stopping and resuming (in half-hour cycles, according to Molly). This pattern made it difficult to get used to the noise. This likely happened because the operation of the compressor was discontinuous. Contrary to the Hybrid cases, the Compact Hybrid systems were equipped with single-speed heat pumps that could not modulate. In periods of low demand or during defrosting cycles, the compressor has to start and stop frequently.

It's annoying but you just get used to it. But when it tuns off and you get this kind of relaxed feeling of: "Oh, it stopped". And then it starts again. And that makes it even more acutely annoying having the noise.

Simon – 2nd interview

External factors like the outdoor temperatures and the main heating mode chosen also affected the system's noise. Simon noticed that in winter because the boiler was running more often, the system was quieter. Matthew and Laurence noticed that the outdoor temperatures affected the noise, but it is unclear if they thought it made it more noticeable or less. Two of the participants explained that the noise was not only transmitted through the air but also through the vibration of the pipes and the walls (Clare, Laurence).

Noise expectations

A wide range of issues can contribute to a noise being tolerable or disruptive. Participants mentioned two different factors: the background noise and the noise expectations in domestic practices. First, several participants explained that the noise was noticeable because it differed from other noises at home (Nicole, Nelson, Simon). Simon emphasised that they were not used to any background noise, as they live in a quiet area and have no air conditioning units (which he believes is not the case in Italy, where the hybrid unit is manufactured). This is consistent with the findings of the previous subsection (Case H1) and some of the literature on the topic (Torjussen *et al.*, 2023). However, the opposite was also true, Dorothy explained that the kids were constantly active and there was more noise in the house, which masked the noise of the heating system.

Second, as explained before, comfort practices aim to provide adequate indoor conditions for other daily activities. In some cases, the noise made it impossible to carry out those activities as expected. The noise was particularly noticeable at night because sleeping is associated with very low noise levels, and six of the participants complained that the system's noise awoke them or their partners (Clare, Jessica, Simon, Matthew, Jim, Molly). Generally, the system's noise was more tolerable during the day (Jim, Molly, Matthew, Clare) without affecting the daily activities of the participants. However, there were a few exceptions. Clare explained that the noise was noticeable for her colleagues when on video calls when working from home if she did not close the room door. Susan complained that, in some cases, it had been impossible to converse in the kitchen, where the compact hybrid was located, because of the noise. The findings suggest that the noise became more or less disruptive depending on the activities at home, as these activities have been associated with different noise expectations.

Adapting to noise

The system's noise was "the hardest thing to get used to" (Nicole). However, participants tried to minimise its effect through different actions. The most noticeable adaptation had to do with changes in the technology. The first four Compact Hybrid systems were originally installed directly on one of the house's walls. In that way, the noise of the system and its vibration travelled through the structure of the building to different areas of the house, making the system's noise very noticeable. The participants complained to the project managers, and all four devices were dismounted and re-installed on an antivibration plate, which minimised some of the problems (Nicole, Nelson). However, these pieces did not completely eradicate the problem. Even after those changes, some participants were unsatisfied with the noise (Susan, Simon, Clare). While they found the noise intolerable, all the engineers sent to solve the problem left without finding any issue with the system. Likely, the normal operation of the system was simply noisier than the participants wanted to tolerate.

Getting used to the noise not only involved changes in technology. Other changes were mentioned. The first one was habituation. Without any noise reduction, as the project progressed, some participants explained that they got used to the noise and did not notice it (Nelson) or became more tolerant of it (Simon). The second one was through the adoption of new know-how. For example, several participants mentioned paying more attention to ensuring that the doors of the rooms where the heating system was were closed (Clare, Nicole).

However, actions to change the heating operation were also implemented. In three households (CH3, CH4, CH7), the participants requested the control manufacturer to force the heat pump to switch off at night. In CH3, the suppression was in place for all the winter, which affected the system's operation and its efficiency as the heat pump could not pre-heat during this period. Additionally, Clare, Simon Susan, Jim and Jessica described other changes to force the system to run on boiler mode. Clare reduced the scheduled temperature setpoint (to 10-12ºC) and manually increased it when needed, which activated the boiler and not the heat pump, as explained in section 5.1.2. Simon and Susan described similar actions, but in their case, the low-temperature setpoint was only chosen during certain times of the day (e.g., when not at home or at night), meaning the heat pump still ran more often than they wanted, and the noise was louder than they expected. Additionally, Susan explained that in some cases, she opened the kitchen hot water tap when the system was too noisy because the hot water demand forced the boiler to engage and stopped the heat pump, which reduced the noise. Jim and Jessica explained that they switched off the system at night to reduce the noise. In their case, switching off the system had consequences for the temperature in the morning as the system did not have time to preheat, and it was colder (Jessica).

The actions taken evidence the trade-offs experienced in the context of heating practices. Sometimes, despite being aware of the negative impact of some of these actions (e.g., higher costs or less comfort), participants preferred them to the noise of the system. That was Jessica’s case, as she explained how she is less comfortable when operating the system manually but her husband cannot tolerate the noise. Some of these actions (e.g., control of the heating times) seem to be retained from heating practices with conventional heating technologies. However, others can only be attributed to an active reflection and decision of the participant to introduce variations in the performance of the practice.

5.3. Comfort in context

The previous sections have explored how the householders in the selected case studies have experienced comfort and how heating practices have evolved after adopting the technologies. The findings suggest that householders are not only concerned about minimum indoor air temperatures and also that their performances of heating practices sometimes do not correspond with the "expected" heating practices, which involve delegating control of the heating system activity to the algorithm. However, the findings rely on a small cohort of participants (3 households equipped with hybrid heat pumps and 7 with compact hybrid heat pumps). Undoubtedly, the small size of this cohort helped to explore the topic in great detail, but it does not allow us to generalise the results or assess how common the situations described are. For that reason, as explained in Chapter 3, the findings were triangulated with the analysis of the information recorded in the Customer Relationship Management (CRM) database. The CRM dataset contains all the communications between the customer service team and the householders who had installed a hybrid heat pump (not compact hybrid) with smart heating controls as part of a specific project (n=130). Therefore, these communications include some of the conflicts and problems that householders encountered when adopting the new heating technologies for 3 years (06/2020 to 04/2023). While this dataset presents some limitations, particularly regarding potential biases in the householders who contact the customer service team, the lack of compact hybrid installations, and the type of issues reported (discussed in section 3.3), the analysis is still relevant for the present research as a way to triangulate the findings described in the previous sections.

Comfort-related issues were mentioned a few times to the customer service team but were not common. Only 23 householders out of the 130 participating households (18%) mentioned the topic and 37 tickets out of 962 included a reference to comfort (4%). Each ticket usually contains all the interactions with one householder during a short period of time. The ticket is closed once the issue has been resolved or after not hearing back from the householder for a while. A new ticket is opened if the householder contacts the customer service team again later. In this case, for each householder who communicated with the customer service team mentioning comfort-related issues, an average of 1.6 tickets were opened to address these issues. That suggests that while the resolution of the householders' communication was not immediate, and the issues had to be addressed more than once, the problems were not recurrent. Only one out of the 23 households reporting comfort issues requested to have the system removed and had the old heating system put back in place (4% of the households who complained about comfort issues, 0.8% of all the households), although the householders in this case also faced other problems. That shows that householders can usually solve or adapt to the issues described in the tickets. As found in the case studies, while some changes in indoor conditions are noticeable, they can be easily and quickly adopted into heating practices. Therefore, it is likely that these changes did not trigger any contact with the customer service team. The topics discussed in the tickets analysed are summarised in Figure 5.3, and the next sections analyse them in detail.

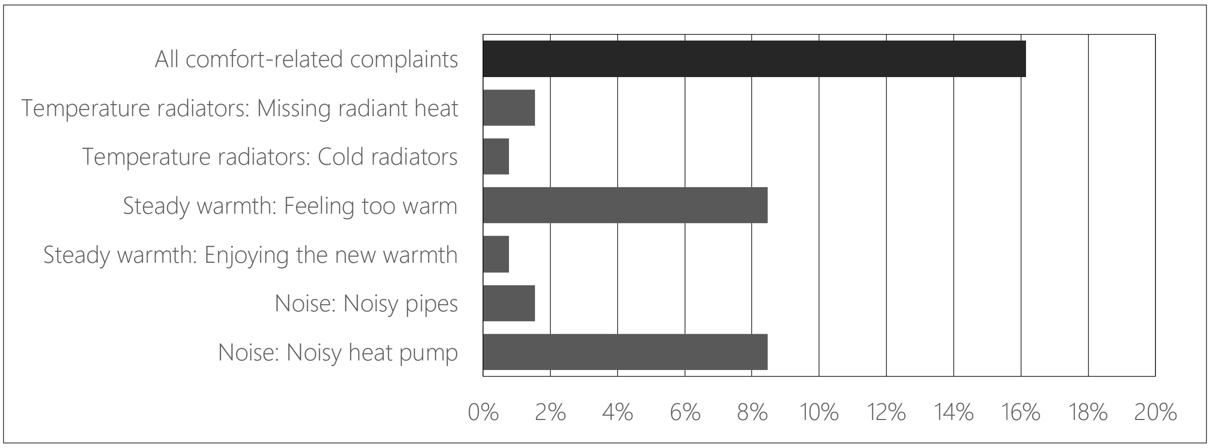

Figure 5.2. Main comfort-related complaints to the customer service team as recorded in the CRM database per number of households in the sample (n=130).

The findings are grouped into four main topics following the same structure as the previous sections. First, the issues related to the temperature of the radiators are discussed. Second, complaints about the steady warmth are presented. Third, the problems related to noise are analysed. Finally, the section explores additional changes in heating practices.

5.3.1. The temperature of the radiators

The change in the temperature of the radiators and their radiant heat was mentioned by three householders (3% of all the households in the sample[32]). In one case, the householder complained about the heat pump not providing enough heat to make the radiators hot, which did not happen when the system was operating in boiler mode, and it is consistent with some of the findings of the case study data. Also reinforcing some of the findings in the previously analysed interviews, another participant complained that his wife missed the radiant heat from the radiators after installing the new technologies. In this case, the participant requested the system to be removed, but because of the existence of other problems (mainly technical failures), it is unclear what role the changes in radiant heat played. The findings suggest that missing the temperature of the hot radiators is not common and that the issue is less prevalent than in the case study data. However, it is important to note that these changes might be underreported in the CRM dataset because they might not disrupt most activities at home or because householders might not require help to achieve the expected indoor conditions with the new system (e.g., by using a secondary heating source).

5.3.2. Steady warmth

As shown in Figure 5.2, changes in the times and characteristics of the warmth provided by the heating system were one of the most common comfort issues discussed. However, in contrast to the findings of section 5.1, most of the tickets analysed involved complaints about feeling too warm at home. This issue was often experienced negatively as it conflicted with the existing expectations of indoor temperatures. Eleven participants (8%) contacted the customer service team (CST) to complain about the excessive temperature in their house and

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[32] When not specifically mentioned, all the percentages presented in this section describe the number of participants who reported a certain issue in relation to the total number of participants reporting to the customer service team (n=130)

the disruption it caused and only one (1%) reported being satisfied with having the house constantly warm as he found it more "pleasant". However, positive experiences are likely underreported in the CRM dataset because the CST is often only contacted when conflicts arise. While a few householders reported feeling too warm during the day, most of them (10 householders, 8% of all the households) were concerned about the night temperatures. The indoor conditions in the house, and particularly in the bedrooms, made it difficult for some of them to sleep, which, as explained before, suggests that a cold bedroom temperature is an important part of sleeping practices. The data is consistent with the findings of the case studies (section 5.1.2) that explained how heating practices with the new technologies resulted in higher temperatures outside warmth-requested periods, which were often experienced as unpleasant when they conflicted with existing expectations. It is important to clarify that in a few cases, they complained about excessive indoor temperatures not because it was uncomfortable but because they understood it as wasteful, which will be explored in the next Chapter.

In none of the cases reported, was the new heating system removed, which suggests that the heating practices were adapted in some way to deal with the problem. For example, one of the householders said, "I guess I have to get used to the house being heated all day", which suggests an awareness of the required changes and the need to develop new expectations for the indoor conditions. However, most of the householders tried to change these indoor conditions and overcame the problem through a reduction in the temperature setpoint in the morning (45% of the householders who reported excessive warmth), delays in the IN period in the morning (18% of the householders reporting excessive warmth) and/or lowering the TRVs settings (9% of the householders reporting excessive warmth). These strategies were most often suggested by the CST, which points out their critical role in balancing the requirements of the householders and the system and developing heating practices more aligned with the "expected" operation of the heating controls. However, it was not always possible to do that. In two cases, the householders decided to open the windows to cool the building down when they felt too warm, forcing the system to use more energy and work harder. In two cases, the householders requested to suppress the night operation of the heating system, not only because the warmth provided disrupted their activities but also as a way to reduce the noise of the system. Later on, in one of these cases, the householders requested that the night operation be resumed because they found that without pre-heating, the house was too cold in the morning, which shows the existing trade-offs between competing expectations.

In a small number of cases, the CRM dataset also included other conversations about other issues that were not related to the warmth outside warmth-requested periods. For example, one of the householders discussed the differences in the warmth provided by the heat pump and the boiler and explained: "Even my wife complains about the 'dry' hot heat when the boiler occasionally kicks in over winter. A heat pump is definitely the better way of heating". The quote is consistent with the findings of the case studies as the experience might be linked to changes such as the temperature oscillations, the heat stored in the building or the radiant heat from the radiators. It suggests that even when achieving the same temperature setpoint, the heat provided by the heat pump and the boiler is different, which could conflict with the hybrid system's alternating use of these two technologies.

5.3.3. Noise

As was found in the data analysis from the interviews, the noise of the new heating system was one of the most noticeable changes compared to the previous heating system. It is important to note that, in this case, the data was collected solely from households equipped with Hybrid heat pumps, not Compact Hybrid heat pumps. As explained in previous sections, one of the main differences between Hybrid and Compact Hybrid heat pumps is the location of the heat pump compressor. In hybrid heat pumps, it is located outdoors and in compact hybrids, it is located indoors. This difference could have important implications for the noise levels inside the building. Therefore, it is important to clarify that the findings of the CRM dataset might more likely be compared to those of hybrid heat pump cases, discussed in section 5.2.1. The householders distinguished between two types of noise: the noise of the pipes contracting or expanding as the temperature of the water in them changed (2% of the householders) and the noise of the heat pump (probably the fan or the compressor) (8% of the householders). Regarding the noise of the pipes, one of the householders explained that it was emphasised by the discontinuous operation of the heating system, which is consistent with the findings of the case studies presented in section 5.2.

The noise of the heat pump was described as "louder than a hairdryer", "like a helicopter", or "like living next to an industrial factory AC unit" by two householders. In the tickets analysed, two main issues were particularly noticed: the timing of the noise and the effect of the noise on neighbours. Four householders complaining about noise explained that it was particularly noticeable and uncomfortable at night (36% of the householders complaining about noise), affecting their sleep. The findings are consistent with the case studies and suggest that sleeping practices might involve not only cold bedrooms but also expectations about noise levels. Four of the householders mentioned their neighbours when discussing noise. They were either concerned that the noise could disturb them, or they reported that the neighbours had complained about the noise to them or, in one extreme case, to the local council. The effect of the noise on neighbour properties was also found in the case study data and the literature (see DESNZ, 2023b, for example). The findings suggest that, as a few of the householders mentioned, the expectations of noise levels are also affected by their ideas of the tolerance of the neighbours to accept the noise.

In some cases, there is evidence that the conflicts between the expected noise levels and the experienced ones were resolved. In one case, that was achieved through a reduction in the temperature setpoint in the morning (which reduced the need to preheat). In three cases, householders requested a change in the controls to force the heating system not to operate at night. Finally, in three cases, the outdoor heat pump unit had to be reallocated. Only in one case, the installation did not comply with the regulation regarding the minimum distances and position of the unit. However, as Torjussen (2020) explained, despite complying with the regulations, the noise of the heat pump can have significant adverse effects depending on the background sound level and the tonality of the noise.

5.3.4. Other elements of the practice

The previous sections have analysed how the changes in indoor conditions and heating practices for thermal comfort identified in the case studies are reported to the CST and recorded in the CRM database. However, the analysis of the CRM dataset has identified a few existing elements of the heating practices that, while not discussed with the case study participants, might also affect comfort and might evidence a misalignment between the "expected" practices and the performances of the practices in real settings. The analysis has highlighted three issues: conflicts between practices, the role of the thermostat placement and the position of the TRVs.

As explained in section 5.1.2, heating practices with conventional heating systems often involve controlling the times of the heating operation. That allows heating only when the householders are at home. However, the analysis of the CRM dataset evidenced that this is also used to balance the needs of different practices. Conflicts can occur as this control is delegated to the smart heating controls without mechanisms for the householder to communicate these competing needs. For example, three householders mentioned cases in which they could not stop the system from heating while airing the house, as they used to do with the old technologies. This also happened in cases in which the householders used secondary heating systems, like log burners. It is complex to measure the prevalence of these problems as they were often raised as part of other discussions and were not the focus of the communication. However, the findings are well aligned with some of the issues discussed when analysing seasonal conflicts (Section 5.1.3): when operating the heating controls before installing the new technologies, the householders could consider a wide range of factors, and those are missed by the smart heating controls.

The analysis of the CRM dataset helped to identify other situations that could affect the efficiency of the system that had to do with the location of the thermostat and the position of the TRVs. While these situations were often not the focus of the conversation with the CST, they were mentioned in a few cases. Five of the 130 householders (4%) explained that the thermostat was located near the log burner (2 cases), in a warm room (1 case), receiving direct sunlight (1 case) or in the line of sight of the door, which was often open (1 case).

Additionally, in two cases, the householders mentioned moving the thermostat around the house, which undoubtedly affects its readings and the process of learning the thermal response of the building by the controls. While it is unclear why these situations happened, whether they were retained from previous heating practices or adopted with the new technology, they are critical for the operation of the new technology. Further research might be needed to understand better these issues and address them.

5.4. Discussion

This chapter has explored how householders experience indoor conditions with the new technologies and how heating practices for comfort evolved after adopting smart hybrid heat pumps. The aim was not to analyse the physical changes in indoor conditions (as in the previous Chapter) but to analyse how some of these changes are experienced and created as part of heating practices. In this case, comfort is studied using a socio-cultural approach which puts the focus on its shared, routinary and dynamic nature. While the approach taken clearly shapes the outcomes of the research, it was believed that it would provide a unique understanding of some of the challenges that the adoption of the technology provides, which have been frequently addressed by control manufacturers from an individualistic and/or purely physiological point of view.

The results presented come from the analysis of the data obtained from two sources: 10 case studies of households equipped with the technologies and the CRM data from a large project with 130 households where the technology was installed. Additionally, the findings of these two data sources have been discussed in relation to the results of the previous chapter. This mixed-methods and multi-sample approach aimed at improving the internal and external validity of the results. It is important to note that the analysis has made evident some limitations of this approach. While people can talk about their practices (Hitchings, 2012), describing their experience of comfort and identifying the physical changes (if any) that contributed to it becomes more complicated. For example, issues like an improvement in the steadiness of warmth could result from changes in many variables (e.g., radiant heat, temperature oscillation, etc.), which are not always easy to identify. Also, participants might not even be aware of the changes as they are taken for granted when installing the technology and immediately contribute to new notions of comfort.

In this section, the main findings are discussed with some references to the literature. The discussion is divided into two parts. First, the experience of indoor conditions is compared with the findings of other projects where similar technologies were tested. Second, the trajectory of the heating practices after the adoption of the technology is discussed in relation to the literature on social practice theories.

5.4.1. Experiencing indoor conditions

The findings of this chapter have shown that the number of comfort-related conflicts is low after the adoption of the technology, as only 18% of the householders contacted the customer service team with comfort-related comments. While the number of customer interactions with the CST has not been studied before, the results are in line with other articles on the topic. For example, Caird, Roy and Potter (2012) also reported overall satisfaction with the comfort and warmth provided by heat pumps (not heat pumps with smart heating controls), with only 11% of the participants dissatisfied.

However, the detailed analysis of the case studies has evidenced that this type of approach masks a more complex picture. In line with previous research on heat pumps or heat pumps with smart heating controls (see Chapter 2), the analysis has identified three different changes in indoor conditions noticed by householders. Those are the lower heat output of the radiators (also reported by Devine-Wright et al. (2014) and Judson et al. (2015), the more constant warmth (also reported by Caird et al. (2012), Lowe et al. (2017b) and Hanmer (2020), among others), and the increased noise (also reported by Torjussen (2020) and Desnz (2023b), among others). However, while they have already been reported before, some have been studied with very niche groups of participants, and the research reported here suggests they might apply to other groups (for example, Devine-Wright et al.'s (2014) discussion of the relevance of cosiness in home-making and the difficulties of providing it with heat pumps relies only on interviews with old adults) and often they are not studied in detail (e.g., the constant warmth is reported as something positive in studies such as Caird et al. (2012) but the researchers do not try to understand its relationship with heating practices). Additionally, the research has also shown that some participants noticed changes in the indoor temperature during shoulder seasons, which have not previously been reported.

However, the reaction to some of these changes is not always negative. In some cases, the new indoor conditions were found to be very appealing to householders, and participants particularly valued the constant warmth during the day, when working from home, or the lack of peaks and drops in temperature. On the other hand, the noise and the temperature at night were often seen as problematic. The issue of noise is particularly relevant if heat pumps have to be installed in urban areas, where the background sound might mask the noise of the heating system, but the concentration of units is going to be higher.

The results suggest that the householders not only notice some differences in indoor conditions between the previous heating system and the new hybrid heat pump. Some of them were able to identify differences depending on the heating mode of the hybrid heat pump (boiler mode or heat pump mode). These differences were particularly relevant for noise and less for the temperature of the radiators or the steadiness of the warmth provided. That shows that changes in the heating patterns (mode) to optimise efficiency or provide grid services might be noticed, contrary to what NEDO (2017) found. Therefore, implementing technology visions based on the idea of a calm technology design (Weiser & Brown, 1996) (technology that remains invisible most of the time) might not be feasible due to the central role of heating systems in domestic settings and the difficulties of anticipating all the householders' needs.

The findings contradict some of the assumptions embedded in smart heating controls. The tested technology optimises the operation of the heating system, considering the temperature setpoints requested by the householders (which are taken as minimum temperatures). As they are the only input from householders, it is assumed that people can communicate all their needs through that. However, the analysis has evidenced that this is more complex, and people not only have preferences for the minimum air temperatures: Even when these are provided, householders can notice other differences in indoor conditions and might not be achieving the expected conditions, which contradicts conventional models of steady-state thermal comfort (for example, Fanger, 1972). The findings also challenge one of the central assumptions of hybrid technologies: that householders do not have preferences for one or the other heating mode as long as the required indoor air conditions are provided. The literature on smart home technology and low-carbon heating has extensively discussed the very narrow understandings of the home dominant in the industry and the failure to account for the diversity of users and routines (e.g., Strengers *et al.*, 2020). The existing research is consistent with the findings reported here.

The technology tested automates the operation of the heating system and "ideally" requires a passive user who does not override the scheduled operation. The householders *delegate* (Latour, 1992) the task of setting the heating operation to the controls. Implicit in that is the idea that the technology is more efficient/better at carrying out this task. The research has shown that in a small number of situations, this is not the case. The observed detailed knowledge that householders have of how to manage heat flows across the house could not be replicated or improved by the controls during shoulder season with very different solar gains across the house. Those situations are unexpected, and the research points out the complexity of automating the control of heat flows during these events. In those extreme cases, householders are probably better placed to deal with the situation, but the limited possibilities available for them to control the heating operation forces them to act in ways that might further affect the efficiency of the system (e.g., opening windows while heating).

5.4.2. The trajectories of the practice

As explained in the previous section, the research presented in this chapter has evidenced that householders experience indoor conditions differently when heating with the new technologies than with conventional heating technologies (or depending on whether the system is on heat pump mode or boiler mode). However, householders are not passive recipients of these conditions. By performing heating practices (monitoring and managing the heat flows (Royston, 2014)), they are active agents in their creation. The findings suggest that, in some cases, the adoption of hybrid heat pumps with smart heating controls was accompanied by changes in the elements that constitute these practices. While the specific trajectories of these changes remain under-researched, the important role of technologies in shaping heating practices has been extensively demonstrated before (see Madsen, 2018, for example). The research reported here has shown how, in some cases, the adoption of the technology triggered the adoption of new elements: new meanings (e.g., accepting more constant temperatures) and new know-how (e.g., letting the controls do their thing and not intervene). However, in others, despite the installation of novel technologies, certain elements of the practice were retained: old notions of comfort (e.g., cold temperatures at night) or know-how (e.g., some still control the heat output manually). The trajectories observed did not always resemble the "expected" heating practices (that maximise the efficiency of the heat pump by letting the algorithm choose the best heating strategy in advance), which suggests, as Aune noted (2002), that the consequences of the technology should not be taken for granted.

Two main trajectories were identified. One in which the new indoor conditions become part of the new notions of comfort and the "expected" know-how that contributed to them was incorporated into the practice without conflicts. Another in which there was more resistance to the changes, the old notions of comfort were retained, and actions were performed to achieve them with the new technologies. While the research did not aim to identify causal links, and the complexity of the practices analysed makes it difficult to identify why those differences existed, the findings suggest some potential explanations. Among them, the existence of strong meanings and images associated with some of the old indoor conditions but not with others seem to play an important role. Additionally, existing know-how retained from previous heating practices might also be relevant. Two examples of these trajectories will be presented in the next subsections.

Constant warmth

Among the changes in indoor conditions easily adopted, the constant warmth during periods when heat was requested, so the uniform temperature and lack of peaks and drops, was acknowledged by most participants as one of the benefits of the technology. The lack of previous meanings associated with the oscillating temperatures and, particularly, the fact that the new indoor conditions were seen as an improvement to a failure of the previous technology might explain the rapid acceptance of the change, which is consistent with Judson et al. (2015). The trajectory in the practices can be understood, in this case, as part of the process of indoor climate convergence and homogenisation, also described by Shove et al. (2008) and Strengers et al. (2020). Adopting increasingly uniform and stable temperatures in buildings frequented by the participants (e.g., offices, commercial buildings, etc.) might help develop notions of comfort associated with these constant temperatures that are later transported to domestic settings. The findings are also consistent with some of the literature addressing the rebound effect of heat pumps (see Winther & Wilhite, 2015; Oikonomou, 2022), which has seen the householder's acceptance of the constant warmth provided as evidence of comfort taking.

Night temperature

On the other side of the spectrum, a few changes in indoor conditions were experienced as disruptive and conflicted with the existing expectations of the indoor environment. That was the case for changes in warmth at night. The constant temperature at night conflicted with the householders' expectations for an adequate sleep temperature. In this case, the performance of heating practices with the new technologies failed to provide the required indoor conditions for sleeping, which shows the existing interconnections between practices. There are multiple reasons that could explain the difficulties in adapting to these conditions. This research, which takes a social practice approach to thermal comfort, suggests that this is rooted in the existence of strong meanings and know-how. People, particularly in the UK, expect bedrooms at night to be colder than other parts of the house (Bruce-Konuah, Jones & Fuertes, 2019). Cold environments in bedrooms have historically been seen as healthier, and not heating these spaces was probably common practice before the adoption of central heating systems and the transformation of bedrooms from sleeping only into bed-sitting rooms (Kuijer & Watson, 2017). Some of these notions of comfort and know-how to deal with low bedroom temperatures have probably been retained until nowadays. For example, sleeping with thick duvets and bedclothes is still common in the UK in winter (see Tweed *et al.*, 2014, for example).

However, the expectations for cold bedrooms can also be explained from a physiological point of view, trying to understand the influence of thermal environments on sleep quality. In this case, two variables are particularly relevant: the temperature in the bedrooms and the temperature profile during the night (how the temperature evolved overnight). Regarding the first, CIBSE Guide A (Butcher, 2006) suggests that sleep might be impaired if temperatures are above 24ºC in bedrooms in summer, which is well above the temperatures recorded in the case studies. However, there is a lack of studies on differences in sleep quality with moderate temperature increases similar to those achieved with the continuous operation of the heat pump overnight and in winter. Nicol (2019), citing Humphreys (1979), showed that while the quality of sleep decreases with temperature increases (also found by Xiong et al. (2020)), the sleep quality is more or less maintained between 15ºC and 21ºC. The second relevant parameter, the temperature profile at night, has also been understudied and mainly measured in summer conditions. Lan et al. (2017) explained that the circadian cycle of sleep is linked to the body temperature and that a rapid decline in body temperature might favour sleep initiation. However, they report that temperature oscillations within the thermoneutral zone (20ºC ±3-4ºC, according to Lan et al. (2016)) did not affect sleep quality, but the results are inconclusive as other studies have found that it might have a moderate effect on the REM cycle (Dewasmes *et al.*, 1996). Lan et al. (2016) found that a decrease in air temperature in the evening and a gradual increase in the morning (Fall-rise change) could prepare the body for waking up and improve the next day's work performance (but not the sleep quality). More research is needed to understand the results found in this research from a physiological point of view.

However, while it is obvious that there are physiological limits to the temperature that people can stand, it is also true that the range at which people have reported being comfortable at night is wide. The specific expectations for night temperatures are likely a matter of culture and convention (Chappells & Shove, 2005), especially given the importance of elements like bedclothes, adaptive actions and posture in bed (Nicol, 2019). A similar situation might explain the noise problems previously described; while the noise of the system reported might have a physiological effect on people living close to the system, it is also true that the noise perception is influenced by non-acoustic factors (DESNZ, 2023b) and social practices might explain them.

5.4.3. Changes in the indoor conditions and the heating operation

The findings confirm some of the initial evidence presented in Chapter 4. The results of the analysis presented in the previous chapter provided robust evidence of the reduction in the flow temperatures and the heat output with the new heating system. Most of the householders interviewed confirmed these changes. However, the previous chapter could not provide conclusive evidence for the reduction in the temperature oscillation during warmth-requested periods, the reduction in the temperature drop at night and the increase in the temperature homogeneity across rooms. The findings of the analysis of the social data suggest that there are changes in the first two parameters (temperature oscillation and temperature drop) and that both are reduced after the adoption of the new heating system. The evidence for the latter (the temperature homogeneity across rooms) is still insufficient, and the findings suggest that the change might vary from case to case and might depend on other factors.

5.5. In conclusion

This Chapter fills some of the evidence gaps found in Chapter 4. While the analysis of some of the parameters through the technical data did not provide clear results, the study of the social data presented here confirms the initial evidence presented in the previous chapter. The findings of this chapter have also revealed the complexity of comfort and showed how the expectations for indoor conditions can conflict with the new indoor conditions provided by the hybrid heat pump and the smart heating controls. However, the analysis showed how not all these issues can be explained as comfort conflicts. Despite being in comfort, some householders were concerned that the new heating patterns and indoor conditions were wasteful and might contribute to higher energy use or environmental impact. The next Chapter 6 will explore that by analysing the impact of the new technologies on the understandings of waste.

6. Exploring waste-related heating practices

A central theme arising from the case study data is that adopting heat pumps with smart heating controls can conflict with understandings of waste and existing ideas of the "right" operation of the heating system to avoid waste. Despite the lack of research on the topic, waste and related know-how are central to heating practices (Mallaband & Lipson, 2020). These practices involve ideas of what is and is not wasteful and know-how to reduce waste (Royston, 2014). The findings of this thesis suggest that people monitor waste by checking when the heating system is running, and heating practices involve specific expectations for it. The new heating technologies can lower the cost for the householder (in environmental and/or economic terms) if the control of the heating operation is delegated to the smart heating controls. The heating algorithm can then choose heating patterns that are different from those of combi boilers (e.g., longer heating duration at lower flow temperatures). However, these new heating running patterns sometimes conflict with the existing heating practices and are therefore experienced as wasteful.

Understanding how the new heating system can challenge the existing heating practices, including the know-how to minimise waste and the ideas of the "right" operation patterns, can be critical for the success of the technology. However, this is a topic that remains poorly understood. This chapter uses the data collected in the case studies and the Customer Relationship Management (CRM) software to bridge this gap. More specifically, this chapter aims to explore the following research questions:

- How is waste minimised in the context of heating practices?

- How do these practices evolve after adopting the novel heating technologies?

In this analysis, waste refers to the resources used unnecessarily or carelessly. The word waste is being used instead of costs or impact because the focus is not on measuring the resources used, calculating the efficiency of the different heating systems, or discussing whether the expected savings are achieved or not but on the householders' interpretation of the usage of resources as part of heating practices. The meaning of waste is not universally defined. Being wasteful can entail expectations about the heating operation, the indoor conditions, the energy costs (economic and/or environmental), etc. and has associated know-how. When discussing waste, the participants sometimes talk about economic resources, other times about environmental resources and in some cases about both.

However, the thematic analysis of the social data showed that a Social Practice Theory (SPT) approach alone could not explain in detail some of the changes in waste-related aspects of heating practices. In particular, the findings suggest that trust plays a critical role in the evolution of these practices and the know-how for minimising waste. The smart heating controls can lower the running costs of the system if the control of the heating operation is delegated to the algorithm and the heating system operates differently. However, these heating practices require trust that the technology will minimise waste, since the know-how for operating the system and minimising waste is delegated to the controls. Therefore, to explore waste and, supplementary to SPT, this chapter will introduce the concept of expert systems, as developed by Giddens (1990). Giddens explained that expert systems are systems that integrate technical knowledge and professional expertise and that organise the material and social environments in modern societies, allowing people to carry out everyday actions without knowledge of the different elements involved in them. Expert systems require trust. Heating systems with algorithmic controls can be usefully understood as an expert system to explore the role that waste plays in heating practices.

The chapter is organised as follows. First, Giddens' work on trust and expert systems is presented. In the second section, the meanings of waste in heating with conventional technologies are discussed along with the required changes to maximise the efficiency of the new heating technologies. The third section briefly analyses the importance of waste in the decision to adopt the technology. In the fourth and fifth sections, the observed heating practices regarding waste are described starting with those that are well aligned with the "expected" practices and then the ones that conflict with them. The sixth section discusses the role of trust in these practices. In the seventh one, the findings are triangulated with the data obtained from the CRM software. Finally, the findings of the previous sections are combined and discussed in relation to the literature.

6.1. The role of trust in expert systems

In his book The Consequences of Modernity, Giddens (1990) explains how the transition from the traditional to the modern society is explained by a disconnect between social activity and its context. Modern institutions broke out from localised contexts and local traditions/habits and restructured social relations across time and space. Therefore, modernity is characterised by relations between absent agents that not only are not present at the exact moment and place, but that often do not even know each other. According to Giddens (1990) critical in this process has been the establishment of expert systems. The modern society relies on these expert systems to carry out their day-to-day activities. For example, there is no need to understand how a gas grid works or to know the grid operators in person to use gas at home: an expert system provides guarantees of expectations across time and space. A practice like heating can be dangerous: gas is highly inflammable, and its explosions are destructive. People rely on the boiler/network manufacturers/operators' expertise to guarantee that this risk is minimised.

Expert systems depend upon trust (Giddens, 1990). People trust the heating system and the constellation of institutions that make heating with a gas boiler possible (e.g., boiler manufacturers or gas providers) while engaged in heating practices. Trust is indispensable because the activities or processes are not transparent to the participant. According to Giddens (1990), trust in these cases is not placed in the individuals but in abstract capacities. Trust is confidence in the reliability of a system, given a set of probable outcomes, in conditions in which one has no full information (Giddens, 1990). This confidence involves faith in the correctness of the principles that underpin the system. Breakdowns and failures, as well as updates in the knowledge provided to the public, can influence trust relationships. Tests, standards, and public critique (which determine the production of technical knowledge) play a critical role in building trust in expert systems.

Trust in expert systems is established in contexts without the copresence of the agents involved. It requires what Giddens (1990) described as faceless commitments. However, he explains how trust relationships are also built during circumstances of copresence. Returning to the example of the gas heating system, the annual boiler revision by an engineer is a situation of copresence in which trust in the expert system can also be built. In contrast to faceless commitments, Giddens (1990) calls these processes facework commitments and explains how they can contribute to support or undermine trust in expert systems. The situations of copresence are called access points. Access points are places of vulnerability for abstract systems: trust in expert systems can be critically influenced (positively or negatively) by experiences at access points. For example, engineers showing insecurity or panic when repairing gas boilers might contribute to disengagement from the system.

Heating requires an ongoing relationship between householders and external institutions that operate at a distance from the home (e.g., gas providers, network operators or boiler manufacturers) to work. The relationship between those external institutions or experts is based on trust and requires constant work and affirmation. Trust in heating systems can be developed in various specific moments, such as the selling point, during the installation or maintenance. These stages offer opportunities to establish, maintain, or lose trust. Adopting heat pumps with smart heating controls adds complexity to the system and enlarges the distance between the user and the expert systems. The algorithmic control is not only driven by the householders' input, as is common with conventional heating controls. Its output results from balancing different parameters in a process often opaque for householders, who might find it hard to know whose interests are being forwarded. Therefore, trust is essential for the smart grid to succeed (Paetz, Dütschke & Fichtner, 2012; Verkade & Höffken, 2018). In the next sections, the importance of trust in the heating system as an expert system will be analysed.

6.2. Old know-how for minimising waste and new heating practices

As explained at the beginning of this chapter, waste plays an important role in heating practices, and this research has shown that waste is often associated with certain heating running patterns and indoor conditions. However, there is not a unique and static idea of waste. What it means to be wasteful and the associated know-how to reduce it has varied over time. To minimise the running costs of the system, the smart heating controls introduce new heating patterns that challenge the existing know-how to minimise waste. Therefore, before exploring waste in heating practices with the new technologies, it is important to analyse its role in current heating practices with boilers. This should help to identify the "required" changes to achieve the expected performance of the new technologies.

6.2.1. Minimising waste when heating with conventional boilers

As Royston (2014) explained, minimising wastage when heating involves monitoring and managing heat to reduce "heating out of place" and "heating out of time". However, across locations and over time the meanings of "heating out of place" and "heating out of time" have changed (see Wilhite *et al.*, 1996, for example). For example, expectations of the spaces or the times that needed to be heated were not the same in heating practices with coal-fired appliances and with central gas boilers. Heating all the rooms of a house was probably considered wasteful when using coal and has become a common practice nowadays (Shipworth, 2011; Kuijer & Watson, 2017). Changes in these ideas accompanied and were accompanied by the adoption of new technologies. For example, the capacity of conventional boilers to provide a large amount of heat and distribute it across the house in a short period of time with no physical effort by the householders (compared to previous heating systems such as coal furnaces) reduced the time needed to heat the house and allowed to heat multiple rooms at the same time. Thanks to these and other changes, the way the heating system was operated changed, leading to what Kuijer and Watson (2017), citing a report by Parker Morris (1962), defined as short-period heating, in contrast to long-period heating typical from before.

Nowadays, heating practices with boilers in the UK usually involve controlling the heating patterns to heat the whole house only during specific times of the day when heat will be directly appreciated and letting the building cool down outside these periods (Lomas *et al.*, 2018), although there are exceptions (e.g., Huebner *et al.*, 2015). For example, when using on-off controls, householders might turn the heating on when they arrive home, and they feel cold and turn it off when their minimum comfort temperature is achieved or when they leave the house or go to sleep. When using conventional thermostats, the heating practices might involve setting heating periods only for those times when the householders plan to be at home, awake and wanting heat, and also ensuring that the temperature setpoint is not too cold but also not too warm. In all these cases, heating outside these specific times of the day, when there is nobody to appreciate the heat (e.g., nobody at home or at night) (Boait, Fan & Stafford, 2011; Caird, Roy & Potter, 2012), or above certain temperature limits (e.g., overheating above the minimum temperature requirements) (Morton, 2016) is considered wasteful in economic or environmental terms. Heating practices involve, among other things, avoiding these heating running patterns. The elements related to waste in heating practices with conventional boilers are summarised in Figure 6.1.

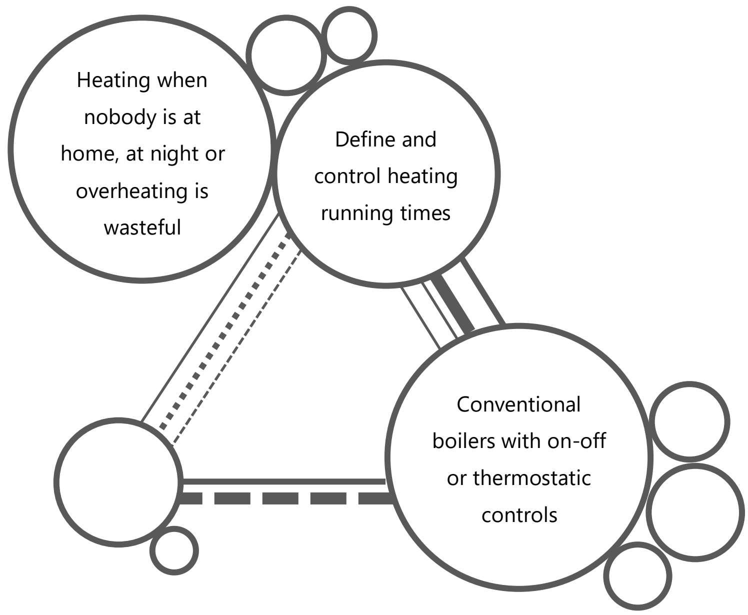

Figure 6.1. Main elements related to waste in heating practices with conventional technologies. Adapted from Kuijer (2014b).

6.2.2. Expected changes in waste-related practices

To minimise the heating costs (in economic and environmental terms) the new technologies require two changes in the heating practices. First, accepting new heating running patterns. Second, delegating some of the tasks involved in minimising waste to the technology. Hereafter, the performances of the practice that incorporate these elements will be called "expected" practices.

Regarding the first, as explained in section 2.2, heat pumps work more efficiently if they run at low heat output during longer periods or even continuously. Additionally, in contrast to gas or oil, the environmental impact of electricity (and the costs when on ToU tariffs) varies depending on the time when it is used. Therefore, the waste of energy in environmental and/or economic terms is not so much determined by the length of the heating operation but varies constantly and is affected by several different variables. The algorithmic heating controls consider these parameters in their optimisation strategy for the heating operation. Heating when nobody is at home, heating at night, pre-heating or heating above the temperature setpoint can be, in certain circumstances, sensible strategies to reduce heating costs. This is because they might allow the heat pump to run at low flow temperatures (which increases its COP) or make better use of cheap electricity outside peak periods. However, these strategies are not common when heating with conventional technologies and sometimes conflict with existing ideas of waste.

The second change involves a redistribution of the roles in managing heat. As previously explained, as part of the heating practices with conventional technologies, householders control the heating patterns of the system. The adoption of conventional thermostats requires some *delegation* (Latour, 1992) of this task to the technology. However, the householder still retains most of the agency. For the new smart technologies to provide demand response and work efficiently, they require an additional step. First, the new controls define how the heating should run, and householders only define when they want to be warm. Second, contrary to the static relationship between waste and heating patterns in heating practices with conventional boilers, the controls establish a dynamic relationship between the two. Rather than choosing a single heating pattern, the algorithm can identify the most suitable strategy to minimise waste (economic and environmental), and the heating running pattern might vary over time depending on several factors. This delegation process requires a passive user who lets the system do its thing and trusts it to operate efficiently.

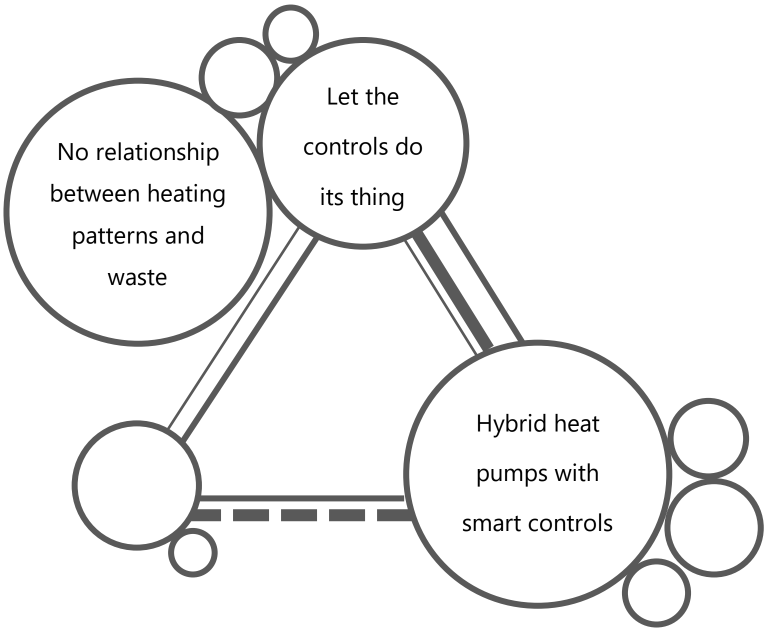

Figure 6.2. Main elements related to waste in heating practices with hybrid heat pumps with smart heating controls.
Adapted from Kuijer (2014b).

6.3. The importance of waste in the decision to adopt the technology

Minimising waste is an essential part of heating practices. The analysis of the interviews with participants made evident that this was also key in the decision to adopt the new technologies. Most of the interviewees stated that one of the main reasons for participating in the project was to reduce their carbon emissions and be pioneers in the energy transition (Nelson, Nicole, Laurence, Simon, Jim, Jessica, Molly, Barry, Richard, Greig). This is consistent with the literature on the topic (see Caird & Roy, 2010, for example) and might come about because participants are "early adopters" of the technology. Some of them also mentioned reducing the heating costs as one of the reasons for the adoption of the technology (Barry, Richard, Greig), however, these participants were all in off-gas grid areas (hybrid trialists) and heating with oil or LPG, which is particularly expensive compared to gas. In contrast, the participants living in gas-grid areas (compact hybrid trialists) were less sure about the change in costs, with some anticipating a decrease (e.g., Jessica), as the documentation they received also mentioned, and others expecting higher costs but improvements in the system's efficiency and environmental impact (e.g., Nelson).

6.3.1. Notes on the 2022 energy crisis

Before presenting the results of the analysis of the interviews, it is important to point out that energy resources during early 2022 became the centre of public debate because of the energy crisis and the subsequent increase in energy prices for domestic consumers (National Energy Action, 2022). That coincided with the monitoring campaign and was still a hot topic during the second round of interviews. This situation might have triggered changes in heating practices and the meanings of waste. While some of these changes might go unnoticed, this topic was openly asked during the interviews. Most participants stated not changing their daily activities because of the energy crisis (Barry, Nelson, Laurence, Dorothy) or only introducing small tweaks like reducing the hot water setpoint (Simon) or shortening their shower times and heating periods, as Jessica explained (despite her partner Jim said that they had not changed anything). Only two participants explained that waste became more relevant due to the energy context. Greig explained that he became more concerned about the operation of the system, particularly the heat pump, and Clare explained that this was one of the reasons why she decided to request the new technologies to be removed from her house at the end of the trial. The impact of the energy crisis on the observed heating practices is low, according to most of the participants. However, it is important to keep in mind that there might be changes not noticed or not discussed by the participants. For example, it may have made them more conscious of waste.

6.4. Heating practices evolving as expected

As explained in section 6.2.2, to minimise costs, the new technologies require changes in different elements of the heating practices regarding waste, particularly around expectations for the operative patterns of the system, and know-how (e.g., delegating the control of the heating times to the controls). Drawing on the data from the case studies, this section presents the cases in which these changes were observed. That does not mean that the practices studied are all the same: the performances observed are the specific reproduction of a practice in time or space, and therefore, they might differ from other performances (Shove, Pantzar & Watson, 2012). However, they all incorporate certain changes that allow the new technologies to operate “as expected”, as described in section 6.2.2. In some cases, the new performances happened immediately after adopting the technology; in others, they were triggered by external factors. Often, the performance still incorporated a small number of elements conflicting with the “expected” practices.

6.4.1. Accepting new heating patterns and developing new understandings of waste

As explained in section 6.2.2, the most efficient heating running patterns of the new technology are often different to those of the boilers that householders are accustomed to. Consequently, the new heating patterns can conflict with existing ideas of how the heating system should operate to minimise waste. However, the analysis of the interviews revealed that in some cases, these new heating patterns were adopted and accepted without opposition (Barry, Richard, Grace, Greig -Interview 1-, Nelson, Nicole, Laurence, Jessica, Dorothy, Daniel). In a few of these cases, the adoption happened without an active acknowledgement of the change. Nicole and Grace, for example, explained that they are not interested in the technology and they simply trust their partners to ensure that the system operates efficiently. They do not monitor heating running patterns and are not concerned about the old or new heating times of the system.

In other cases, despite accepting the new heating operation, householders were aware of the changes, described preferences for certain heating running patterns and kept monitoring the heating operation. In these cases, instead of looking for short heating periods at high flow temperatures, as is typical when using conventional boilers, the householders expected longer heating times at lower temperatures. They described the longer heating periods as the “right” way to heat (Jessica, Barry, Richard, Laurence), explained that maintaining the temperature and "keeping the fabric warm was the right thing to do" (Richard) or expected the heat pump to run most of the time (Nelson, Laurence). However, they still explained that reducing waste involved avoiding certain heating running patterns, but these patterns were not the same as before installing the new technologies. That provides evidence of the relationship between waste and heating system activity but shows how the understanding of whether a heating running pattern is wasteful or not can change. For example, Jessica and Barry described heating gradually instead of boosting as more efficient and not wasteful, and Laurence also used similar terms.

> *There's the old school of thought: What is more efficient, having it completely off and then ramping up quickly when you need the heat later? Or is it better just to take over? And I think that it's probably better to take over.*
>
> *Laurence – 1st interview*

However, the expected heating practices described in section 6.2.2 assume that householders have no expectations for heating system activity and accept the dynamic relationship between waste and the system's operation. In this case, the findings of the interviews suggest that despite accepting the new heating running patterns, participants still described preferences for the operation of the hybrid heat pump. While they still delegated the control of the heating system activity to the smart heating controls, that turned out to be problematic in some of the cases explored through the CRM data, which are presented in section 6.7.

Adopting new practices over time

The participants' adoption of the new know-how and practices for minimising waste occurred at different times throughout the project. Participants in H1, H3, CH1, and CH6, explained that they were aware of the need to change their understandings of waste even before installing the technologies. That was probably because of their previous interest in heat pumps (H1, H3, CH1) and their job at the company developing the controls (CH6). Interestingly, none of them mentioned the project's documentation. However, this previous awareness of the needed changes did not always happen. In H2 and CH2, the interview data revealed that the participants were not aware of that and halfway through the project, they changed their understanding of heating system activity regarding waste, mainly thanks to the intervention of the customer service team at the smart controls manufacturing company.

Relationship between costs and waste

For some Compact Hybrid participants, the new heating patterns were understood as less wasteful despite a slight increase in energy costs after the adoption of the new technologies. This is because even though they believed that the system was more efficient than their old boiler, they were aware that the new fuel used (electricity) was more expensive (Dorothy, Daniel). However, they were willing to pay more because the new heating running patterns were seen as more environmentally efficient (as they used less energy or a lower-impact fuel) (Nelson, Laurence). In this case, the increase in costs was not seen as wasteful. Waste was associated with environmental impact rather than costs. Nelson explained that this cost increase might not be acceptable for everyone because others are not so environmentally driven. At the same time, the understanding of waste might also change as a result of the context, and Greig explained how the existing energy crisis and change in fuel costs made him more concerned about the economic waste than the environmental impact of the system, changing his expectations for the operation of the system halfway through the project (becoming more concerned about the extended operation of the HP and forcing the LPG boiler to work). The findings reveal that understandings of waste are not universally defined or immutable.

Other changes in meanings

The changes in the meanings of waste observed not only had to do with accepting the new operative patterns of the technology. The interviews evidenced that some expectations around non-wasteful indoor conditions were relaxed after adopting the technology. For example, Laurence and Jessica explained that they started using more energy for heating and aimed to be more comfortable. Nelson mentioned how after adopting the system, he started being less strict about switching off the heating when going away for some days.

We were on holiday for a week, and it just stayed as it was. We just didn't bother. Because the economics are not too punishing, then it doesn't matter.

Nelson – 2nd interview

Despite the limited evidence available, those examples suggest that the adoption of the technology might trigger a rebound effect in some cases and are consistent with Winther and Wilhite (2015) or Oikonomou (2022). On the contrary, Richard noticed that after adopting the new system, he and the other people living with him became more cautious when heating and tried not to overheat, probably as an effort to continue reducing their environmental impact and costs in a period of increasing energy prices.

6.4.2. Reinforcing the new understandings of waste through monitoring

Monitoring is a key part of social practices, and multiple authors have explored its role in their reproduction (which does not mean continuity) (Giddens, 1986). As Shove et al. (2012) explained, monitoring provides practitioners feedback on previous performances of the practices and feeds forward into future ones, shaping both the practice-as-performance and the practice-as-entity. Heating practices are not the exception. Householders collect feedback that is used to monitor the "quality" of the performance regarding waste. However, it should be pointed out that important differences were observed among participants regarding their efforts to monitor the new technologies. Some participants were not interested in monitoring the waste generated and simply trusted the system to minimise it (e.g., Nelson). Others monitored the system in detail (e.g., Richard). The three main types of feedback linked to waste were monitored: costs, fuel use, and heating system operation.

Regarding the mechanisms for monitoring costs, participants relied on the information provided by the app (Dorothy) or the bills (Nicole, Nelson, Laurence, Greig). However, some participants were aware of their limitations and explained that comparing costs before and after installing the system might not be useful for understanding waste. For example, Laurence and Greig mentioned that bills are indicative but not definitive in comparing systems because of the energy context and the rapid increase in fuel costs at that time. Barry explained that because they changed homes, he could not compare costs, and he discussed the difficulties of monitoring costs: "Maybe it saved me money. But I have not done any calculations. It's too hard to work out if it saves me money or not".

Participants used feedback on fuel use to assess the system's environmental impact. Molly and Matthew mentioned using the energy bills to monitor their environmental waste: as less gas was used, they assumed that their environmental impact was reduced. In some cases, participants did not monitor fuel use; instead, they relied on the information provided at the beginning of the trial and trusted that they were saving carbon (Daniel, Barry), which is consistent with some of the cases analysed in Winther and Wilhite (2015).

As explained in section 6.2.2, monitoring waste through the heating running patterns is not useful with the new technologies. This is because the relationship between waste and heating patterns is continuously changing (e.g., heating at night might be the cheapest way to run the system in some cases but not in others). However, some of the participants continued to monitor the operation patterns of the system, sometimes in a very detailed way. A few participants relied on the noise of the compressor of the Compact Hybrid internal unit (Laurence, Nelson, Daniel) or the Hybrid heat pump external unit (Richard) to tell if the heat pump was running at times when heating was not expected. However, most of the systems were installed away from areas of the house where noise might be a problem, making it hard to notice the noise. To monitor when their system was operating in boiler mode, Laurence and Barry relied on the noise of the pipes (cracking when the hot water circulated through them). Other feedback mechanisms include the app and the radiator temperatures (Richard, Barry) or self-installed monitoring devices -heat and electricity meters for the heat pump- (Richard). The latter was particularly crucial for Richard to accept the new heating running patterns because he calculated that the strategy chosen by the smart heating controls was the most efficient way to provide the required heat. The findings show the importance of feedback for adopting heating practices more aligned with the efficient operation of the novel technologies and point out the importance of external (and trusted) mechanisms (e.g., Richard's monitoring devices).

6.4.3. Minimising the interactions with the controls

As explained before, by scheduling the temperature requirements and not overriding the heating controls, the smart heating controls can plan ahead the operation of the heating system and improve its efficiency (or provide grid services). To do that, the householders have to delegate the control of the heating times to the smart controls. Some participants acknowledged that some changes in know-how were required and suggested that "living with a heat pump is just different to living with a pure gas combi boiler" (Laurence). Most participants mentioned in the previous subsections as those who adopted new expectations for heating running patterns (H1, H2, H3 -1st winter-, CH1, CH2, CH6) also show a low number of interactions for the whole period analysed or parts of it, according to the data analysed in section 4.3. In fact, they are the six with the lowest number of days with manual interactions over the whole heating season studied.

For example, Nelson explained that he forgot his password and lost access to the app, which did not bother him because he admitted not interacting with it at all. In other cases, the lack of interactions was described as an active decision to reduce environmental waste or cost. These participants explained that they refrained from overriding the programmed operation because they realised that the boiler would respond (as it is more powerful and, therefore, more responsive), and it has a higher environmental impact than the heat pump (Laurence, Richard) or is more expensive to run (Greig -1st interview-, who had an LPG boiler).

> *Basically, if you boost the temperature, the gas is going to kick in and override the heat pump, isn't it? Which is not the objective, really.*
>
> *Laurence – 2nd interview*

In some cases, as shown in section 4.3, the number of interactions fluctuated during the analysed period, with either fewer interactions over time (H2, CH2) or more (H3). Changes in the understanding of waste and its relationship with the heating system activity can explain some of these differences. For example, Richard explained in the first and second interviews that, at the beginning of the project, he did not believe that the system was operating efficiently, so he forced it to operate in boiler mode. However, that changed through the project after he realised it was more efficient to let it work without interactions. Laurence also explained that he was forcing the system to operate in a certain way at the beginning, and that changed after talking to the customer service team, who convinced them that it was more efficient to let the controls work autonomously. In contrast, Greig became concerned during the second winter (between the first and the second interviews) that the algorithm was optimising for environmental impact instead of costs and thus was forcing the HP to run too often. Since then, he begun to force the system into boiler mode. In all these three cases, the change in the understandings of the relationship between waste and heating system activity could explain the changes in the number of days with overrides of the scheduled operation, as presented in section 4.3. In these cases, it seems that the adoption of the expected practices happened when the number of days with interactions was below 14-15 days with manual overrides per month. Further research with more cases and longer monitored periods might be needed to provide more reliable data on the specifics of the relationship between the number of interactions and understandings of waste.

Other changes in know-how

In a proportion of the cases presented so far, participants refrained from making non-scheduled changes to the temperature setpoint and, instead, modified their immediate environment to be comfortable by putting on extra clothes or closing doors (Richard, Laurence). In some cases, that was already part of their heating practices with the old boiler (Richard).

> *I hardly changed the thermostat at all. if we feel a little bit cold, I'll shut up a couple of doors and put sleeves on or something else.*
>
> *Richard – 1st interview*

This is consistent with Greig, who explained that because the heat pump heats slower, now he tries to be more conscious of not letting the door open for a long period because the heat will escape and it will take longer to reheat.

In contrast, the availability of the app and the low complexity of the controls allowed one participant to make more frequent changes. Dorothy saw the app as an opportunity to further reduce waste by reducing the duration of warmth-requested periods (IN periods in the language of the app) where possible to ensure that warmth was not requested when not at home. This might explain their relatively high number of days with manual interactions (section 4.3).

> *Now I can be on top of it. I don't want it to run unnecessarily. So, if I'm out I want to let the system know I'm out for a short time. (-) So, I feel that I can manage it more efficiently. Same with the hot water needs.*
>
> *Dorothy – 2nd interview*

However, it is important to point out that the system would still be running outside these warmth-requested periods to preheat and ensure that the temperature setpoint is achieved at the scheduled time. Also, short no-warmth-requested periods between warmth-requested periods will probably be disregarded by the system as the algorithm might prioritise maintaining the temperature instead of letting it drop.

Finally, despite developing new heating practices regarding waste that were more aligned with designers' expectations, participants did not use the heating periods of the app (IN, OUT, ASLEEP, and AWAY) as envisioned. For example, Laurence explained that he chooses OUT periods during the day, even when planning to be at home because the preheating provides a sufficient temperature to be comfortable. He does that because he is happy with a lower temperature during these periods, and, in that way, he minimises waste.

6.5. Conflicts

Shove *et al.* (2012) explained that social practices are transformed through the adoption of new elements or the abandonment of existing ones. In the cases reported in the previous section, the adoption of the novel heating technologies was accompanied by new understandings of waste, expectations for the operation of the heating system and know-how. These practices offered more opportunities to the heating controls to minimise costs (e.g., choosing to heat at night). However, that was not always the case, and some of the practices observed did not incorporate these elements.

The existence of alternative meanings, particularly ideas of what is and what is not wasteful, seemed to critically affect participants' satisfaction with the system as it became difficult and not always possible to achieve the expected outcome with the new technology. In certain instances, these meanings sparked alterations in other elements of the practice (e.g., meanings of waste triggered changes in the associated know-how for managing heat, and there was an increase in the number of unscheduled interactions with the controls). The following three sections explore these understandings of waste and their relationship with the other elements of the practice. However, before starting, it is important to point out that practices are in constant evolution, and the cases studied did change over time. The present section reports on the described and observed waste-related practices in specific periods and explores some elements that triggered changes in them. In a few cases, the experiences of participants who were also mentioned in the previous section are also included in this section – for two reasons: First, their experience evolved over time, and while, in some moments, it was well aligned with the "expected" practices (as reported in the previous section), in others, it was not. Second, their described practices fit well with the "expected" trajectories but still retained some elements that did not correspond with them.

6.5.1. Retaining old meanings of waste

The analysis of the interview data revealed various conflicts between the expected activity of the heating system and the observed heating running patterns of the new technologies. These conflicts often affected the householders' satisfaction with the heating system and shaped their heating practices, leading to practices that limited the options of the smart heating controls to minimise the running costs. However, the way the heating system behaved did not only conflict with ideas of the "correct" operation of the technology. The participants described the operation of the new technologies in certain conditions as "wasteful", "inefficient", "costly", "expensive", "unnecessary" or "pointless". Significantly, in most cases, that conflict was not linked to whether their energy use increased or not after the adoption of the technology, as this is often very difficult to assess, or did not have to do with disliking the heat pump, but with the existence of certain unexpected heating patterns.

As Susan summarised, "It's probably more the people that own the system rather than the actual air source heat pump". These understandings seem to be built on "prior experience" and already established practices (Shove & Pantzar, 2007).

The heating running patterns understood as wasteful were heating at times when warmth was not immediately wanted, heating discontinuously, and heating above the requested temperature. The next subsections analyse them in detail.

Heating when warmth is not immediately wanted

Even when satisfied with the technology, participants in CH1, CH3, CH4, CH5, CH6, H2 and H3 explained that they found the heating system, and particularly the heat pump, to be running more often than they expected. In some cases, that surprised them despite being aware that the heat pump would run at a lower flow temperature than their previous heating system and would need more time to provide the same amount of heat. Some of these participants found this type of operation unnecessary and wasteful. They seemed to see a direct relationship between the length of time the system was running and its economic and/or environmental costs. So, the longer the system was running, the more wasteful they thought it was. This was mentioned by Susan and is evident in the following quote from the second interview with Clare.

> *My feeling is that it's gonna be more expensive. Just because of the amount of time that it's on, it feels instinctively like I'm gonna have a bill from hell, which is why I haven't put my meter readings in, to be honest.*
>
> *Clare – 2nd interview*

The expected correlation between the system's length of operation and its running expenses is based on heating practices with traditional gas or oil boilers because this relationship usually holds true for conventional heating systems[33]. Minimising waste with a boiler is

[33] This might be dependent on maintaining a constant flow temperature and running always at constant flow rate, which happens often with traditional boilers.

usually achieved by reducing the time it is running. After adopting the novel technologies, this understanding was retained despite the change in the system's characteristics and efficiency. In some cases, they were mainly concerned by the extended running times of the heat pump, not the boiler, because they were aware that electricity was more expensive than gas. This was notwithstanding the significantly increased efficiency of the heat pump compared to a traditional gas boiler (especially if it runs at lower flow temperatures and for longer periods). However, that was less evident in the Hybrid cases, probably because the householders were aware that the difference in costs per kW between LPG or oil and electricity is smaller than between gas and electricity.

Heating when sleeping or not at home

In addition to the established relationship between time of operation and waste, some participants were particularly concerned about heating when nobody was home. Conventional boilers in the UK are traditionally operated with one or two heating periods (Hanmer *et al.*, 2019a) (although Huebner et al. (2015) found that 30% of the households maintained a flat temperature across the day). The boiler only fires during these heating periods, so controlling these times is central to heating practices. People try to heat only during periods when they are at home and awake, and this practice has been encouraged by the government, charities, etc., for many years (Energy Saving Trust, 2024a; GOV.UK, 2024; Centre for Sustainable Energy, 2024). Therefore, heating when no one is able to enjoy the heat directly, what Rubens and Knowles (2013), call heating with no benefit to occupants, is often seen as unnecessary, which has also been reported by Caird, Roy and Potter (2012). As the technical data presented in section 4.1 shows, the new heating technologies often run continuously or during times when it is not common to heat when using boilers intermittently.

Unsurprisingly, a few of the participants complained about this. For example, Simon and Susan, in CH3, were unhappy when they found that the system was heating the house in the morning when nobody was at home:

It's like constantly having something running. All morning, none of us have been here (-). It doesn't need to be on.

Simon – 1st interview

Also, Richard explained that at the beginning, he thought that the operation of the system was wasteful because it maintained the temperature at night when he did not require heat. He was expecting the temperature to drop as it happened with his LPG boiler and considered this extra heat unnecessary. Greig also did not like the system preheating at night, and he explained that he was on a flat rate tariff and the electricity at night was not cheaper. And Jim complained that "prewarming literally happens all the time". Finally, Simon was concerned that the energy moved into the house outside the periods when they were at home would end "just going out the windows" and that pre-heating with the heat pump was not cost-effective.

Despite perceiving preheating as wasteful, some participants enjoyed the new indoor conditions. Clare and Jessica saw the constant temperature as one of the benefits of the heat pump operation (since this was not the case with the boiler) in terms of comfort and health but expressed concern about the costs that could entail.

Heating above the temperature setpoint

The perception of waste in relation to heating practices does not only have to do with not being present to enjoy the heat directly. There are also indoor conditions that are considered wasteful. Two Compact Hybrid participants mentioned how heating above the temperature setpoint was unnecessary, despite being perfectly tolerable from a comfort point of view.

(At 10am) Where we are now, why is it heating my house at 20 degrees when it only needs to be at 10 (degC) and I only need to be 19 degrees at 7 at night. It's not gonna take 10 hours to heat the house. If it does take 10 hours to heat the house, then there is a problem.

Simon – 1st interview

If I set the temperature to 20 degrees and then in the evening it would be quite warm, about 21.5 degrees. And then the (hybrid) boiler would switch off at 9 o'clock, when we *go to bed. But then at 10:30 it would come back on again. () And it was just- I don't think it was necessary.,*

Jim – 2nd interview

The same also happened with conventional hybrid heat pumps. Richard explained that he found the system running a few times when the temperature setpoint had already been achieved.

That doesn't make sense, does it? It is predicting that my temperature is going to be higher than my setpoint, but also predicting the heat pump is going to carry on running.

Richard – 2nd interview

The issue was also experienced during shoulder season, with some participants complaining that the system was heating even though the setpoint was already reached (Simon) or the sun had heated some of the rooms well above the temperature setpoint for the house, and the system was still heating (Richard). It is important to note there seems to be a conflict between what some householders understand as temperature setpoint and what the system understands as temperature setpoint. For some participants, the temperature setpoint is the trigger that activates the heating operation (if the temperature falls below it). For the smart heating controls, it is simply one of the many temperature requirements that have to be met during the day. As the setpoint chosen is usually low, the heating system disregards it, and it usually focuses on providing the required heat for the next warmth-requested period (IN period using the terms of the app) at minimum costs (which might involve not letting the temperature drop).

The understanding of waste described is probably retained from their previous heating practices with conventional thermostats, as these devices stop requesting heat when the temperature setpoint has been reached. Continuing to heat after that might be experienced as wasteful. In two of the three cases (CH3 and H2), participants had a conventional thermostat before installing the new technologies. Householders in CH5 had on-off controls before installing the new system, but they might be aware of how conventional thermostats work and expect the smart heating controls to operate similarly. Additionally, some householders understood some high temperatures as wasteful, despite being comfortable.

This is exemplified by Laurence, who explained that "I consider that to be pretty wasteful if I'm sitting around in a T-shirt".

Heating discontinuously

In a small number of HyCompact cases, the operation of the new heating system was understood as wasteful not because of the length of the operation of the system or the temperatures reached but because of its discontinuity. Susan described the heating system as erratic because "it seems just to come on when it wants" and "it will just come on for a couple of hours. And then it will go off for like an hour. And then it'll come back on again". Simon was also concerned about that.

> *And it'll turn off and it'll turn back on, and it'll turn off- That seems massively wasteful and inefficient. So, I'm not, at the moment, () satisfied with how it operates.*
>
> *Simon – 1st interview*

He continued explaining how that type of operation only happened with the heat pump, not the boiler, and he believed that this could result from the algorithm's poor understanding of the thermal characteristics of the building (Simon). A similar issue was also described by Jim, who explained that he found that the heat pump was randomly turning on and off and thought that that could result from a technical failure. Molly explained that the system had periods when it was "coming on for two to three minutes every half an hour", which she did not expect. She also believed that could also be due to a technical failure. As explained before, the heat pump in the Compact Hybrid system is a single-speed 4kW output heat pump. That means the heat pump is either on or off but cannot modulate the energy used. Also, the heat pump has a program that runs a defrost cycle depending on the outdoor temperature. This prevents damage to the system by stopping the compressor, which is the main source of noise. However, it may also cause the system's operation to seem erratic.

Notes on the vocabulary used by the app

The vocabulary used in the app to communicate the times at which each temperature setpoint is requested seemed to reinforce the idea that the system was running when not needed. The system allows participants to choose IN, OUT, and ASLEEP periods, three terms that refer to the occupancy of the house and when they want to be warm. The fact that the system ran during OUT or ASLEEP periods was understood as wasteful and unnecessary, as Molly explained. Simon mentioned that the system was heating when "no one is in as far as the system knows". Both participants suggest that because they communicated to the system that nobody was home, the system should not be heating.

> *I would expect when we program the system to- When you say OUT, the system doesn't work. I did not pay close attention to what was happening when the system was programmed to be on OUT period but if you look at the usage of gas and electricity, it doesn't seem that there is a huge difference between this year and last year. () I would just expect to see a bit less gas being used this year.*
>
> *Molly – 2nd interview*

Previous research done by Mennicken et al. (2014) emphasised the importance of using natural and non-technical language in smart technologies to resolve ambiguities and prevent conflicts.

6.5.2. Retaining the old understandings of waste through monitoring

To minimise waste, people engage in activities to control or reduce what they understand as wasteful. These procedures require specific skills, sometimes held by people and others embedded in objects (Royston, 2014). Royston (2014) distinguishes between two types of know-how: monitoring and managing. In this case, monitoring waste and managing waste. Monitoring processes provide feedback on the outcomes of past performances and are critical in their circuits of reproduction of the practice, linking past and current performances (Shove, Pantzar & Watson, 2012). This section explores the monitoring skills linked to the previously discussed meanings of waste: feedback that contributes to maintaining outdated views of waste and experiencing the new technology as not effective for reducing waste. Participants described two main strategies to monitor waste: they monitored the economic resources (costs) involved in heating, or they monitored the system's operation patterns.

Monitoring costs

Heating costs were monitored through energy bills (Clare, Simon, Molly) or the smart meter (Susan). In this case, "expected" (section 6.2.2) and "retained" practices involve the same feedback processes. However, in this case, the feedback contributed to understanding the new heating running patterns as wasteful. The reason why that happened is well exemplified in CH3; Susan, one of the householders, explained that before installing the new system, their energy use was averaging £1.7-£1.8 per day. After the adoption of the new technology, it reached £4 per day. However, they moved houses before installing the new heating system, so they were comparing energy use from the previous year in the old property with the current year in the new property. Still, they compared costs and believed that the wasteful operation of the system mainly caused the increase observed. However, these comparisons can be misleading since external factors, such as differences in the thermal requirements of each property or changes in energy prices, especially during an energy crisis, can affect them. An increase in costs may even conceal an improvement in the system's efficiency. They were aware that other factors might influence the cost increase. However, in the absence of other feedback, they relied on costs, which contributed to perceiving the system as wasteful. Unsurprisingly, Simon suggested that he would like to experience the system in boiler mode only for a few weeks to compare it with his current costs and see if the controls are helping him reduce energy usage by running the heat pump continuously or preheating in advance. The findings are consistent with Lowe et al. (2017b) who described a few cases in which the householder's perception of high electricity bills triggered changes in heating practices and shaped the poor performance of the system.

However, in some cases, as explained in section 6.4.2, the feedback obtained through energy bills effectively contributed to changing the heating practices. For example, Simon's experience of the system started to change after receiving a communication from his energy supplier comparing his energy bills with those of similar properties. Realising that he was using less energy than the average made him aware that the system was more efficient than he thought. That was critical in his decision to keep the system at the end of the trial and triggered changes in his understandings of the heating running patterns. These findings are consistent with Greig, who was satisfied to see that his energy bills were lower than those of his neighbour. However, despite acknowledging that if he had not installed the new system, he would have paid significantly more due to the surge in energy prices, he was still concerned about the heat pump operating too often instead of the boiler.

Monitoring the operation of the heating system

As explained in the previous section, the understandings of waste are sometimes intimately linked to expectations of the system's operation. Therefore, an important part of the heating practices studied involves monitoring the operation patterns of the heating system. The participants identified several feedback mechanisms to monitor them: the temperature of the radiators (Susan, Richard), the Passiv app (Simon, Clare, Jim, Greig), which provided information on past and future heating operations, or the energy supplier app (Greig). However, those mechanisms are often secondary. For the compact hybrid trialists, the most relevant monitoring process was the heat pump's noise (Simon, Clare, Jim). This might be because the compact hybrid heat pump is located inside the dwelling. Therefore, the sound of the compressor was noticeable when the heat pump was running. Only one of the three hybrid trialists (Greig) mentioned the system's noise as a feedback mechanism, which might be because they are less likely to be aware of the noise of the system as the compressor is located outdoors. Regarding other noises, all the participants explained that the noise of the boiler was unnoticeable, and only Greig noticed that when the boiler turned on, the hot water pipes started cracking (probably because of the higher flow temperatures). He also explained that he could smell when the boiler was running, probably because the dust accumulated on the radiators burnt.

In some cases, participants used the feedback on the system’s times of operation and their understanding of the price of running the heat pump or the boiler per hour to calculate whether the chosen mode of operation (heat pump or boiler) was the most efficient way to run the system. For example, Simon believed that a half-hour pre-heating with the boiler was cheaper than the 8 hours of pre-heating that the heat pump was currently doing. Greig explained that with the recent rise in electricity costs, he noticed that the heat pump was operating excessively and, in certain circumstances, using the LPG boiler would be more cost-effective.

All these cases show the importance of monitoring the heating system activity to minimise waste when heating. Despite the fact that the heating running patterns are not relevant to assess the real cost or environmental impact of the new heating system, this know-how is retained. That contributes to experiencing the system as wasteful and to act to retain control of the heating running patterns, as is explored in the next section.

6.5.3. Reproducing the old heating running patterns

Managing waste involves a wide range of elements and skills. Among those elements, the heating controls play a critical role. Conventional heating controls usually allow householders control over the heating running times. With traditional on-off controllers, people actively define the heating system's activity. With the adoption of conventional thermostats, they cannot control the operative times. Still, they can define a period when they want heat, and the controls automate the heating operation within this time window based on a temperature threshold. The smart heating controls studied achieve the lowest heating costs if they fully control the heating system activity, and the householder delegates the control of the heating running times to them. However, the analysis of the interviews showed that some householders did not want to delegate this control to the algorithm because they were concerned that the heating patterns proposed by the system were wasteful. Instead, they controlled the heating times, using know-how often retained from heating practices with conventional boilers.

Changes in the temperature setpoint during warmth-requested periods

One of the most common strategies to reduce heating outside warmth-requested periods (pre-heating) was to reduce the scheduled temperature setpoint for the warmth-requested periods (Simon, Clare, Richard). Often, that was encouraged by the customer service team as an answer to the participants' complaints. However, in some cases, this was combined with manual and non-scheduled increases in the temperature setpoint (using the wall thermostat) in the evening if they felt cold (Simon, Greig). This type of operation has also been described for comfort and noise control in Chapter 5, and it resembles how a conventional on-off heating control would be operated. However, the participants in the study did not always increase the temperature setpoint if they felt cold. Simon explained how he tries to encourage the other people at home to put on extra clothes or use the electric rug in the living room instead of manually increasing the temperature setpoint. Greig also mentioned using secondary heating sources to reduce the usage of the heat pump, which is consistent with some of the cases analysed by Lowe et al. (2017a) and Oikonomou (2022).

Changes in the length of the warmth-requested periods

To reduce the length of the preheating time, and in addition to reducing the temperature setpoint, some participants also delayed the period when heat was requested (IN period) to later than when they really wanted heat (Simon, Clare). For example, they set the warmth-requested period to start at 7pm despite arriving at 5pm. By doing that, the system still preheated, but preheating started later. The heat provided for preheating maintained the house at a reasonably comfortable temperature even before the warmth-requested period: the air temperature was below the setpoint but close to it. That was also often suggested by the customer service team when participants complained about the preheating length. The right delay in time was usually chosen after a try-and-test period. However, in some cases, if householders found that the house was still cold when they arrived, they increased the temperature manually, which has obvious consequences for the capacity of the controls to plan in advance and maximise the efficiency of the system.

The only reason I've set the evening to 7 until 9 because I'm trying to get the system to operate how I want it to operate. I did have it set to 5 o'clock but it would- The air source will come on so early to get the temperature to be at 19 degrees at 5 o'clock. It just seems very wasteful. So, by pushing it back to 7, (in my mind) what should happen is the heating starts later. So, at 5 o'clock it won't be 19 degrees but it would be kind of 17-18 degrees, which is all we need.

Simon – 1st interview

Simon explained that over time, they established a routine and minimized unplanned interactions with the controls. However, that was only because they got tired of manually operating the system and not because the system was providing their desired outcome:

I mean, generally I've got it set and we just let it do its thing now. So it's not like I'm sitting there every night twiddling with the numbers and the dials, but we've just kind of resigned (inaudible). But it doesn't operate how I want it to operate.

Simon – 2nd interview

On the other hand, Greig began managing the system manually *more* frequently over time (2nd winter), due to his concerns about the heat pump running excessively, especially with rising energy costs.

Consequences of the changes

Some of the actions described above have consequences for indoor conditions (e.g., the temperature in the morning might be lower if the beginning of the warmth-requested period is delayed). The findings suggest that, in some cases, in order to minimise what is understood as wasteful, participants are willing to sacrifice comfort. Heating practices involve trade-offs between different variables, and, in these cases, there is an active decision to prioritise minimising waste instead of achieving the chosen air temperature. The findings also suggest that achieving the temperature setpoint at the beginning of the warmth-requested period might not be necessary under certain circumstances. Probably because the expectations for these temperatures are retained from heating with conventional controls in which it is not always possible/common to achieve them (see Bennett & Elwell, 2020, for example). In this case, by assuming that householders want that, smart control designers might be contributing to normalising increased temperatures. Strengers (2008a) has reached similar conclusions in her analysis of demand management of air-conditioning loads.

These actions that involve unscheduled changes of the temperature setpoint also have consequences. In this case, they affect the capacity of the algorithm to plan in advance and maximise the efficiency of the system. These consequences were discussed with those participants who described them. They were asked about the impact that they believed this type of operation entails. None of them mentioned any effect on the running costs of the system (economic or environmental) or the capacity of the controls to provide grid services, but they believed the opposite: that the non-scheduled operation of the system was helping them reduce costs. Participants in four households admitted forcing the hybrid system into certain heating patterns: H2 (first winter), H3 (second winter), CH3 and CH4. All of them had a relatively high proportion of days with manual interactions (see section 4.3), and it is likely that waste-related issues could explain the results. However, as explained in Chapter 5, other factors might be behind these interactions, such as minimising the noise of the system. Interestingly, not all the householders who found the heating patterns of the new heating system wasteful described actions to control the heating times, this was the case for Barry or Jim. It might be that they simply did not discuss these actions, which is likely to be Jim's case (the analysis of the technical data shows that the number of days with manual overrides was very high compared to other cases) or that they simply did not force the system to change the heating running times (as the technical data suggests in Barry's case).

Unsuccessful attempts to stop the heating system

The previously described actions successfully managed to control the heating periods, but that did not happen with all the actions performed, and some attempts were unsuccessful. For example, when trying to force the system to stop during times in which they did not expect it to heat, one of the first actions that participants tried to do was to reduce the current temperature setpoint (Susan, Simon, Nelson). However, that did not usually have any effect because the system often plans in advance for the next heating period. The lack of response of these actions generated frustration in some cases. This know-how is retained from heating practices with conventional thermostats, in which the system stops if the temperature setpoint is reduced below the air temperature. Conventional thermostats are often used as a on-off switch. While a conventional thermostat can be effectively used like that, the smart thermostats tested here are not. This highlights the importance of the legacy of previous practices with other technologies in heating practices with smart heating controls.

6.6. The role of trust

The findings presented so far have shown the importance of heating running patterns in the context of heating practices. The heating system activity is used to monitor waste, and controlling it is a critical part of heating practices with conventional technologies. For the smart heating controls to achieve the lowest running costs of the system, this know-how for monitoring waste and minimising it (the control of the heating running patterns) has to be delegated to the smart heating controls and, as this process becomes less transparent for householders, they need to trust the algorithm to minimise waste.

The new technologies (including the algorithm) could constitute what Giddens (1990) described as an *expert system*. They can establish a relationship between householders and experts operating at a distance from the home that provides "guarantees" of the expected outcome (Giddens, 1990). However, as explained in section 6.1, *expert systems* require trust. Trust in the capacity of the system to provide what is requested, in the people running the system and in the principles of the science underpinning the technology. Giddens (1990) explained that in many situations, the circumstances of daily life enforce trust and trust towards *expert systems* is routinely incorporated into practices (e.g., one cannot disengage from the monetary system completely). However, trust in this expert system is negotiated, and householders can decide to disengage from the system completely if they do not trust it. For example, participants volunteered to have the technology installed; they could remove it completely and install the old boilers back (in the compact hybrid trial, this can be done without any costs for the householders), and, as explained in section 3.2.1, they have ways to bypass the algorithm and retain control of the heating times. Therefore, trusting in the new *expert system* is critical for the adoption of heating practices that allow the smart heating controls to run. However, trust is not simply acceptance (Smale, Spaargaren & Van Vliet, 2019) and needs to be built (Meyer *et al.*, 2008) and constantly maintained (Bellaby, 2010).

As the analysis of the interviews showed, the decisions and reasoning of the algorithmic controls are not visible to householders and sometimes not even to the control manufacturer (black box). Therefore, the existing know-how for monitoring and minimising waste is delegated to the controls, and householders need to trust that the system minimises waste and operates efficiently to maximise the opportunities of the smart heating controls to lower the running costs. Unsurprisingly, several of the householders discussed this issue, explaining that the lack of trust in the novel technologies drove some of their actions to control the heating times.

> *(Talking about why he does not want to let the system operate autonomously) 'Cause I don't trust it. I think if I had had a better experience and I felt that it had come on more efficiently, perhaps I would trust it. But as it stands today, I want to take manual control and say: "I don't want you to turn on before X". And I will learn how long you will take to heat the house and what we can tolerate before we want it on and off.*
>
> *Simon – 2nd interview*
>
> *(Talking about letting the controls automate the operation of the system) If I knew that if I left it, it is the most efficient way for it to work, and it's the most financially efficient way and it's the most carbon efficient way, then I'd leave it. But at the moment it doesn't- it doesn't make logical sense in my own head.*
>
> *Jim - 2nd interview*

In line with what Smale, Spaargaren and Van Vilet (2019) suggested, the findings discussed in the previous sections have shown how an accountability system based on transparency could contribute to trust-building. For example, Richard was reluctant to let the system do its thing or change his understanding of waste until he started measuring the energy usage of the system and its operation and realised that the new technology was effectively providing what he wanted (minimising waste). However, that was not always possible. The analysis of the interview data suggests several factors that affected (positively or negatively) the trust of the participants in the new heating system as an expert system.

6.6.1. The trial

Some of the participants discussed the new heating patterns and the perceived erraticism of the system in the context of the trial of the technology. As explained in section 3.2.1, the compact hybrid participants received the new technologies for free as part of a trial. Some participants understood the erratic heating system activity as a consequence of the innovative nature of the project. For example, Susan explained that “because we’re on this trial, it just seems to do its own. It just turns on when it wants”. Dorothy and Simon also described a similar situation. The analysis of these cases suggests either that they understood the erratic heating running patterns as failures (as in subsection 6.6.3) because it was a new technology that was being trialled or that the interest of the controller was in testing some new functionalities rather than addressing their needs (misaligned interests as in subsection 6.6.2). The fact that they were also offered compensation at the end of the trial if the tests ran as part of the project increased energy costs (as explained in section 3.2.1) might have contributed to that understanding. None of the householders who installed the hybrid heat pump (not the compact hybrid) mentioned that, which suggests that the issue is likely affected by the specific design of the compact hybrid system or the project in which it was deployed.

6.6.2. Misaligned interests

In some cases, a mismatch was observed between what people wanted and what was provided by the heating system, which could have affected the participants’ trust in the system. In some cases, they had to do with different understandings of the heating system activity, as extensively discussed in the previous two sections. So, householders wanted specific heating running patterns that they believed could contribute to minimising waste, but the heating system was operating differently to what they thought was necessary to achieve what they wanted. In other cases, it had to do with non-shared objectives between the algorithm and the householders. For example, these could have happened in cases in which the algorithm was trying to minimise costs, but the participant was more interested in maximising the use of the heat pump to reduce the environmental impact of the system. Or in most of the cases in which the comfort expectations of the householder and the outcome of the heating system did not align, as discussed in Chapter 5 (e.g., participants who wanted to minimise noise and the algorithm did not take that into account).

> *And sometimes that heat pump can be on all night, whereas if the gas boiler comes on, it only needs to be on for 20 minutes to do the same effect as what the heat pump has been doing all night. So I think, especially with the change in costs of energy- I think that to have the opportunity to optimize it on price would be an advantage.*
>
> *Greig – 2nd interview*

The findings are consistent with Smale, Spaargaren and Van Vliet (2019) who suggested that when the objectives of the smart technology do not match those of the householders, the trust relationship between the two can break down.

6.6.3. The past performance

Since the installation of the technology, numerous participants experienced failures and technical problems, which is one of the issues that, as suggested by Giddens (1990), can affect the judgements about the trustworthiness of an expert system. Most of the technical problems happened due to the low-quality installation of compact hybrid heat pumps carried out by the first contractor. In those cases, the disruption caused by these problems eroded the trust in the system (Laurence, Simon, Clare), as discussed in the next subsection. In some cases, the lack of available trained installers close to the participants' homes delayed the required remedial work, further reducing the trust in the system and generating concern about not being able to repair future problems with the system (Richard, Laurence). Moreover, the bankruptcy of one of the firms involved in the project also affected the participants' trust in the people involved in the project and the technology installed (Richard, Greig). However, these failures did not happen only because of installation issues. For example, Clare explained that she experienced overheating problems with the heat pump at the end of the first winter, which affected her trust in the capacity of the system to deal with changing indoor conditions. Since then, she decided to increase the number of manual interactions in shoulder season to control it herself. In a few cases, some issues were perceived as problems even though the system was operating correctly. This is the case of the "erratic" heating system activity described in the previous section, which was often described as a system failure. Real or not, those problems contributed to the system being perceived as unreliable.

6.6.4. Experiences at access points

Giddens (1990) has explained that while trust in expert systems does not require encounters with the people or groups that are "responsible" for them, often those encounters happen, and they have a critical influence on the development of trust (or lack of it) between the *expert system* and the individual. Giddens (1990) named these encounters *access points*. The present study has identified two main *access points* in heating practices with smart heat pumps: the installation/handover and the communications with the customer service team. In the following sections, each of them will be analysed in detail. The aim is not to understand how the access points are designed but to study the participants' experience with them.

Installation and hand-over

The analysis of the interview data suggests that the installation process is critical in building trust in the *expert system*. This was the case for some of the compact hybrid participants. As explained in the previous section, the quality of the installation in CH1 to CH4 was very low. The participants in three of these four installations were disappointed with the works carried out (CH2, CH3, CH4), which required remedial work soon after installation[34], including installing an antivibration kit to minimise the noise of the heat pump. For example, Simon complained that the installers had to come twice because they did not have the right equipment to do the job and that, due to poor planning, they had to remove the carpet because they needed to fit some extra wires, despite him specifically asking them if they would need to work in this area before installing the carpet. Clare was also unhappy with the installation because the installers left her to clean their mess and broke her washing machine. Laurence mentioned that the system broke down minutes after the installers left the property (and the installers had to come back). Additionally, the installation in CH1-CH4 was carried out in two separate parts: first, the householders received the hybrid heating system with a set of conventional heating controls, and a few weeks later, they received the smart controls. Simon and Clare described this process as disruptive: they had to learn to use the hybrid boiler system with the conventional controls and then learn how to operate it with the smart controls when these replaced the conventional controls. These experiences caused concerns about the system's reliability, but it is unclear if they contributed to the participants retaining control of the heating running patterns in CH3 and CH4. However, in CH2, Laurence explained that these concerns were one of the main reasons why they requested the system to be removed at the end of the trial despite the fact that, as explained in section 6.4, he did not complain about the algorithm and he delegated the control of the heating activity to it.

Communication during the installation

Discussing the installation process with the participants showed that the interactions during the installation with the installers were minimal, and the information provided during the handover process might have contributed to shaping their understanding and expectations for the system. The participants explained that they almost never talked to the installers,

[34] The company who commissioned these installations was not hired for the second round of compact hybrid installations (CH5 to CH7) due to the numerous problems experienced.

which is consistent with what was observed in the installation that the researcher attended. Some householders mentioned that only the location of the thermostat was discussed during the installation (Nelson. Laurence, Greig), and others, like Clare and Laurence, explained that the installers wanted to leave quickly once the installation was finished, and they did not discuss the system with them. In general, some participants complained that not much information about the heat pump/hybrid boiler itself was provided during the installation and handover (Jim, Daniel, Molly, Richard). This could have contributed to the system being perceived as a 'black box'. In contrast, most participants seemed very satisfied with how the heating app was explained to them (Laurence, Nelson, Jim, Richard), although some described the app as self-explanatory. Regarding the issues related to the heating patterns of the system, some of the participants said that preheating was discussed during the handover process (Laurence, Barry, Nelson, Greig, Jim), but others, that it was not (Simon, Richard, Molly). Those cases in which it was discussed explained that they were told that preheating would be shorter than it was in reality (Nelson, Greig, Jim). For example, Jim complained that they told him that preheating in the morning would start around 4am-5am but not that the heat pump needed to stay on all night. The information provided set the expectations for the heating system's operation, and, in some cases, it did not match their experience, which might have contributed to experiencing the system as faulty.

Getting in touch with the customer service team/operations team

Once the system was installed and running, the Customer Service Team (CLT) dealt with the participants' questions, complaints, and suggestions. Their role is critical, and the interviewees widely discussed their impact on heating practices. In contrast to the previously discussed *access points*, those meetings happen once the participant has had experience with the system. In some cases, it was not the householders who approached the customer service team but the converse. Most of the participants seemed to be particularly satisfied with those interactions, and, in some cases, those encounters contributed to building trust in the system and delegating control of the heating system activity to the smart heating controls. As Barry explained, the customer service team was easy to reach and able to solve some of the problems remotely.

The range of topics discussed with the customer service team was extensive. Nelson explained that he approached them a few days after installing the technology to understand why the system was heating even when the temperature setpoint had already been reached; the answer reassured them of the need to let the system operate freely. Laurence and Jim explained that they were told by the customer service team that they were overriding the temperature schedule too often. For Laurence, this was a tipping point that led to the adoption of new understandings and a change in how he operated the heating controls (with fewer manual interactions and an active effort not to boost it). However, the interaction had a smaller effect on Jim because one of the reasons behind his selected operating patterns was to reduce the system's noise and not only because he thought that the heating activity of the system was wasteful. Clare explained that the customer service team helped her understand that the new system was not like a traditional boiler and helped her control the house's temperatures, adjusting the times when the heat was requested. However, while that changed her practices in the short term, it did not in the long term as she began to use the system manually, forcing it into certain heating patterns (see section 5.1.1). Finally, Simon contacted customer service multiple times to better understand the heating system's operation patterns and requested more feedback. However, he expressed frustration with the lack of assistance and unwillingness to share data, which hindered his trust in the system. Despite that, for most participants, talking to the customer service team contributed to building trust in the algorithm. This is because the conversation reassured them that the system was working correctly (e.g., that heating at night was not wasteful), provided advice on how to set the system to help the algorithm achieve lower heating costs, and helped them to better understand the reasons behind the heating system activity.

6.7. Waste in context

The findings presented so far are the result of the analysis of a small set of 10 case studies. While the low number of cases is useful for studying the experience of the householders in detail, it does not provide much information about how common those situations are. Therefore, to complement these findings, the project has analysed the communications between the Customer Service Team (CST) and the householders for a project where 130 hybrid heat pumps with smart heating controls were installed. The Customer Relationship Management (CRM) database includes all the interactions (e-mails and summaries of all the phone calls and face-to-face interactions) between these 130 householders and the customer service team (CST). After the installation, the CST is often the first point of contact for householders when facing a conflict with the new technologies, as several participants explained in the interviews. Therefore, the CRM dataset provides a unique perspective on the heating practices of householders regarding waste. The analysis of this data should help triangulate the findings of the previous sections and assess the spread of the situations described by the interviewees.

As discussed before, waste is a broad term encompassing many elements. The data from the CRM database evidenced the heterogeneity of these meanings. This section analyses the communications where householders, explicitly or not explicitly, discussed their understanding of wasteful heating practices in those cases in which those were not the result of technical failures. Waste in the context of heating practices was the second most commonly discussed topic in the communications between customer service and householders. This topic appeared in 107 tickets (11% of all the tickets) and was mentioned by 61 householders (47%[35]). It is important to point out that new tickets are opened for each new discussion, not for each new communication or for each householder. Therefore, the relatively low proportion of tickets discussing this issue and the high number of householders involved suggest that waste-related issues are widespread but not recurrent. On average, addressing waste-related issues required 1.7 tickets per household, with one or more communications in each ticket and a few months between the tickets. In three of the six cases where the system was requested to be removed, waste-related issues played a crucial role in this decision, which was usually also accompanied by some technical failures

[35] When not specified, all percentages refer to the percentage of all the households (n=130) that mentioned a certain topic in their communication with the CST.

that affected the householders' confidence in the technologies. Figure 6.3 summarises the findings.

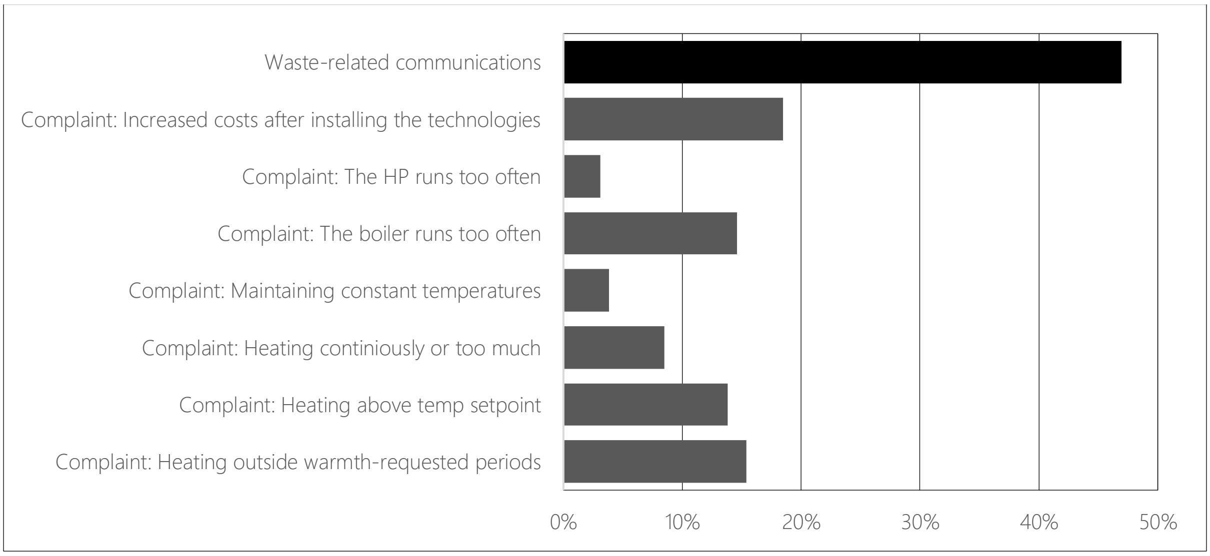

Figure 6.3. Main waste-related communications to the customer service team in the CRM database per number of households who mentioned the topic.

While the concept of waste is often associated with economic expenditure, only 18% of the householders referred to energy costs. Instead, heating running patterns seemed to be the focus of householders' concerns. The CRM data evidences substantial differences in householders' understanding and expectations regarding these patterns. The analysis of the interview data has identified two distinguishable variations in heating practices: those that delegated control of the heating system activity to the algorithm and those that retained the know-how for minimising waste from heating practices with conventional technologies. The analysis of the CRM data helped to identify a third variation: heating practices that involved the acceptance of the heating running patterns of the new technologies (longer operation at lower temperatures) but without full delegation of the control of the heating periods. In the next subsections, the two performances not involving delegation will be analysed.

6.7.1. Retaining understandings of waste from practices with the old technology

As explained in the previous sections, some householders retained the meanings of waste associated with specific heating patterns after adopting the new technology. Thirty-seven householders (28%) contacted the CST concerned with the heating running patterns of the new technologies, of which 71% of them discussed understandings of waste that seem to be retained from heating practices with conventional boilers. Among those patterns, the most reported one was heating outside warmth-requested periods (15%), which is consistent with the findings of the interview data. The following quote from an e-mail sent by a participant to the CLT (CRM dataset) summarises that:

> *This installation was supposed to save me money, yet it is costing me a fortune in electricity and oil by heating the house when I am out.*

Also, several communications include complaints about the heating system heating when the indoor temperature was above the temperature setpoint (14%), particularly during night periods. During these periods, the setpoint is usually low, and householders do not expect the heating to be on (or only to ensure a minimum temperature in the building in extreme conditions - setback). However, the heating algorithm often calculates that it is better to maintain the temperature overnight instead of reheating before the next warmth-requested period. Those two "wasteful" heating patterns were often reported simultaneously and demonstrate the difficulties of adopting meanings of waste that were more aligned with how the new technologies operate. In some cases, it was not possible to identify a specific heating pattern in the communications; householders simply complained about the continuous heating operation or reported "too much" heating operation (8%), which they understood as wasteful. Finally, a few participants (2%) also complained about the heating system operating with warm or sunny outdoor conditions when the indoor temperature was already comfortable, particularly during the shoulder season, which suggests that temperature requirements can vary over the year and reinforce some of the issues discussed in the interview data.

In addition to these heating patterns, the analysis suggests that certain indoor conditions are also understood as wasteful. Five householders complained that maintaining constant temperatures all the time was wasteful (4%), and another three explained that the house was often too warm (2%), which was described as unnecessary. These findings resonate well with the analysis of the interview data and suggest that indoor conditions are evaluated in terms of waste in addition to thermal comfort. All the understandings described so far are rooted in an expected correlation between the operating time and the waste generated (economic or environmental), which, as explained in section 6.5.1, is characteristic of the heating practices with conventional boilers: The longer the heating is on, the greater is expected to be the waste generated.

As found in the interview data, the app's language seems to be reinforcing some of the meanings of waste previously discussed. Twelve participants (9%) referred to the IN, OUT, ASLEEP and AWAY periods when discussing waste-related issues. They did that in different ways. The most common complaint was about the system heating during OUT, ASLEEP or AWAY periods (6%). The IN periods were often understood as periods in which the heating system was supposed to run (warmth-requested period), and OUT, ASLEEP, and AWAY were periods in which that was not supposed to happen. This understanding is probably inherited from heating with heating timers or conventional thermostats, in which the heating operation periods can be defined, and suggests that communicating when they want to be warm instead of when the heating should run can be confusing for some householders. For example, in one extreme case, one of the householders explained that he set the IN period at night during hours when his ToU electricity tariff was cheaper. In that way, he expected to take advantage of the low electricity price. However, this is not how the algorithmic controls operate. Other conflicting understandings of the app's language include expecting the temperature setpoint to be the target temperature, not the minimum temperature, which can create conflicts when the heating system heats above the temperature setpoint to preheat or maintain the temperature for the next warmth-requested period. That is summarised in the following quote from an e-mail sent by a householder (CRM dataset):

I have temperature settings for IN, OUT, ASLEEP and AWAY. My IN setting is currently 19 and my OUT, AWAY and ASLEEP setting is 8 degrees. However, the heat pump delivers to the IN setting all the time. The variation in temperature at night time, for example, is just 1 degree less. So what is the point of separate settings if the heat pump is going to deliver a pretty constant temperature?

The CRM data does not include much information on the actions that householders took to address the unexpected heating patterns and achieve the expected outcome. However, the few communications that mentioned that were consistent with the findings of the interview data. For example, a few householders used the AWAY, OUT and ASLEEP periods in ways that do not correspond with their actual presence in the building in an attempt to reduce the preheating time or the system's operation outside warmth-requested periods. Also, others admitted using more secondary heating or switching off the HP or the heating system to stop what was understood as wasteful heating. Finally, a few complained that they lowered the temperature setpoint to force the system to stop heating at unexpected times, but that did not prevent the system from operating, which is also consistent with the interview data.

The customer service team helped householders adopt the new meanings of waste by explaining the importance of the new operation patterns or suggesting actions that could modify the heating system's operation and make it more aligned with their expectations. Those actions mainly included lowering the temperature setpoint (to reduce the length of the preheating) or delaying the warmth-requested periods (to delay preheating). It is unclear if the support triggered the delegation of the control of the heating running patterns to the smart heating controls because the CRM dataset mainly includes records of complaints and/or problems. However, it seems likely that this happened as, in most cases, the tickets were closed without further interactions with the householders.

6.7.2. New understandings of waste

Several of the communications recorded show that a few householders accepted some of the new running operation patterns. They accepted maintaining the temperatures or preheating outside of their warmth-requested periods. This is consistent with the findings of the interview data. Still, some of them complained about the heating operation of the new technologies. While previous Chapters have evidenced that householders can notice differences between the two technologies in the hybrid system (heat pump and boiler), the analysis of the CRM dataset has found that some of them also have preferences for which of them heats at each time. They complained that one or the other technology was running less or more than they expected, which they understood as not efficient or wasteful.

Nineteen householders (15%) explained that they thought the system was prioritising the boiler over the heat pump in cases where they were expecting the heat pump to engage. Four (3%) complained that the heat pump was running too often. In other cases, it was the pattern of operation that concerned the householders. Two of them (2%) reported that the boiler was performing like a heat pump, maintaining the temperature at night, which they did not think was efficient. The following quote from an email sent by a participant (CRM data) summarises it:

> *the issue is that when the temperature goes too low, the boiler kicks in and acts like the heat pump and tries to keep the heat up. Which is really bad for my oil consumption, having a larger house in a rural location. What I believe it should do when it drops to boiler, is to drop to dumping a lot of heat into house just before IN period and maintaining during that period. This would be so much more economical. The system really needs 2 modes "Hybrid" using ASHP and Boiler and "Boiler only" for when the ASHP cannot generate enough heat and is not functioning. By replacing the ASHP with the boiler to maintain heat levels meant that I ran through over 700 litres of oil within weeks, which was frightening.*

This experience might result from setting a high-temperature setpoint in a building with a low thermal performance. The heating system is unable to provide the required temperature setpoint and forces the boiler to keep running to achieve it. The smart controls take the householder’s desired setpoint as a rigid requirement despite it not being realistic given the characteristics of the building.

The findings of the CRM dataset show that some householders do not trust the system to operate efficiently and minimise waste as they expected, even when the new heating running patterns were accepted. Therefore, the analysis suggests that in addition to the two distinguishable groups of performances of heating practices described in sections 6.4 and 6.5, a third variation exists. This one involves continuous monitoring of the heating operation and having expectations for it but accepting of the new heating patterns of the heat pump (e.g., longer heating duration at lower flow temperatures). While a few examples of this performance were identified in the interview data, the small sample size made it difficult to observe the issue in perspective.

The CRM dataset shows that the customer service team had a crucial role in adopting these practices by setting expectations for the heating operation. For example, as one of the householders explained, they were told that the heating system would run 80% of the time on heat pump mode. In their case, the system used the boiler more often than that because of the low thermal performance of the building. However, the householder relied on the information provided to assess the system's operation. Other information provided by the project team, such as the outdoor temperature at which the heat pump would be more efficient to run, was also used to complain about the operation of the heating system. That shows the important role that the available information provides in setting the expectations for the heating operation. It suggests that the information provided should be targeted to the specifics of each case or that it is critical to emphasise to householders that these expectations are based on average properties and conditions and that how the system runs in their property might be different.

In other cases, the participants approached the customer service team to ask for information they could use to develop some of these understandings. For example, one of the householders contacted to ask about the energy required to increase the temperature with the boiler and with the heat pump to assess if the system was operating efficiently. Others requested information about the outdoor temperature at which the heat pump was more efficient than the boiler. The development of these preferences conflicts with the expected passive role of the users. The following quote from an e-mail sent by a participant to the CLT team (CRM dataset) summarises some of the issues discussed:

> *How is the heat pump efficiency measured or, more importantly, how is the 'effort' required from the heat pump to maintain the target temperature calculated?... I'm just trying to get my head around how the heat pump's point of being switched off is determined.*

However, not all these understandings were built with the mediation of the customer service team. Some householders had preferences for one or the other system because of their awareness of the LPG costs (used for most of the boilers in the CRM dataset) or their interest in the heat pump technology (typical of early adopters).

The findings evidence the difficulties of completely abandoning know-how for minimising waste associated with the operation of the heating system and delegating that to the smart heating controls, even in those cases when new heating running patterns are accepted. This process is key for the algorithm to be able to run the heating system at the lowest cost and, as explained before, requires trust in it (*expert systems*).

6.7.3. Monitoring waste

As found in the interview data, monitoring waste is complex. Ten householders (8%) communicated with the CST to ask if the system was performing as expected or to simply complain that it was impossible to know if it was operating most efficiently. Findings presented in previous sections suggest that householders monitor the heating running patterns to minimise waste. However, this is not the only way how they do that. As also found in the interview data, the analysis showed that waste is also monitored through energy costs. A few participants mentioned the increase in fuel costs after adopting the technology (18%). Most of those (62%) reporting increased costs mentioned the energy bills or the smart meter. Unsurprisingly, all the participants complaining about increased costs also mentioned that the heating running pattern was wasteful, which suggests a link between the two. In some cases, householders provided exact values for the experienced increase in energy costs. In others, they described the detailed calculations they carried out to calculate that the heating operation was not the most efficient. In all these cases, the CRM dataset evidences that the CST could prove that the heating system operation was the cheapest way to achieve the temperatures requested by the householder. However, as shown in the interview data, householders compare the energy costs with what they used to pay before the system was installed. Big jumps in the energy prices due to the energy crisis, not calculating the proportion of the electricity costs incurred by the heat pump, not including changes in the gas consumption in their calculations or, in a small number of cases, moving houses before installing the technology, affected the "counterfactual" used. In other cases, when calculating the energy costs, they did not consider the efficiency of the system or the fact that the system was not operating at full power. Correct or not, this feedback contributed to shaping the meanings associated with the technology.

6.7.4. The role of trust

To delegate the control of the heating operation to the smart controls, the householders have to trust that the heating controls are operating the system most efficiently and not wasting energy. It is not enough to accept that the heating system would operate outside warmth-requested periods or not let the temperature cool down. The analysis of the CRM data confirms the findings of the interview data and suggest that it can sometimes be challenging to build the required trust. As shown below in one of the internal notes that one of the customer service employees wrote, the operation is not intuitive or easy to accept:

> *we have done the calculations in detail (they are run all the time on the hub) and the system has determined that the current operating mode is the cheapest (the thermodynamics are unintuitive but ultimately he has to believe us / the laws of physics!)*

The lack of trust was particularly evident after the increase in energy prices resulting from the energy crisis.

The CRM data confirms some of the findings of the interview data regarding the factors that contributed to not building trust in the system. First, householders experienced numerous problems and failures with the technology. As explained before, all householders (130 in total) got in touch at some point with the customer service team since installing the technology. Technical problems were the most common reason they got in touch with them, as shown in the quote from an email sent by a participant in the project (CRM data) below.

> *We are really disappointed with the system thus far, we went with it because we trusted **** (company that ran the project) and wanted a greener option. We now find that we are using more electricity than ever before, plus what was once an effective domestic water system is now not working.*

Second, a mismatch between the objectives of the householders and the system was also evident in the CRM dataset. For example, in one case, the householder wanted to use the heat pump only, even when that would mean not achieving the temperature setpoint. In others, participants wanted to participate in DSR trials or optimise the operation of the heating system for a particular ToU tariff. In all these cases, the smart heating controls were trying to achieve the lowest running costs but this is not what the householders wanted, which likely caused dissatisfaction with the system and a lack of trust.

6.8. Discussion

This chapter has explored how the understanding of waste in heating practices evolved after adopting hybrid heat pumps with smart heating controls and the importance of heating patterns in the know-how to minimise waste. Some elements that trigger changes in the know-how have been explored, particularly emphasising the role of trust in delegating the control of the heating system activity to the smart heating controls and communications with other stakeholders. The study did not aim to be exhaustive in finding all the ways in which ideas of waste are related heating practices but to carry out an initial exploration of a largely understudied topic. The results come from the analysis of the data obtained from two sources: 10 case studies of households newly equipped with hybrid heat pumps with smart heating controls and the Customer Relastionship Management (CRM) data from a large project with 130 households equipped with these technologies. The mixed-methods approach used should improve the robustness of the findings and the representativeness of the results.

These insights have been explored using an SPT approach and combined with some of the concepts developed by Giddens on *expert systems*. The SPT framework has already been applied and demonstrated to be useful in studying change in domestic heating practices before (see Gram-Hanssen, 2011, for example). However, it was deemed insufficient to capture the importance of trust, which often emerged in the thematic analysis of the case studies. Therefore, the concept of *expert systems* and *access points*, as discussed by Giddens (1990), was included. Trust has often been explored as part of the adoption of energy-related technologies at home (see de Wilde & Spaargaren, 2019, for example), but it has not often been combined with SPT. The study builds upon the pioneering research of Smale *et al.* (2019) by showing the importance of trust in heating practices. Additionally, the inclusion of the concept of *access points* helped to explore some of the external elements that have "punctured" (Hitchings, 2011) the heating practices in the studied households and also helped to understand the role of interactions between householders and other stakeholders in heating. While this has been studied for domestic heat pumps before (see Gram-Hanssen *et al.*, 2017, for example), the analysis has mainly been limited to the initial stages of adopting the technology. In this research, the communications with the customer service team once the technologies have been installed have also been analysed.

6.8.1. The role of waste in domestic heating practices

The analysis has evidenced that minimising waste is an important part of heating practices, both before and after adopting the new technologies. Previous work on heating practices has identified waste as one of the core elements of these practices (see Rubens, S. Knowles, 2013; or Mallaband & Lipson, 2020, for example). However, other than pointing out this need, the existing research has not explored the topic in detail and has not tried to study what minimising waste means in practice. Even the research on heat pumps or smart heat pumps has not systematically analysed the topic and often only provides partial accounts of how waste is understood in heating practices with these technologies by identifying specific situations that are seen as wasteful (e.g., heating at night). This chapter has tried to bridge this gap.

The findings suggest that the know-how for minimising waste in the context of heating practices is not static, and it changes over time. The existing know-how was developed as part of the heating practices with conventional technologies and it was linked to the specifics of these technologies. However, it was often not abandoned after installing the new technologies. This know-how was fundamental to maximising the efficiency of the practices with conventional technologies. However, it became obsolete as it conflicts with the efficient operation of the new technologies. While some authors like Shove (2003) have shown how meanings and competences co-evolve with the technologies, in some of the cases observed, that was not immediate. The non-evolution of this know-how affected the capacity of the smart heating controls to minimise the running costs of the system. Therefore, while the concern in Shove's (2003) case has been in how the evolution of these practices might lock people into resource-intensive practices, the concern behind the analysis presented is the need to develop new know-how more suited to the characteristics of the new technologies.

The evolution of heating practices has implied a distancing and decontextualization between everyday actions and waste, as Petersen (2008) has also pointed out. The data presented here shows that what people experience as wasteful or not often does not have to do with the energy used or the cost incurred, or at least not with the "real" amount of energy billed. While minimising waste is essential to heating practices, waste is not visible or tangible for householders. Therefore, they rely on feedback on costs or expectations for the "correct" operation of the technology to monitor it. The research has identified some of the consequences of monitoring waste in these ways.

Energy costs (bills or the smart meter display) were found to be one of the main sources of feedback on waste and had an important role in how heating practices evolved after the adoption of the new technology. This is not new, as several academics have already discussed the importance of information on costs or energy usage in the context of smart metering (see Darby, 2006). However, the analysis suggests that the understanding of these costs (whether the heating costs with the new technologies are seen as high or low) is largely based on expectations, which is consistent with some cases analysed by Lowe et al. (2017a). This is because it is very difficult for householders to calculate the changes in costs resulting from changes in heating (e.g., installing a new heating system). As other authors have also pointed out (e.g., Energy Technologies Institute, 2018), other factors might affect these changes, such as changes in energy prices, changes in the fuels used, etc. Despite the fact that these calculations are often not accurate, they are still used to inform the heating practices regarding waste and shape the experience with the system.

As explained before, waste is also assessed through heating running patterns. The findings of this research suggest that certain heating patterns or indoor conditions are understood as wasteful: heating when nobody can directly benefit from the heating, heating above the setpoint temperature, and heating discontinuously (constantly starting and stopping). Echoing Douglas's (2003) famous definition of dirt as "matter out of place", waste in the context of heating practices is heat out of place. However, what it means to be out of place is not always the same. The expectations for these heating patterns are shaped by the characteristics of conventional heating technologies: high heat output, high flow temperature (quick response) and the option to control the heating running times. However, due to the different characteristics of the new technologies, those heating running patterns understood as wasteful are often an efficient way to operate the new system. Despite that, they are still unaccepted by some of the householders. Some of these "wasteful" operative heating patterns have previously been identified in the literature on heat pump field trials and analysis of heating controls. For example, various authors have explained that heating at night (Boait, Fan & Stafford, 2011; Caird, Roy & Potter, 2012; Sweetnam *et al.*, 2019; Hanmer, 2020) or heating all day (Caird, Roy & Potter, 2012; Owen, Mitchell & Unsworth, 2013; Judson *et al.*, 2015) is often understood as wasteful and that people try to avoid these patterns as part of heating practices (Oikonomou, 2022). That contrasts with Rubens and Knowles (2013), who reported that participants were more dubious about the implications of how the system operates regarding waste. However, the novelty of the present research is in the identification of certain operative heating patterns as the core element of the know-how for minimising waste. Minimising waste involves monitoring and controlling the heating running patterns to ensure that the system does not heat when nobody can directly benefit from the heating, heat above the temperature setpoint or heat discontinuously. The findings are consistent Royston's (2014) who pointed out the importance of senses in minimising waste.

The research shows that the new technology tested does not automate the actions that householders already do to minimise waste. The smart heating controls introduce new heating running patterns that have to be accepted and the control of the heating system activity has to be delegated to the new controls for the algorithm to be able to achieve the lowest running costs. New practices are required more aligned with the characteristics of the new technologies, a point consistent with the work done by Judson et al. (2015). However, the adaptation of these practices is often more complex than usually acknowledged (for example, in the documentation provided as part of the project). Some of the new heating running patterns, such as the continuous operation of the system, might be counterintuitive, as pointed out by Oikonomou (2022). This is likely to be because some of the know-how associated with reducing heating waste might be shared with other domestic practices at home. For example, reducing the running time to reduce costs or waste is also part of daily practices involving most domestic appliances, such as cooking with a hob. For example, Anderson and White (2009) found turning the appliance off or using it less to be two of the most common actions taken to reduce energy use.

6.8.2. Trajectories of the heating practices regarding waste after adopting the novel technologies

The analysis presented in this chapter has observed different performances of heating practices with the new heating technologies and grouped them, to identify different trajectories for these practices. The simultaneous existence of a wide range of performances involving old and new elements of the practice is critical for the transformation of practices-as-entities, as has already been pointed out by Shove and Pantzar (2007).

The trajectories

Three trajectories for heating practices with the new technologies have been identified, which have been called: *Delegation*, *Management*, and *Supervision*. They show differences in the understandings of waste and the know-how for operating the controls.

Delegation

This performance is well aligned with the characteristics of the new technologies as it helps the algorithm to run the heating system with lower costs. It involves mostly delegating the control of the heating running times to the smart heating controls combined with a low number of manual un-scheduled changes of the temperature setpoint, as summarised in Figure 6.2. Delegating control over heating system activity requires trusting the algorithm to minimise waste and accepting the heating running patterns chosen by the smart controls (there is no need to monitor them). The observed practices in CH1 are clear examples of this performance because the householders did not override the temperature schedule often and they were not concerned about the heating running times.

The performance described encapsulates the idea of people as passive recipients of automated energy services, which is common among smart technological utopian visions (Strengers, 2013). This vision has been frequently criticised for not accounting for the complexity of everyday life and the often non-rational process of decision-making. However, the research reported here found this type of performance to be common. Therefore, while the vision portrayed should not be taken for granted, it successfully represents some of the practices developed after the adoption of the technologies. It is important to point out that this performance is sometimes not immediately adopted, and householders might require external help to adapt their practices.

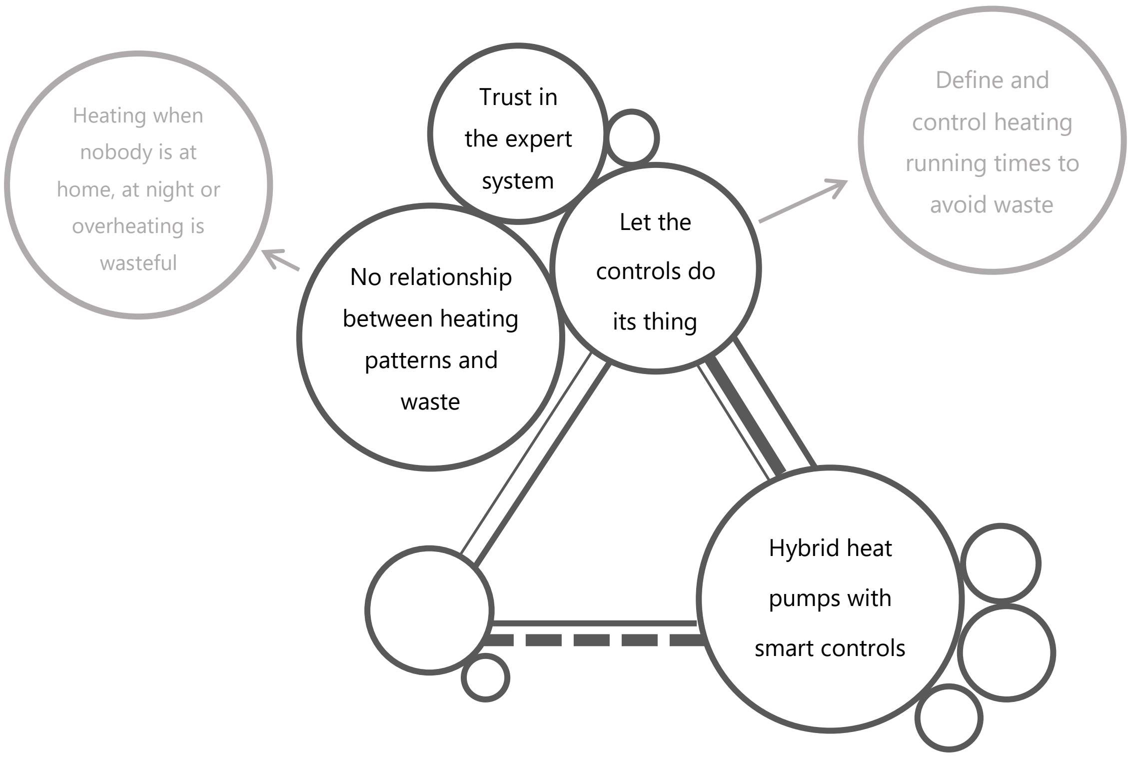

Figure 6.4. Delegation: Main elements related to waste in heating practices with hybrid heat pumps with smart heating controls
Adapted from Kuijer (2014b).

Management

This performance is characterised by the conservation of the know-how for minimising waste common in heating practices with conventional technologies. This know-how has to do with expectations for the heating operation: heating only when heat can be enjoyed directly (e.g., not at night or when nobody is at home), heating only when the temperature is below the setpoint, or not heating discontinuously (stopping and resuming the heating operation in short periods). It also involves monitoring the heating operation and, in some cases, forcing the heating system into certain heating patterns. The common elements in this performance are summarised in Figure 6.4. Both the expectations of the heating system activity and the control of the heating running times seem to be retained from heating practices with conventional heating systems. Often, householders do not seem to trust the expert systems (the new technologies and the associated systems of provision), which explains why they do not delegate control of the heating times. The heating practices observed in CH3 or H3 (second half of the winter) are well aligned with the practices described here. In those cases, householders were concerned about how wasteful the system was and forced it into certain heating running patterns to minimise waste.

This performance is also compatible with some of the findings of the existing field trials of heat pumps and heat pumps with smart heating controls, which have described conflicts with certain heating patterns (e.g., Hanmer, 2020; Oikonomou, 2022).

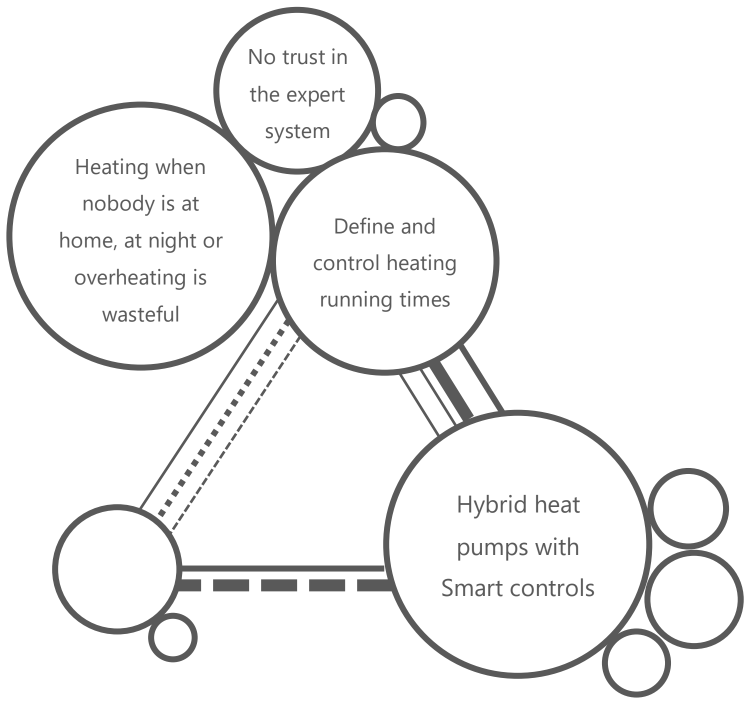

Figure 6.5. Management: Main elements related to waste in heating practices with hybrid heat pumps with smart heating controls
Adapted from Kuijer (2014b).

Supervision

In between the two variations previously described, a third performance was observed. It involves accepting the new heating running patterns of the hybrid heat pump: the lower flow temperatures and the need to heat for longer, which involves pre-heating well in advance or heating continuously. However, the householders still monitor the heating operation and have clear expectations for it. There is often no delegation of control over the heating operation to the smart heating controls. Instead, the householders might force the system to operate in certain ways, which are understood as less wasteful. The automation of the heating operation is not accepted. The expectations for the heating times sometimes involve reducing the heat pump's operation or vice versa. This performance was mainly observed in the analysis of the communications with the customer service team. There is no reference to this type of performance in the literature on smart heat pumps reviewed.

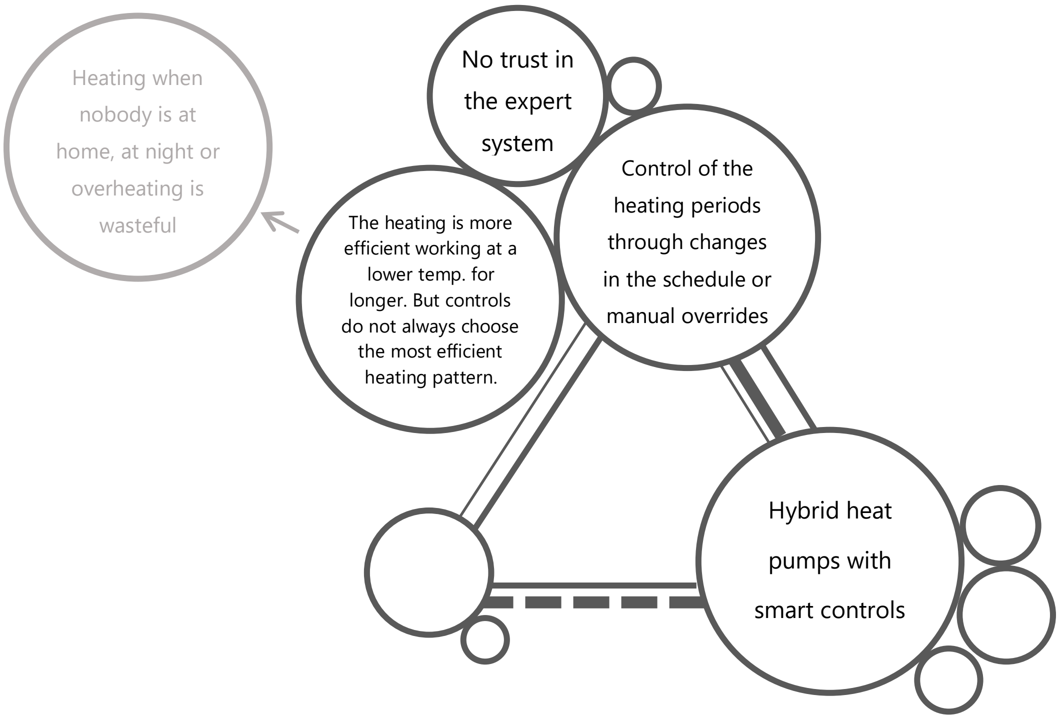

Figure 6.6. Supervision: Main elements related to waste in heating practices with hybrid heat pumps with smart heating controls.
Adapted from Kuijer (2014b).

The triggers

The trajectories previously described should not be seen as definitive or static. Heating practices, like any other social practice, are constantly evolving (Shove, Pantzar & Watson, 2012). Therefore, it is important to understand what drives these changes. Academics within the SPT tradition have argued that monitoring usually plays a key role in the reproduction and change of social practices: feedback on the outcomes of past performances could feed forward into the subsequent performances of the practice (Shove, Pantzar & Watson, 2012). This is consistent with the findings of this research.

This research has highlighted the important role of certain types of feedback in retaining know-how for minimising waste from heating practices with conventional heating technologies. Those were energy data and heating running patterns. Regarding the first, the findings of this research show that, in many cases, energy data is often misinterpreted and contributes to maintaining heating practices that do not help the smart heating controls to run the system with the lowest costs. That contrasts with previous research, which has seen energy feedback as an opportunity to help householders lowering their environmental impact (e.g., Fischer, 2008). Only in two cases did feedback on energy costs help the participants delegate the control of the heating system to the smart heating controls. In one case, that might be due to the participant's (Richard) previous interest in energy-related matters and the fact that he installed his own energy monitoring devices. On the other, Simon, the feedback was provided by a third party not involved in the project, and it offered information on household energy use in comparison to other similar properties. In addition to energy data, the feedback on the heating operation proved to be a critical part of the know-how for minimising waste with conventional heating technologies, and it did not help householders adopt heating practices that are more aligned with the new technologies.

In contrast, the feedback provided by the customer service team regarding the previous performances of the practice (e.g., a high number of manual overrides) and the "right" performance were helpful for adopting new practices. The finding is consistent with the work done by Consumer Focus (2012), which has pointed out that while installation is the natural point for providing advice, the feedback and information provided after installation might be more useful in triggering changes in the practice. However, that did not always work in the expected direction as the information provided sometimes created new expectations for the operation of the heating system that reduced its operating efficiency, a finding that echoes Parrish et al. (2021). These findings highlight that the conventional feedback mechanisms (energy data and heating patterns) may not be useful for triggering the adoption of new practices and that external help might be needed.

6.8.3. The role of trust

The analysis of trust in the context of the energy transition has often focused on exploring people's trust in different issues related to the energy system, such as trust in specific actors, like energy researchers or organisations (e.g., Greenberg, 2014; Stenner *et al.*, 2017; Sovacool *et al.*, 2021), climate science (e.g., Rayner, 2010), etc. Following the approach developed by Giddens (1990), the research presented here has analysed trust in the new technologies and their systems of provision as *expert systems*.

Trusting the heating system was found to be critical for the adoption of heating practices more aligned with the characteristics of the new heating technologies in the absence of transparency in the operation of the heating system and the process of decision-making of the controlling algorithm. As the new technologies redesign the existing relationship between the operating patterns and waste, trust in the heating system should replace the existing know-how of monitoring and minimising waste so that the smart heating controls can run the system with the lowest costs. The need to let the system do its thing with almost no householder interaction requires trust that the heating system would provide the expected outcome, as several researchers have pointed out before (e.g., Rubens, S. Knowles, 2013; Verkade & Höffken, 2018). However, while Giddens explained that trust is "usually routinely incorporated into the continuity of day-to-day activities" (Giddens, 1990:p.104), this is not the case in new heating practices with the tested heating technologies. The previous practices with conventional technologies do not require trust to minimise waste. Instead, some sorts of feedback, particularly the heating operation of the system monitored through noise, make it almost visible. This is not the case with the new technologies. The findings are consistent with Strengers (2013), who highlighted the importance of embodied sensory feedback (e.g., monitoring the operation of the heating system) in heating practices.

The absence of trust in the heating system could explain some of the heating practices observed (e.g., CH3) and why some householders requested the system be removed at the end of the trial (e.g., CH2). The three trajectories of waste previously described are also partly determined by the participants' trust in the heating system as an expert system. Those who did not trust the new heating technologies might be less likely to delegate the control of the heating patterns to the smart controls.

Four factors were found to play a critical role in the process of trust-building: the fact that the project was presented as a trial of the technology, the misalignment between householders' needs and the algorithm objectives, the failures of the system and the experience at access points, particularly the experience with the installation and the communications with the customer service team. Other authors have previously identified some of these processes. For example, Smale et al. (2019) noticed that as the objectives of the smart grid technologies did not connect to the meanings associated with the practice of heating, the trust in the expert system started to break down. However, while they see this experience as part of a process of building trust, in this case, it was the opposite: the bad experience of a group of participants in the installation critically affected their trust in the system to achieve their needs. The importance of the installation experience has also been pointed out by Gram-Hanssen et al. (2017), Owen et al. (2013), Judson et al. (2015) and Smale et al. (2019) as a critical determinant of trust in the system.

6.9. In conclusion

The findings presented in this chapter suggest that minimising waste is an important part of heating practices before and after the adoption of the technology. However, the existing know-how for minimising waste involves monitoring the heating system activity. With the adoption of the new technologies, this activity changes, generating conflicts that often involve retaining control of the heating running times. This Chapter and the previous

Chapters 4 and 5 have reviewed two of the main themes that arose from the analysis of the social data and have contributed to better understand the heating practices with the new technologies. The next Chapter 7 discusses the main findings presented in these three chapters in an integrated way. And it does that by drawing on some of the literature on the topic.

7. Global discussion

This chapter takes a step back to look at and discuss the findings of the three empirical chapters in an integrated way and in relation to the literature. It discusses the limitations of the research as well as how generalisable the findings are for homes with stand-alone heat pumps, either with or without smart heating controls.

The chapter is divided into three parts. First, the findings of the heating practices with the new technology are discussed in relation to the literature. Second, the limitations of the research are presented to help better understand its boundaries. Finally, the applicability of the findings beyond the specific technologies tested in this research is discussed.

7.1. Heating practices with the new technologies

The findings of this research suggest that the new heating technologies cannot remain invisible and simply replace current systems with minimal disruption. In line with what Wilhite (2008) explained, heat pumps with smart heating controls are not “silver bullets” that are able to penetrate everyday practices, bringing efficiency improvements and providing grid services without having any subsidiary effects on these practices. Instead, this research has shown that changes to indoor conditions and the heating system's operation can sometimes conflict with the existing heating practices and trigger changes in their performance. This thesis has analysed some of these changes, focusing on the issues of comfort and waste. That does not mean that those are all the changes in the heating practices after the adoption of the technology. Or that the only changes arise from alterations in the indoor conditions and the heating operation. While the issues studied were the most prominent themes in the interview data, the sample recruited and the approach chosen (Social Practice Theory - SPT) would naturally have an impact on the results.

The findings of the previous chapters suggest that some of the changes in the indoor conditions and the heating operation are noticed, and others are not. If noticed, some of these changes are accepted and incorporated into the practices, and others are rejected, triggering the adoption of certain actions to re-establish the old conditions. An integrative analysis of the findings brings some clarity to the determinants of these trajectories. Therefore, in the next subsections, some of the high-level findings of the research are presented, analysing why some changes are noticed, how some of them are accepted and why some of them are rejected and identifying the trajectories of the practice after the adoption of the new technologies.

7.1.1. Noticing the changes beyond nuisances

Previous research on heat pumps or hybrid heat pumps with smart heating controls has identified some of the changes in indoor conditions and the heating operation that are intrinsic to the efficient operation of this technology in contrast to a conventional boiler. However, too much emphasis has been put on those changes that generate conflict or complaints from the householders and affect their comfort: the temperature at night or the noise of the heat pump (e.g., Fell, 2016; Sweetnam *et al.*, 2019; Hanmer, 2020; Parrish, Hielscher & Foxon, 2021). This research takes a step forward and has mapped all the different ways in which the technologies, if operated as expected, might change the indoor conditions and the heating system's operation compared with a conventional boiler. It has also measured some of these changes.

This research highlights that acknowledging the changes beyond comfort nuisances is particularly important for two reasons. Firstly, it helps to create positive stories for the technologies tested. As the research has shown, some of the changes are positively experienced. These experiences can be used to create new narratives that appeal to a wider population and that make the low-carbon future desirable and the change acceptable, as

Howarth (2017) has previously suggested. Developing these new narratives could help to improve the uptake of the technology. For example, the constant heat and the lack of peaks and drops can be very appealing to people who spend a lot of time at home, such as householders working from home or the elderly, or groups more sensitive to temperature changes, such as women, as Crawley et al. (2023) suggested.

Secondly, this research suggests that changes in the characteristics of indoor conditions and heating system activity have an impact on heating practices beyond comfort. Some of the parameters studied are critical in the provision of feedback on the previous performance of heating practice. Despite the existing focus on externally provided energy feedback, embodied sensory feedback plays a critical role in heating practices (Royston, 2014; Madsen & Gram-Hanssen, 2017; Martin & Larsen, 2024). Therefore, the changes, even when not negatively experienced from the point of view of comfort, can affect the practices that rely on this feedback. For example, increases in heating times conflicted with the householder's expectations for the heating operation and were experienced as wasteful. The findings contrast with the existing social research on heat pumps reviewed in Chapter 2, which has often focused on understanding the satisfaction of the householders with the technology and the factors affecting it (e.g., Caird, Roy & Potter, 2012). While this is indubitably important, it overlooks some effects that the adoption of the technologies has, and that affects how they are used and experienced.

However, not all the changes in the indoor conditions and the heating operation are noticed by the householders. Several factors make some changes more noticeable than others. The physical characteristics of the building and the location of the new heating system were two of these factors. The most obvious example of that is the noise of the system. When the heat pump was installed outdoors or in a well-insulated room, its noise was not noticeable. That affected the comfort of the householders. But, because the noise of the system is one of the mechanisms that people have to monitor the operation of the heat pump, it also affected their understanding of the heating running times. Those are issues that might seem obvious but have been overlooked by most of the technical field research on the topic, which has been more concerned with measuring the technical performance of the system or specific operational issues such as defrosting (see Carroll, Chesser & Lyons, 2020) than measuring the parameters that more likely affect the experience of householders (with the only exception of the limited literature on noise and heat pumps (e.g., Torjussen *et al.*, 2023; DESNZ, 2023b).

Additionally, whether or not changes are noticed was also affected by the householders' heating practices with their previous technology and the rest of their practices at home. For example, changes in the temperature pattern indoors were affected by how the previous system was operated. It was found that those householders who operated the system manually (on-off control) were used to large temperature oscillations, and the reduction in the temperature oscillation after the adoption of the new technologies was more noticeable. Previous research on heat pumps has emphasised how the experience with legacy systems affects whether or not the changes once the new technologies are installed are acceptable or the way heating practices with the new technology are performed (e.g., Judson *et al.*, 2015; Owen, Mitchell & Unsworth, 2013). However, this study also found that whether those changes were noticed or not was also affected by the existing practices.

The result of this analysis reinforces the idea previously suggested by authors like Judson et al. (2015) that the new technologies do not simply recreate the indoor conditions that householders used to achieve. They create a completely new situation. It is unlikely that some of these changes generate complaints from the householders (as this and none of the previous studies have identified them). However, acknowledging that there are changes beyond "nuisances" should help to understand how heating practices evolve after the adoption of the technology. Additionally, the findings suggest that it is possible to adapt to some of the changes that the technologies bring, which leaves us with a question: why are some changes easier to accept than others?

7.1.2. Accepting the changes: the importance of practices

The changes intrinsic to the "expected" operation of the new technologies (a low number of manual overrides to the scheduled temperatures) are sometimes described as disruptive and unpleasant, and at other times as smooth and pleasant. For example, noise at night, as several authors have already pointed out (e.g., Sweetnam *et al.*, 2019), is seen as a downside of the technology, while the constant warmth (the lack of peaks and drops) is often seen as very pleasant. Behavioural approaches to the topic, such as psychology or human-computer interaction, would focus on the individual and cognitive differences explaining these trajectories: the values and attitudes driving the behaviours individuals choose to adopt. Therefore, the preference for certain conditions and not others would be the result of cognitive processes, which could potentially be changed, for example, by appealing to the environmental benefits associated with those changes. However, sociologists such as Shove (2010) note that these approaches fall short of accounting for the social dimension of heating at home and the importance of these elements in the idea of heating.

The analysis found that the conflicts arising from the installation of the new technologies mainly result from a clash between the elements associated with heating practices (meanings, competences and materials) and the new indoor conditions and heating operation. For example, maintaining a cool bedroom is one of the expectations associated with heating practices and the overnight running of the heat pump conflicted with that. In contrast, the absent role that some of the changes played in heating practices, could explain the rapid acceptance of some of the differences between the old and the new heating technologies. Therefore, it is not a matter of the householders' willingness to tolerate the changes but of how well the changes dovetail with householders' existing practices. The findings of the research also point out that the difficulties in adopting or abandoning some of the elements of the practice might be influenced by the role of these elements in other practices. So, those elements that are shared with other practices, such as the know-how for minimising waste (e.g., the idea that if you operate an energy-consuming appliance longer, that will increase costs), are difficult to abandon. In contrast, those that are already part of other practices merge and are easier to adopt. For example, the constant temperature (without peaks and drops) in offices or public buildings circulates and converges in domestic heating practices with the new technologies

The work by Kuijer (2014a) provides some theoretical foundations to better explain this. In her analysis of the differences between practices-as-entities and practices-as-performances, Kuijer differentiates between more and less "essential" elements in a practice. Those elements (meanings, competences or materials) that occur in many or all the performances of the practice constitute the core of the practice-as-entity. In this case, some elements associated with indoor conditions or heating patterns were found to be more "essential" than others. In those cases in which the outcomes of the new technologies challenged those core elements, conflict arose. This is the case of noise, night temperature, or specific heating running patterns. In cases where the new outcomes of the heating system were not associated with the existing practices or were less "essential", the new conditions were rapidly accepted, or the conflicts only arose in very small number of cases. For example, this is the case of the lack of peaks and drops in temperature during warmth-requested periods. As having big temperature oscillations was not an "essential" part of domestic heating practices, the more constant temperatures were very welcomed.

While the specific expectations for heating operation and indoor conditions have already been discussed in Chapters 5 and 6, respectively, it is important to point out that these expectations are often the result of the evolution of heating practices, often together with the adoption of certain technologies, as Shove (2003) pointed out more than twenty years ago. For example, monitoring heating patterns described in Chapter 6 is useful to maximise the efficiency of a gas boiler and minimise waste. The technology and the meanings associated with the operation of the heating system and the indoor conditions evolve together. That does not mean that the adoption of the new technologies incorporates these changes, although academics in the STS tradition might suggest that it is sometimes the case (e.g., Akrich, 1992). Instead, it means that in order to be successfully adopted, it is not enough to install the technology; the heating practices might need to evolve and incorporate all the required elements.

7.1.3. Rejecting the changes: taking control

The adoption of the technologies was not always accompanied by a change in the heating practices to accommodate the new indoor conditions and heating patterns. Often, householders did not accept these changes. As explained before, the new heating system algorithm optimises for various factors (costs, carbon, or maximising the operation of the HP). For the new heating system to optimise for these factors, the system requires almost complete delegation of heating management from households to the controls and trust that the system is going to provide the expected outcome: set and forget. However, in some cases, householders did not delegate the control of the system to the heating controls. Instead, they forced the heating system into specific heating patterns to achieve the expected outcome.

The issue of control has been studied in the demand response and smart heating controls literature previously (e.g., Fell, 2016; Hargreaves *et al.*, 2015; Jensen, Kjeldskov & Skov, 2018). Hargreaves et al. (2016) suggest that the existing studies had three distinct emphases: *artefactual*, *perceptual* and *relational*. Each of them puts the focus on a different aspect of control. The first focuses on technologies and how they are used. The second focuses on users and tries to understand how they experience control with the new technologies. The third focuses on how smart technologies interact with everyday life, activities and relationships. Hargreaves et al. (2016) explained that it is the interrelationship between the three that matters as they shape each other. In the cases analysed, all of them are the result of the heating practices.

Relational control

From a *relational* point of view, controlling the heating system is one of the resources that householders have to achieve the outcome they expect. The adoption of the new technologies aims to replace this know-how by delegating it to the controls and expect the householders to trust that the system is effectively providing what they want. However, that overlooks some of the pre-existing control relationships within homes, as Hargreaves et al. (2015) have pointed out. Davidoff et al. (2006) have identified one of these relationships:

householders want control of their lives, not control of the technology. In this thesis, two additional relationships have been studied: householders want control of comfort and control of waste, which match well with two of Fell's (2016) four motivations for control (service level -comfort-, timing of activity, spending and a general sense of autonomy).

The heating controls only allow householders to define minimum air temperatures. However, heating practices with conventional technologies do not only involve expectations for minimum air temperatures. The old heating controls were found to be critical in the provision of cold temperatures at night, radiant heat from the radiators, quiet environments, minimising overheating during shoulder season and minimising wasteful heating patterns. With the previous heating controls, householders could control these characteristics of the indoor conditions and the heating system activity. However, these other needs were often left off the picture and not automatised with the new smart controls. That resulted in conflicts, which ended with some householders retaining control of the heating system. More individualistic approaches to the topic, such as Fell (2016), suggest that behind the interest in controlling the system, there is information (or the lack of it), familiarity, predictability, trust and choice. However, the research found that this is better explained by the existence of heating practices that are not updated with the adoption of the new technologies. Therefore, householders did not want control per se. By controlling the heating system, they are trying to reproduce the old heating practices and restore the pre-existing control relationships.

Artefactual control

From an *artefactual* point of view, the findings of this research suggest that when facing an unaccepted outcome from the heating system, householders acted in two different ways. First, through changes that did not involve overriding the temperature schedule. For example, changes in parts of the practice that did not involve the controls (e.g., changes in clothing) or changes in the temperature schedule, such as scheduling temperatures that might be different to those that they want to achieve (e.g., lowering the temperature setpoint to delay the pre-heating) or setting schedules that do not correspond with the occupancy of the house (e.g., delaying the warmth-requested periods). Second, through manual in-the-moment changes in the temperature setpoint, overriding the temperature schedule and therefore retaining control of the heating operation.

Some of the actions observed suggest that the temperature setpoint is a complex and contested concept. Conventional thermostats or heating controls are not just used as air temperature controls. Regardless of whether they are designed for that or not, they often have other functions and are used, for example, as a switch. With conventional heating controls householders often only chose the air temperatures. However, that does not mean that they only care about air temperature. This is because, through the air temperature setpoints, they were able to change other characteristics of the indoor conditions and heating system activity, such as the times of operation of the heating system. However, these parameters remained out of their control with the new heating controls. Even when manually operating the new smart heating controls they were unable to modify some of them. For example, they were unable to define the maximum temperature (at night) or the heating times. These mismatches generate frustration and conflicts. As Hanmer (2020) explained, the new technologies disrupt some of the practical understandings related to how to operate the heating system.

It is sometimes difficult to combine technical and social data, in part because of the difference in the frequency of the data collected (technical data was collected every 5-minutes whereas social data was only collected twice during the whole heating season). However, the results of the analysis show that the times with a higher number of manual overrides match well with the times in which the householders reported trying to achieve an outcome different to that provided by the new technologies. In CH3 and CH5 that was during the whole heating season studied. In H2 and CH2, it was at the beginning of the heating season before speaking to the customer service team. In H3 and CH4 it was towards the end of the heating season. In most of the cases, except in CH4, the manual overrides of the temperature schedule had to do with conflicts related to noise or waste and not so much with thermal comfort. However, not all the manual changes in the temperature schedule can be explained by the findings of this research. It is likely that some of them respond to other needs, such an alteration in the routine or small comfort adjustments, but further research is needed. The impact of the householders' manual actions on the indoor conditions and the heating operation is difficult to assess, as it is influenced by a wide range of parameters, such as the thermal characteristics of the building, the sizing of the radiators, etc., that have not been analysed in this thesis.

Perceptual control

From a *perceptual* point of view, the research found that householders experienced a lack of control and frustration when the system did not provide the expected outcome (indoor conditions or heating system activity), and they were unable to achieve it. Two of the clearest examples are CH3 and CH7. The former reported not being able to minimise noise and achieve the expected heating patterns, which was frustrating. The latter was angry that they could not control noise at night with the new system. Those who achieved the expected indoor conditions and heating system activity felt in control, even when that involved manually controlling the heating system (e.g., CH4 during the second half of the winter). The findings are consistent with Jensen et al. (2016), who explained that despite being able to control comfort settings, the participants in their study felt disillusioned when the system did not act as they expected. Feeling out of control is not a result of a poor usability design of the controls but a disconnect between what householders expect in the context of heating practices and what the system is providing. The sense of autonomy is only a side effect of this conflict, and it is not relevant in itself.

7.1.4. Trajectories of the practice after adopting the new technologies

In their analysis of stand-alone heat pumps (without smart heating controls), Judson et al. (2015) have identified three paths that heating practices follow after adopting heat pumps (without smart heating controls). The first path is characterised by conflicts between the new technology and the existing practices, which can only be changed incrementally. The second path is characterised by resistance and alienation towards the new technology. The third path is characterised by a rapid reconfiguration of the household's heating practices to better integrate the heat pumps.

Although some of the elements that constitute these trajectories were also found here, the trajectories themselves are not consistent with the findings of this research. Firstly, in contrast to Judson et al. (2015), the findings of this research suggest that meanings associated with heating practices did not only change incrementally (to overcome what was experienced as a failure) in those cases in which conflict arose. While there are a few examples in the research reported here that support this idea (e.g., constant heat was very welcomed for those using on-off heating controls), this is not always the case. Defining what is an incremental change is subject to interpretation, and while it might explain some of the differences between households, it is not useful to explain the trajectories of the practice. Instead, as suggested before, the position of the changing parameter in relation to the practice (whether what changes is a core element of the practice or not) might better explain why some changes are accepted and others are not. Secondly, in none of the cases studied, were feelings of alienation towards the new technology observed. This happened despite the fact that the technology studied was more complex than the cases reported by Judson et al. (2015), as it was a hybrid system (not a stand-alone heat pump), and it incorporated smart heating controls. However, it is likely that the differences observed could be explained by the differences in the samples studied. Judson et al. (2015) mainly recruited elderly people living in social housing, who were forced to have the new technologies, while the participants in the research reported in this thesis were younger and volunteered to get the technology (early adopters). Third, the classification of the trajectories of the heating practices proposed by Judson et al. (2015) does not capture some of the differences in the practices observed in this research. In particular, it does not acknowledge variations in the *doings* of the householders, which are critical for the smart heating controls to forecast the heating demand and optimise the heating operation for costs or carbon.

To better acknowledge the findings of this research, this thesis suggests two alternative trajectories for the heating practices after adopting the new technologies: *keeping control*, and *delegation*. The differences between the two have to do with whether the householders retain control of the heating system or delegate it and trust that it will provide the expected outcome. In *keeping control*, householders maintain some of the existing meanings and know-how associated with heating practices with conventional technologies and force the system to recreate them. This trajectory encapsulates the two trajectories identified for waste-related heating practices (*Management* and *Supervision*). In *delegation*, the householders adopt new meanings and know-how that are more aligned with the operation of the new technologies and delegate the control of the heating operation to the new smart controls. This is similar to the third path described by Judson et al. (2015), in which the heating practices are reconfigured to integrate the new heating technologies better.

In addition to these two trajectories, in some instances it was possible to observe a third trajectory. It involved retaining some of the meanings and the know-how associated with heating practices with conventional technologies but still delegating control of the heating system to the smart controls. Examples of this trajectory are householders, such as those in H1, who raised concerns about the operation of the heating system but did not force the system to modify the heating patterns. Or the participants in H3, who missed the cosiness of a hot radiator but, instead of forcing the system to operate on boiler mode, used alternative strategies to provide it, such as using secondary heating devices. However, the evidence for this trajectory is the weaker of the three and further research might be needed to confirm the findings.

The research has shown that installers and the customer service team play a critical role in shaping these trajectories. The installers' lack of communication and the low quality of some of the installations were found to undermine the householders' trust in the system and not contribute to delegating control to the smart heating controls. The installers silence contrasts with previous research on heating installers (e.g., Gram-Hanssen *et al.*, 2017; Wade, Shipworth & Hitchings, 2017). In contrast, the CST plays a very active role in helping householders adopt practices that promote heating system efficiency (either minimising costs or environmental impact).

7.2. Limitations

As well as providing important insights, the research design naturally has some limitations. The main one arises from the collaboration with an industry partner. This had implications for the research design. The second most important limitations are due to the sample studied and to most of this research being carried out during the 2020-21 covid pandemic and the 2022 energy crisis.

Part sponsorship of this doctoral research by an industry partner, Passiv UK, provided a wide range of opportunities that would have been impossible without their support. Beyond the obvious financial support, the most significant benefits have been access to participants, supervisory support and more opportunities for the research to have an impact on industry. However, the collaboration has also affected the research in ways that have had an impact on the findings and should be acknowledged. Firstly, the research design was shaped by the opportunities offered by the industry sponsor. The analysis was mainly limited to studying householders, and it was not possible to pursue other interesting paths, such as observing the installation and handover process. Additionally, it was not possible to monitor the cases pre-installation, mainly because of the differences in the timelines between the industry and the academy, an issue that Strengers (2014) suggested is one of the challenges of industry collaboration in research. Secondly and most importantly, the collaboration with the industry sponsor affected the sample studied. Passiv UK was involved in the selection of the projects analysed. These projects only included hybrid heat pumps and, in one of the cases, a specific type of compact hybrid heat pump, which is not commonly found in the UK (the Murelle revolution 30 hybrid boiler). While that offered an opportunity to study an extreme and critical case (according to the criteria developed by Flyvbjerg (2006)), it makes it more difficult to generalise the results (as will be explored in section 7.3). For the same reason, only one type of smart heating controls was tested: the Passiv UK heating controls. Thus, it is possible that some of the findings might be different if different heating controls had been used. Some of the issues identified, particularly around the different understanding of the language of the app (IN, OUT, AWAY and ASLEEP), might not apply to other types of algorithmic controls.

In addition to the limitations arising from the research design chosen, it is also important to acknowledge some of the limitations of the sample studied. The participants in the compact hybrid project volunteered to participate and, as they got the technology for free, it is likely that their expectations for it were different to other groups of people. For example, they might be able to tolerate some changes that others would not, as two of the participants (Richard, Simon) suggested when discussing the limitations of the technologies. Additionally, the participants in the hybrid project were all off-gas grid and heated their homes with oil or LPG boilers, which involve heating practices different from those of gas boilers. For example, oil or LPG are more expensive than gas, which might have affected the householders' heating practices to minimise waste (e.g., they might be more concerned when the boiler run and not the HP). Also, the fact that all the householders owned the houses where they lived means that it is likely that they were more affluent than the average population, which might have affected their practices and concerns for minimising waste. Finally, as some of the technologies tested were new, they were more prone to technical problems. For example, all the households in the CRM dataset had contacted the customer service team at least once, mainly because they experienced technical problems. The participants in the compact hybrid also experienced technical issues, particularly in CH2, CH3 and CH4, mainly because of the low-quality installation done by the first group of contractors. As explained in Chapter 6, the experience with the installation can affect the householders' trust in the system, making them less likely to delegate the control of the heating system to the smart heating controls.

Other limitations arose from research design decisions taken to overcome some of the threats that the pandemic posed to the research. For example, the only environmental parameter monitored in the studied households was air temperature because this monitoring equipment was easy to install, essential given that householders were asked to put the equipment in place themselves. Although air temperature is one of the most relevant environmental parameters, it would have been useful to monitor other aspects of the indoor conditions, such as the radiant temperature and the vertical temperature gradients, and especially the noise of the system, as this proved to be a critical factor in the experiences of the householders.

Finally, as acknowledged in Chapter 6, the fact that part of the data was collected during the 2022 energy crisis might have affected the householders' experience of waste. However, as explained before, the participants only acknowledged changing their practices in a small number of cases as a result of this context. However, some of the changes might have remained unnoticed by the householders, or they might have decided not to share them with the researcher during the interviews.

7.3. Lessons applicable to other technologies

The technologies studied as part of this research are hybrid heat pumps with smart heating controls. The combination of the three technologies (conventional boiler, heat pump and smart heating controls) creates a level of complexity that is difficult to find in other simpler technologies like stand-alone heat pumps. While analysing such a complex case is useful, as it constitutes an extreme and critical case (according to the criteria developed by Flyvbjerg (2006)), it is unclear if and, if so how, the findings of this research could be generalised to other technologies. To discuss this, is it worth analysing the two main characteristics of the technologies separately: the change in the indoor conditions due to the specific characteristics of the heat pump system (e.g., low flow temperature) and the external control of the heating times through the smart heating controls.

As explained previously, heat pumps operate at lower flow temperatures and heat output than conventional boilers and require more time to provide the same indoor conditions. As a result, the indoor conditions and the heating operation when heating with these technologies might differ from those achieved with conventional heating systems. The research has found that these changes are sometimes noticed and trigger changes in heating practices. While the technologies studied were hybrid heat pumps, stand-alone heat pumps also operate under the same logic, and therefore, it is likely that the indoor conditions and the heating operation are similar to those measured in this research when the system operated in heat pump mode. That is especially the case for hybrid cases (not compact hybrids), in which the size of the heat pump is similar to that of a stand-alone heat pump and its noisy components are also located outdoors. Obviously, the boiler component of the system adds variability in the indoor conditions as sometimes the system will operate more similarly to a conventional boiler and other times more similarly to a heat pump. However, while that might create more confusion for householders, it is likely that some of the problems discussed as part of this research might also arise when using stand-alone heat pumps combined with smart heating controls. In fact, some of the findings of this research echo previous studies of stand-alone heat pumps, as pointed out before (e.g., overheating at night, noise, etc.).

The control of the heating system is the second issue that is worth analysing. As explained before, smart heating controls require householders to delegate the control of the heating operation and trust that it is providing what they want. In some cases, when the outcome of the heating system does not match the householders' expected outcome, that creates conflicts that usually end with householders retaining control of the heating system. The conflicts are likely to be specific to the technology controlled (hybrid heat pumps), although they might also occur with stand-alone heat pumps, as explained before. However, the difficulties arising from the need to delegate control of the technology and trust a system to provide the expected outcome are likely to apply to other technologies, too. The smart technologies aiming to automate domestic activities also require delegation of the control of the technology to some sort of smart control. Therefore, issues of trust or actions to try to retain control are likely to be found in trials of other smart technologies. Other findings, such as those specific to the heating controls tested, might not be generalisable to other heating control designs.

8. Conclusions

The previous chapters have presented the findings of this research and have discussed them in relation to the literature. To conclude this thesis, this chapter reviews the main findings of the research. First, it tries to answer the three research questions presented in Chapter 1 by summarising the findings presented in the previous chapters. Second, it discusses the contributions of the research for different knowledge areas.

8.1. Summary of the findings

At the beginning of this thesis, it was explained that the energy transition requires changes in how energy is used to cope with the variability of supply from renewable energy sources. The adoption of hybrid heat pumps with smart heating controls enables this. However, these technologies do not operate under the same logic as conventional boilers: they require different heating practices, and they provide different outcomes (indoor conditions and heating operation). This thesis has attempted to analyse the householders' experience with these new technologies and to study how heating practices evolved after their adoption.

From these starting points, I set the following research questions:

1. What are the indoor conditions and the heating patterns after the adoption of the new heating technologies?
2. How do people experience the indoor conditions and the heating patterns after the adoption of the new heating technologies?
3. How do heating practices evolve as a result of these experiences?

In the next subsections, the major findings of this thesis are reviewed to try to provide a summarised answer for each of these three research questions.

What are the indoor conditions and the heating patterns after the adoption of the new heating technologies?

Three variables relating to the heating operation were analysed: the flow temperature, the heat output and the heating duration. The average flow temperature of the new heating system was 45.6ºC and the average heat output when the heating was on was 5.7kW. In both cases there were important differences between cases and within cases. The differences within cases were mainly affected by the dominant heating mode: in boiler mode, the flow temperature was higher than in heat pump mode. The flow temperatures measured are, as was expected, lower than those usually found in combi boilers (60-88ºC according to Rossi and Bennett (2024)). That means that, despite the absence of pre-installation data, the flow temperature was likely reduced after installing the system. That also means that the temperature of the radiators in the cases studied was cooler than in most homes equipped with conventional boilers. This was confirmed by most householders in the interviews.

The average heating duration in the cases studied was 10.8 hours per day, which varied importantly across cases and within cases. The lack of studies in boiler-equipped homes using similar methods makes it difficult to confirm the exact changes in the heating duration. However, the most relevant differences between combi boilers and the new technologies studied, was the times when the heating was on. The study of the heating patterns showed that the heating system is either constantly on (hybrid cases) or heating outside the periods when heating is conventionally assumed to be on in BREDEM (Building Research Establishment Domestic Energy Model) (compact hybrid cases). The findings were also confirmed by the participants during the interviews who reported noticing that the heating was on during periods when they usually do not request warmth (at night or when outside the home).

Three parameters relating to the indoor conditions were measured: the temperature oscillation when warmth was requested (evening), the temperature drop during periods in which warmth was not requested (at night) and the temperature differences across rooms. The average standard deviation of the temperature in the evening was found to be below 0.5ºC in all the cases. However, it was impossible to compare the calculated value with the temperature oscillation in boiler-heated buildings due to the lack of literature on the topic. The results of the analysis of the correlation between the heating duration and the temperature oscillation did not provide robust results. However, in most of the cases studied, householders confirmed that they noticed fewer peaks and drops when heating with the new technologies in contrast with their old boilers.

The mean temperature drop from 8pm to 4am was 1.2ºC (0.14ºC/h), with important differences between cases and within cases. In most of the homes, the average drop was smaller than that measured in buildings with combi boilers. The findings of the analysis suggest that the heating duration might be one of the factors affecting that. The results are consistent with the analysis of the technical data: most householders noticed that after the adoption of the new technologies, the temperatures dropped less, particularly at night.

The average standard deviation of the temperatures across rooms was 0.94ºC, and the results were similar across cases. It was not possible to determine, using the available technical data, if there was a change in this characteristic of the indoor conditions after the adoption of the new technology. The social data was also not useful to understand this topic: most of the interviewees did not comment on it and there was no agreement on the direction of the changes among those who discussed it.

Overall, some of the characteristics of the indoor conditions and the heating operation changed with the adoption of the new heating technologies, usually following the expected trajectories. However, the small sample and the wide range of factors affecting each of the indicators (in particular, the variability introduced by the smart heating controls) made it difficult to draw relevant conclusions from the technical data regarding the change. Further research with pre-installation and post-installation data might be needed to confirm the results of the analysis.

How do people experience the indoor conditions and the heating patterns after the adoption of the new heating technologies?

The findings of this study suggest that the changes in the indoor conditions and the heating operation after the adoption of the new technologies were noticed by householders.

Regarding the parameters related to the indoor conditions, householders noticed that the radiators were cooler than before, that the warmth provided by the heating system was different, that some rooms overheated during the shoulder season, and that there was more noise from the heating system. Regarding the change in the warmth provided, householders mentioned noticing that the temperature was more constant (fewer peaks and drops) and that it was warm outside warmth-requested periods, particularly at night and during working hours (when it used to be cool when using the old heating system with standard controls set to not heat during working hours). The noise of the heating system was mainly driven by the heat pump's compressor and fan; it varied a lot depending on their position within the house. In those cases in which those two components were located outdoors or in a well-insulated room, the noise was less noticeable. Regarding the parameters related to the heating operation, householders noticed that the heating system was operating for longer periods and outside the times when they requested heat. Additionally, they also noticed that the heating was operating when the temperature setpoint had already been achieved.

While some of these changes were positively experienced and rapidly accepted, others generated conflict and were seen as downsides of the technology. Among the changes noticed, the constant warmth during the warmth-requested hours was appreciated, particularly by householders who used to operate the heating system manually and whose temperature in the building used to constantly fluctuate. The lower temperature of the radiators was valued by some, as was the higher daytime temperatures outside warmth-requested periods for those working from home. However, some of the changes were negatively experienced. Those were the ones usually reported to the customer service team. They had to do with the heating system activity and the indoor conditions. Regarding the first, householders complained about (1) heating outside heat requested periods, (2) heating above the temperature setpoint or (3) noticing the boiler or the HP running too often. Regarding the second, householders complained about (1) the increase in temperature outside warmth-requested periods (usually at night) and (2) the noise of the system

This research brought some light into why some of the changes are experienced positively and others are not. The findings suggest that the essential role of some of these changes in heating practices or other social practices is what defined whether the change was acceptable or not. In those cases in which the parameter was linked to the meanings of the practice or its know-how, there was more reticence to the change, and it was often unwelcome. For example, heating duration was used to provide critical feedback on waste. Therefore, the increase in the heating duration was seen as wasteful, and some householders tried to oppose to that change by controlling the heating running times manually (manual un-scheduled changes in the temperature setpoint). Additionally, maintaining a cool and quiet environment at night seems to be an important part of heating practices (which might be affected by some physiological factors), which was disrupted by the adoption of the new technologies. In contrast, when there was no particular meaning associated with a parameter that changed, those changes were rapidly accepted. For example, the reduction in the temperature oscillation during warmth-requested periods and the constant warmth provided by the new technologies were very welcomed.

That does not mean that the responses were unanimous. Participants' performances of these practices varied, being affected by many additional factors, such as the thermal characteristics of the building, the position of the heat pump in the building, and heating practices prior to the adoption of the new technologies.

How do heating practices evolve as a result of these experiences?

For the new heating technologies to maximise the efficiency of the system (in economic or environmental terms), a specific set of practices is required. Those involve delegating the control of the heating system to the smart heating controls, trusting that it will provide what the householder wants and accepting the previously mentioned changes in the indoor conditions and the heating operation. However, the research found that the adoption of the new technologies did not always transform the practices in that direction. The non-adoption of the expected heating practices can have an effect on the efficiency of the system and its capacity to forecast the heating demand, which is critical if grid services need to be provided.

The smart heating controls ask householders to provide a minimum temperature setpoint for each time of the day, and then optimise the operation of the heating system to provide these thermo-temporal conditions while minimising costs or carbon. By doing that, they aim to provide the same level of service as before and improve the efficiency of the process. With conventional heating controls, householders usually control many aspects of the heating system activity and indoor conditions indirectly using the temperature setpoint (e.g., the operation of the heating system, the maximum temperature achieved, the temperature of the radiators). The temperature schedule that householders communicate to the smart heating controls cannot capture some of these requirements. Therefore, the algorithm does not take them into account when calculating the optimal heating pattern, and the outcome of the optimisation sometimes conflicts with the existing heating practices.

When those conflicts arise, householders sometimes try to retain control of the heating system. That is often done by manually overriding the temperature schedule. The analysis of the number of manual overrides for the cases studied showed a clear link between the periods in which householders reported trying to force the system to provide the certain outcomes and those times with higher number of interactions per month. That usually happened during periods with more than 40-45% of the days per month with manual changes in the temperature schedule. However, manually overriding the temperature schedule was not the only strategy used to achieve the expected outcome. Other actions were also observed that involved changes not directly related to the heating system, such as wearing additional clothes or using secondary heating devices, or changes in the temperature schedule, such as delaying the warmth-requested periods or lowering the temperature setpoint. Manual overrides were particularly common for controlling waste and noise.

Two trajectories for the heating practices were identified: *Keeping control* and *Delegation*. The first is characterised by not adopting new meanings of comfort or know-how for reducing waste and retaining control of the heating system through manually overriding the temperature schedule. The second is characterised by delegating the control of the heating system to the smart heating controls and transforming heating practices to better integrate the new technologies (e.g., accepting new indoor conditions). The findings of this research suggest that some stakeholders might play an important role in these trajectories. In particular, interaction with installers and the installation process could result in householders not trusting their new heating system; this difficulted delegating control. In contrast, the customer service team usually played a critical role where expected heating practices were adopted.

8.2. Contributions of the research and recommendations for future work

This research has contributed to a better understanding of the heating practices with hybrid heat pumps with smart heating controls. In this section, these contributions are presented. First, by focusing on interdisciplinary themes and ideas. Second, by exploring the specific contributions to the fields of research, policy and technology and identifying potential areas for future work.

8.2.1. Core contributions

The findings, as summarised in the previous section 8.1, have brought light to the householders' expectations of indoor conditions when using the new heating technologies in domestic environments and the existing competences associated with heating practices. However, the findings not only contributed to a better understanding of heating practices with the new technologies but also to explore heating with conventional technologies. This is because while the participants lived in houses equipped with hybrid heat pumps with smart heating controls, this thesis found that their heating practices are partly retained from heating with conventional heating technologies. Therefore, exploring heating practices with the new technologies contributes to better understand heating practices with the old technologies. At the same time, as explained in section 7.3, some of the findings of the research might also apply to heating with other technologies or to other domestic practices.

Technology substitution is not enough

The research suggests that comfort expectations associated with heating practices go beyond minimum air temperatures, and include issues like the maximum air temperatures at night, the noise of the system, the temperature oscillation, etc. The adoption of the new technologies made some of these expectations emerge and become evident as a result of the mismatch between the expected outcome of the heating system and the provided indoor conditions. Some of these expectations match the characteristics of the previous heating technologies (combi gas boiler) and, therefore, this research shows the importance of the links between the elements that constitute domestic practices: the meanings, competences and technologies evolve all together. Conflicts arise when one of the elements changes without changes in the other.

These findings contributes to challenging one of the central assumptions embedded in the design of smart heating controls: householders are not only concerned about minimum air temperatures. Even if the same values for this parameter are achieved before and after installing the system, conflicts arise, and householders might experience discomfort. This is because there is a wide range of expectations linked to the indoor conditions that are relevant in the context of heating practices, which are not achieved after the adoption of the new technologies and cannot be communicated effectively using the smart controls.

The findings show that, contrary to what the calm technology approach suggests (see Weiser & Brown, 1996), making new technologies invisibly substitute existing systems might not always be feasible. This is because it is almost impossible to take into account the complexity of the existing practices and the differences between heating technologies. The design of the new technologies is often based on simplified assumptions about these practices and the process of installing and adopting the new technologies often does not consider this limitation. Therefore, the author suggests that instead of invisibilising the technology change (e.g., treating heat pumps as boiler replacements), it might be more successful to acknowledge and value the differences and help householders to transform their heating practices accordingly (section 8.2.4 includes some suggestions to do that). This situation is also found when adopting other smart grid and smart home technologies, as other researchers have pointed out (see Verkade & Höffken, 2018) and section 7.3 shows.

Escalating expectations

However, not all the changes in the indoor conditions after the adoption of the new technologies conflicted with the existing expectations. The research suggests that, in some cases, the new indoor conditions were rapidly accepted and incorporated into heating practices. Often, those new conditions represented higher levels of comfort compared to those achieved with the previous heating technologies. For example, the new smart controls ensure that the temperature setpoint is always achieved, which does not always happen with combi boilers (see Bennett & Elwell, 2020), or contributed to extending the number of heated hours.

The adoption and normalisation of these new indoor conditions might contribute to escalate the expectations for domestic environments. Often, this process of escalation does not increase the total energy used and in fact, when it helps the heat pump improve its COP, it reduces it (as it was explained in section 2.2). However, it conflicts with the idea of energy sufficiency (see Fawcett & Darby, 2018), which has received a lot of attention in recent years. The author of this thesis holds a nuanced position on this topic. In some cases, this escalation is indubitably positive, particularly for those who might not be achieving minimum comfort standards, such as people living in fuel poverty or with health problems. However, in others, it might have collateral effects that it is worth considering. The new indoor conditions might contribute to normalise higher comfort standards and to increase expectations. Trying to achieve these comfort standards with other heating technologies, such as combi gas boilers, ASHP, biomass boilers, etc. will increase the total energy used. Still, the author believes that in those cases where the new indoor conditions are improving the efficiency of the heat pump, it is worth taking the risk. However, this is not always the case. Some of the new indoor conditions are not contributing to improve the efficiency of heating and they are simply the result of erroneous assumptions about the existing heating practices. This is the case of the smart controls low tolerance to unmatched temperature setpoints. In this case, relaxing these assumptions is critical and might contribute to not escalating comfort expectations.

Trust is critical to adopt new competences

The conflicts arising from the adoption of the new technologies are not only related to the expectations for indoor conditions. As shown in Chapter 6, the new technologies require different competences that can conflict with the existing know-how for minimising waste. Changing these competences seems critical for the adoption of the new technologies and not successfully doing that, explains an important part of the householders' communications with the customer service team.

The example of waste is paradigmatic: in the absence of direct or tangible feedback on waste, waste is often defined indirectly as a result of certain heating patterns and indoor conditions, which have to be avoided to heat the house "correctly". However, this know-how conflicts with how the new technologies operate. For these technologies to operate as expected, new know-how must be adopted. The research pointed out that in the absence of direct feedback, trust plays a key role in adopting these competences and analysed the new technologies and the systems of provision as expert systems. This is not new. Historically, the evolution of heating practices, as many other domestic practices, has involved decontextualising the social relations across space and time (social action breaking out from localised contexts). That required the introduction of expert systems and trusting them. This research has explored the role of trust in adopting the last step of domestic heating technologies: smart controls and heat pump. However, this thesis also provides a useful approach to understand and explore the evolution of heating practices and, in particular, the idea of waste. Because it is obvious that previous transitions also required increasing levels of trust. For example, moving from coal furnaces to gas central heating meant less control over the fuel used and adopting new competences to minimise waste. The findings of this research should contribute to understanding these transitions and, at the same time, develop new approaches for the adoption of smart technologies. For example, the role of installers and the installation experience were found to be critical in the process of building trust in the new technologies and the expert system and it is likely that they also played a key role in previous transitions.

The previous paragraphs have explored some of the main contributions of this research in general terms. However, this thesis has also hopefully contributed to specific areas and disciplines. In the next subsections, the main contributions of the research to the fields of research, policy and technology are discussed and potential areas for future work are identified.

8.2.2. Research

This research has explored and provided evidence of heating practices with hybrid heat pumps and smart heating controls, continuing the work of previous researchers on the topic (e.g., Hanmer, 2020; Parrish, Hielscher & Foxon, 2021). The contributions are located in two main areas: contributions to the knowledge of heating practices and contributions to the study of heating practices.

Regarding the knowledge of heating practices, the research has contributed in three different areas. First, it has measured in detail the indoor conditions and the heating operation of a hybrid heat pump with smart heating controls. While some of the reviewed studies in section 2.2 have measured the performance of heat pumps in field studies (e.g., Boait, Fan & Stafford, 2011; Lowe *et al.*, 2017a; Oikonomou, 2022) or the householders' interactions with the controls (e.g., Jensen, Kjeldskov & Skov, 2018; Hanmer, 2020), only Hanmer (2020) and Boait et al. (2011) have previously measured indoor conditions. However, in those two studies, the authors focused on air temperatures and thermostat settings and did not look into the heating operation or other parameters related to indoor conditions in detail. Second, it has contributed to a better understanding of the householders' experiences of the change in indoor conditions resulting from the adoption of new technologies. The research has been able to analyse in detail some of these changes. For example, while previous studies have found that people value the constant warmth provided by the new technologies (e.g., Caird, Roy & Potter, 2012; Lowe *et al.*, 2017b), this study has unpicked these experiences by identifying the elements that contribute to it. Additionally, it has explored how the changes conflict with the existing practices. Third, the research has contributed to a better understanding of the role of waste in heating practices. While previous research has pointed out its importance in heating practices (e.g., Mallaband & Lipson, 2020), there is no specific research on the topic, and this thesis hopefully contributes to bridging that gap. Finally, this research has contributed to a better understanding of the resistance to delegating the control of the heating system to the smart heating controls and the consequences of that, emphasising the importance of trust in that process. While that has already been explored before (e.g., Hargreaves, Wilson & Hauxwell-Baldwin, 2016; Jensen, Kjeldskov & Skov, 2018; Fell, 2016) the research presented here has identified how control is retained as a result of the conflicts between the outcome of the system and the existing heating practices and has identified some of the elements that contribute to not trusting the new heating system.

Regarding the contributions to the study of heating practices, the research reported here has added to the commonly used framework of social practice theory that might be useful for future studies. The research has used social practice theory to study heating practices with hybrid heat pumps equipped with smart heating controls, an approach that has been widely used before for the study of energy-related topics (e.g., Gram-Hanssen, 2010b). By so doing, the approach avoided other more individualistic frameworks that only focus on the individual and more technical approaches that ignore people. The research has also successfully used the concept of trust, as developed by Giddens (1990), to explain the changes in know-how for minimising waste after the adoption of the new technologies. To the authors' knowledge, the combination of SPT and the Giddens' concept of trust in the context of heating automation has only been used before by Smale et al. (2019). The findings of this research proved the usefulness of the approach used and hopefully will inspire future research.

Recommendations for future work

While preparing this thesis, several gaps in the existing knowledge were identified, suggesting opportunities for future research:

- The research has focused on hybrid heat pumps with smart heating controls. While, as explained in section 7.3, some of the findings of this research can be generalised to other technologies, more field research on stand-alone heat pumps is needed to confirm the generalisability of the findings. In particular, given the importance of noise and the heterogeneity of heating patterns in the experience of the householders, analysing quieter technologies with less variability might be useful to put the findings of this research in context.

- As explained throughout Chapters 4-6, the experience of the householders is critically affected by the physical context where the new technologies are installed (material arrangement): the thermal characteristics of the building, the location of the heat pump, the size of the radiators, etc. While most of the technical analyses of heat pumps have focused on studying the performance of the system, further research is needed to understand how those different factors affect the experience of the householders.
- This research has identified a small number of instances in which heating practices with the new technologies conflict with other domestic practices, such as those of drying clothes or ventilation practices. The evidence presented here is very limited, and further research on the topic is needed.
- The analysis of the technical data has shown that there is a lack of studies on how indoor conditions and the heating operation change after the adoption of heat pumps with smart heating controls. To overcome that, more monitoring studies that combine pre and post-installation data are needed.
- The technical analysis of the indoor conditions presented in this research has been limited to those variables that could be studied through the monitoring of the air temperature. While that has provided interesting insights, as explained in Chapter 4, the technologies studied have the potential to affect other parameters of the indoor conditions, such as the vertical temperature gradient, the radiant temperature, noise, etc. Therefore, further analysis of these parameters through monitoring might be useful to better understand the experience of householders with the new technologies.

8.2.3. Policy

This research has not aimed to study the existing policies related to the technologies studied, and therefore, its contribution to policy is through the implications of the findings for policymakers. The research has identified some very positive experiences with the technologies that could be useful to develop new narratives for it that contribute to creating more positive stories and improve public awareness of low-carbon technologies. At the same time, the research has identified some of the ways in which the new technologies are disruptive, which could contribute to designing policies for the adoption of these technologies that help to overcome some of the challenges that they create. For example, the conflicts of overnight warmth might require sociotechnical solutions that involve promoting the uptake of more sophisticated TRVs to control the bedroom temperature independently, as well as encouraging people to close bedroom doors or use lighter duvets. The problem with noise can be addressed through policy by improving the existing requirements regarding the location of the HP or incentivising the development of more noise-insulated HPs. The recent independent review of evidence on noise emissions from air source heat pumps (see DESNZ, 2023b) provides a good starting point. Moreover, the problems arising from the unexpected heating running times might require commissioning research on how to better communicate these issues. Finally, the research has pointed out the importance that trust in the new system plays in how the technologies are used and integrated into heating practices and suggests that there is a need to take that into account when developing new policies and actions related to the technologies. Improving the installers' training and monitoring the installations in more detail to pick up any early reports of potential problems can be extremely useful.

8.2.4. Technology manufacturers

The findings of this research are particularly relevant for heating controls manufacturers and heat pump manufacturers as they contribute to a better understanding of how the new technology is experienced and how it is integrated into householders' practices. The research has pointed out that the adoption of the technology is disruptive for householders, and the findings suggest that the changes in the indoor conditions and the heating operation might trigger some conflicts, particularly regarding the expectations for noise and the understanding of waste. The findings suggest that the new technologies do not allow householders to communicate all of their goals regarding these issues (e.g., the requirements for a cool and quiet environment at night). The research presented here might be useful to design new ways to capture these needs. Additionally, the research has identified a few changes in the indoor conditions that are positively experienced and that could be used to build a more positive narrative for the technologies tested that contribute to improving their public acceptance.

At the same time, the findings suggest that while the technologies require a particular set of practices in order to operate efficiently (minimise costs or carbon emissions), the existing heating practices do not always evolve in the expected direction after the adoption of the new technologies. Trust in the new heating systems was found to explain some of these alternative trajectories. The research has also been useful in understanding the elements that shape these heating practices involving a high number of manual in-the-moment changes in the temperature setpoint, and the next subsection suggests a few options to address this problem.

Finally, the research has helped to identify the roles that two different stakeholders involved in the provision of the technologies have in the way the technology is used and experienced: the installers and the customer service team. The poor job of the first in some of the installations was found to critically affect the householders' trust in the new technologies. In contrast, the customer service team (CST) was found to play a very positive role in shaping heating practices in the expected direction. The experience of the CST could be very helpful for improving the training that installers receive.

Recommendations to improve the tested technologies

The research reported here has shown that the adoption of hybrid heat pumps with smart heating controls is not always accompanied by the adoption of heating practices that allow the algorithmic controls to maximise the efficiency of the system (minimise costs or carbon).

The findings suggest that heating system does not always provide what householders expect and that householders might need help to transform their heating practices. During the research, a few ways in which the technologies could be improved to overcome some of these challenges have been identified. These proposals can be divided into two groups: changes to help householders transform heating practices and changes aiming at better capturing the needs of the householders to provide the expected outcome.

Suggestions to transform heating practices

Regarding the first, it is essential that all the communications with householders (in leaflets, through installers, in advertisements, etc.) make it clear that the new technologies are not boiler replacements. This should help householders develop new expectations for the new technologies. These technologies operate under a different logic, require different practices and provide different indoor conditions. Acknowledging differences between the two groups of technologies is important and could help householders build expectations that are more aligned with the way the new technologies operate. More research might be needed on how to successfully communicate these differences. However, given the findings of the research, installers are probably the ones more well-suited to engage in this sort of dialogue with the participants, and they could present to them the differences between the two technologies and provide useful information to help them to transform their practices. For example, once at the property, they could suggest participants to use thinner duvets to reduce the risk of overheating at night or discuss with them the new heating patterns.

At the same time, the findings of this research showed the important role that feedback plays in maintaining outdated ideas of waste. Therefore, helping householders to develop new feedback on waste, is critical. However, previous research has pointed out the difficulties of integrating new feedback to transform the practice (e.g., Strengers, 2013), and when it has been done, researchers have reported very poor results (e.g., Jensen, Kjeldskov & Skov, 2016; Alan *et al.*, 2016). For feedback to be relevant and integrated into the practice, it should be targeted to the specifics of the heating practices and be communicated in meaningful terms. Therefore, it is important that technology makers work with policymakers and researchers to commission more research on how to develop these mechanisms.

Finally, I suggest that mechanisms should be put in place to help householders to trust the system. One of the most obvious options is, as previous research has suggested (e.g., Smale, Spaargaren & Van Vliet, 2019), to create an independent accountability system. However, that could be difficult to implement as for it to be really independent, it would require involving additional stakeholders. If that is not possible, obtaining externally certified accreditation for the new technologies from trusted bodies might be useful. Additionally, the research has pointed out that the installation quality and the experience with the process are key to building trust in the system. Therefore, better training the installers and ensuring that the installations are of high quality is critical. Finally, previous research by Menniken et al. (2014) suggests that smart technologies should allow householders to incrementally develop trust. That can be done by limiting the automated functionalities of the system at the beginning, by letting householders control the heating times, and later on, by offering them more advanced functionalities. That can be extremely useful to help them get used to the changes in the operation of the heat pump before having them automated.

Suggestions to better capture the existing practices

Regarding the need to better capture the householders' needs, the research has found that some of the conflicts that arose could be improved by better acknowledging the multiple and often unstated goals that householders have for heating. Some of them could be addressed by making some tweaks to the technology. For example, by developing new features, such as creating a quiet and expensive mode that forces the heat pump not to operate, or by physically changing the technology. For example, noise can be improved through better insulation of the fan and the compressor or by choosing a better location for the heat pump. At the same time, the discontinuity of the noise, which is one of the issues that the householders reported more often, can be improved by changing the design of the heat pump. Instead of using single-speed compressors that either operate at full speed or are off, if technically suitable, it might be better to use inverter compressors as the noise is modulated and it might be less noticeable.

However, it is also important to revisit some of the assumptions embedded in the technology, as the new heating system might be contributing to normalising increased energy use. This is the case for the algorithm's goal of always meeting the temperature setpoint during warmth-requested periods. As the research found, householders are not used to achieving the temperature setpoint at the beginning of the heating period; they are used to being colder at certain periods. Allowing a more flexible temperature target at the beginning of heating periods could reduce energy use and costs and improve the comfort of the householders as the need to pre-heat at night might be reduced. The need to revisit some of these assumptions could be done by commissioning more research using the available CRM database. Nowadays, the CRM dataset is only used to keep track of ongoing issues, but no analysis is currently done of these communications. That misses opportunities to better understand the needs of the householders and to develop a two-way communication system in which householders are not only supported to adapt their practices, but the technology is continually improved to address their needs.

In addition to that, installers could also play a critical role in tailoring the technology to the existing heating practices and, in particular, to the specific characteristics of the performance of these practices in each home. For example, installers could enquire (verbally or through dedicated monitoring devices) about the current temperature patterns in the house. This information can help set the initial temperature setpoints and assess the potential to flexibilise the temperature requirements (e.g., not always meeting the temperature setpoint), particularly in the morning. Additionally, the installers could ask about the participants' awareness of the need to change practices after adopting the technology (e.g., assess how they currently measure waste) and use this information to tailor the materials provided to the specifics of each household.

Finally, the research has pointed out that the heating controls language (IN, OUT, AWAY and ASLEEP) is confusing. Mennicken et al. (2014) suggest that communication between householders and smart technologies should be natural and not require technical language. The terminology based on occupancy is contrary to that and does not fit well with how householders actually program the heating controls (Meier & Aragon, 2010), which is by defining heating running times. It might be useful to develop new communication mechanisms based on those aspects more relevant to heating practices, such as the maximum temperature at night or noise control.

9. References

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10. Appendices

10.1. Information sheet

Example of the information sheet provided to the participants.

Participant information sheet (Users' analysis)

Title of the study: How can smart platforms help negotiate a transformation in home heating practices?

Department: UCL Energy Institute (University College London)
Name and contact details of the Researcher: Adria Martin Vilaseca (adria.vilaseca.19@ucl.ac.uk)
Name and contact details of the Principal Researcher: Michelle Shipworth (m.shipworth@ucl.ac.uk)

You are being invited to take part in a research project. Before you take part, it is important for you to understand why the research is being done and what participation will involve. Please take time to read the following information carefully. Discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Thank you for reading this.

What is the research about?

This project analyses heating needs and thermal comfort in households equipped with a SIME compact hybrid. The research focuses on the sensations and preferences that matter for users. The research should help to make the technology more relevant for them and reduce their environmental impact. The research is being funded by La Caixa Foundation and PassivUK Ltd.

Who is conducting the research?

Adria Martin Vilaseca is conducting the research as part of his PhD in Energy Resilience and the built environment at the UCL Energy Institute (University College London). Michelle Shipworth, from the UCL Energy Institute is supervising the research.

Why have been invited?

You have been chosen because your house or flat is equipped with a SIME compact hybrid. For this project, approximately five to fifteen users like you will be recruited. Only adults are invited to participate in the project

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and will be asked to sign a consent form. You can withdraw your consent at any time up until the interview notes and the data from the monitoring devices is analysed and summarised (at that point it becomes difficult to separate your answers from the all the other data). To do that, you have to email Adria Martin Vilaseca (adria.vilaseca.19@ucl.ac.uk). If you withdraw your consent, you do not need to give a reason and it will not disadvantage you in any way.

What will happen to me if I take part?

Participation involves two interviews, placing six temperature and humidity monitoring devices in your home (no permanent fixture) and analysing data from your heating controls. You would be interviewed once at the beginning of the winter and again at the end. The interviews would take place online or in person (you can choose) and will be recorded. If it is possible, the researcher would like to interview all the adults in the household to capture the different views of the technology. The interviews will take about one hour each. The recordings will be used only for data analysis although your words may be quoted for illustration using a pseudonym (false name).

Meanwhile, we would like to measure the temperatures and humidity in six rooms of your home during six months. This is because the study aims to understand the indoor conditions created by your heating system. The devices are about the size of your hand, make no noise and do not have a light. If the interviews are in person and the researcher visits your house, he can install the devices. If the interviews are online, the researcher will send them the monitoring devices to you in the post and you would place them following our instructions (expects no permanent fixture). If needed, Adria is on hand to help you with this. At the end of the project, you would post back all the monitoring devices to UCL. The carrier costs will be paid by the researcher. In addition, Adria would analyse data from your PassivUK heating controller and link it to the information from the interview and the monitoring devices

The results of the analysis, the quotations and the data obtained from the monitoring devices and the heating controls might be included in Adria's PhD thesis, conference presentations and publications. Your name and other personal information will not be used in these publications. Anonymised data collected might be used for future research but no one except Adria will be allowed to access the interview recordings or your personal information (e.g., name or email address). The interview recordings will be destroyed at the end of this research project. The data obtained from the monitoring devices and heating controls will be fully pseudonymised at the end of the project and the pseudonymous data might be used for other research purposes.

Will I be recorded and how will the recorded media be used?

Your responses to the interview questions will be recorded. The recordings will be used only for transcription and will be deleted after this process is finished (approximately two weeks after the interview). No one except Adria will access the recordings.

What are the possible disadvantages and risks of taking part?

The research is designed to understand the challenges that users face when using the technology and their preferences for thermal comfort. Therefore, your answers might help to improve the provision of heating in domestic buildings and identify failures in the technology. Your name and other potential identifiers (e.g. location) will be pseudonymised and will not be recognisable from the study by anybody. That should avoid these findings to negatively affect the reputation of you. If you decide to be interviewed in person and to reduce the risk of getting COVID, the researcher will take a COVID test the day before the interview, he will wear a face mask during the whole interview and will maintain social distance.

What are the possible benefits of taking part?

Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will help to design technology more relevant for your needs. That might result in a better integration of the interests of the users and the energy system.

What if something goes wrong?

If you are concerned about any part of this research or your participation, please contact the Supervisor, the Dissertation Coordinator and/or the Director of Ethics at the UCL Bartlett School of Environment, Energy and Resources:

- Supervisor: Michelle Shipworth, m.shipworth@ucl.ac.uk, +44 (0)20 3108 5991
- CDT Academic manager: Jenny Crawley, jenny.crawley@ucl.ac.uk.
- BSEER Director of Ethics: Michelle Shipworth, m.shipworth@ucl.ac.uk, +44 (0)20 3108 5991

If you remain unsatisfied, you may wish to contact the Chair of the UCL Research Ethics Committee: ethics@ucl.ac.uk

Will my taking part in this project be kept confidential?

All the information that we collect about you during the course of the interview will be kept strictly confidential and will only be accessed by the researcher (Adria). The data recorded by the monitoring devices and the heating controls will be fully anonymised before publication. You will not be identifiable in any reports or publications. Any personal data (e.g. name, affiliation and email address) collected from you will be stored on a secure UCL file store and will be processed in accordance with Data Protection legislation. Your interview transcription and monitoring data (dedicated monitoring devices and heating controls) will be stored separately from your personal data also on a secure UCL file store. The video files of the interviews will be destroyed after transcribing the interview (approximately two weeks after the interview).

What are the limits to confidentiality?

Assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research?

This research will be included in Adria's PhD (due to September 2023). It is possible that the results will be included in reports, presentations, and academic papers. You will not be identifiable in any report or publication. If you wish to receive a copy of the dissertation, please let the researcher know.

Local Data Protection Privacy Notice

Notice:

The controller for this project will be University College London (UCL). The UCL Data Protection Officer provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk

This 'local' privacy notice sets out the information that applies to this particular study. Further information on how UCL uses participant information can be found in our 'general' privacy notice, click here.

For participants in research studies, click here.

The information that is required to be provided to participants under data protection legislation (GDPR and DPA 2018) is provided across both the 'local' and 'general' privacy notices.

The categories of personal data used will be as follows:

- Name
- Organisation
- Email address

The lawful basis that would be used to process your personal data will be performance of a task in the public interest.

Your personal data will be processed so long as it is required for the research project. If we are able to anonymise or pseudonymise the personal data, you provide we will undertake this and will endeavour to minimise the processing of personal data wherever possible.

If you are concerned about how your personal data is being processed, or if you would like to contact us about your rights, please contact UCL in the first instance at data-protection@ucl.ac.uk

Who is organising and funding the research?

This research is made possible by the in-kind support from the EPSRC-SFI Centre for Doctoral Training in Energy Resilience and the Built Environment (ERBE), grant number EP/S021671/1 and with the financial support from "la Caixa" Fellowship for postgraduate studies and PassivUK Ltd.

Who can I contact for further information?

If you have questions or want more information on the research, please contact Adria Martin Vilaseca on adria.vilaseca.19@ucl.ac.uk

10.2. Consent form

Example of the consent form to participate in the research.

Dear [Participant's Name],

Thank you for agreeing to participate in my research project. Your participation will be very useful for my research and will help to improve the technology and the experience of the users with it. Regarding the data monitoring of the indoor conditions, we can organise it at the end of the first interview. If the interview is face-to-face, I can bring with me the sensors and discuss with you where to place them. If the interview is online, we can discuss during the interview where you would like them to be send by post (I pay the carrier costs) and how to place them in the different rooms. The monitoring devices are about the size of your hand, make no noise and do not have a light (*add link to the website of the manufacturer of the devices*). At some point during the winter, I will ask PassivUK to provide me access to the data collected by your heating controls (you do not need to do anything) to understand, for example, how long does it take to the heat pump to achieve your temperature setpoints.

Before we start the research, I need a record of your consent. Please write YES next to each of the following to show that you agree. By not giving consent for any one element, you may be deemed ineligible for the study.

- I have read and understood the Participant Information Sheet for the study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction.
- I have understood that participation is entirely voluntary. If I decide I no longer wish to take part in this research I can withdraw at any time (up until the researchers start analysing and summarising my data), without giving a reason, and any data I have provided will be deleted.
- I consent to the use of my personal data (name, postal address and email address) for the purposes of this research. I understand that it will be treated as strictly confidential (only accessed by Adria), will be securely stored and will be handled in accordance with Data Protection legislation, 'public task' will be the lawful basis for processing.
- I understand that the data published will not disclose my identity.
- I understand the direct/indirect benefits of participating.
- I understand that the information I have submitted will be published in reports, publications or academic documents (e.g., PhD dissertation).
- I am aware of who I should contact if I wish to lodge a complaint.
- I agree to participate as outlined on the Participant Information Sheet.
- I agree for the interview to be recorded as outlined on the Participant Information Sheet.
- I consent to PassivUK Ltd releasing data from my home heating controller to Adria Martin Vilaseca of UCL, for the purposes of academic research.

Once again, thank you for agreeing to take part in my research.

Kind Regards

10.3. Interview guide

Example of the interview guide prepared for the second round of semi-structured interviews.

Thank you very much for agreeing to participate in this interview. I am a PhD researcher at the University College London's Energy Institute, and this interview is part of my PhD. Although I am I am not employed by Passiv UK, or any other company involved in the HyCompact project, I have signed a confidentiality agreement with Passiv UK and I will be sharing the results of my work with them..

I will be recording and transcribing our conversation. These recordings will be deleted once I finish the transcription process. No one except me will have access to the recording or the transcription and you won't be able to be identified from the research.

Your data will be held confidentially and will only be shared anonymously with Passiv UK and the project partners under the terms of Passiv UK's agreement with you and in accordance with their privacy policy.

The purpose of this interview is to record and understand your views and opinions on your experience of the HyCompact project, and the technology installed as part of it. This means that there are no right, or 'wrong' answers and it's your experience what matters to me.

INSTALLATION PROCESS AND LEARNING TO USE THE SYSTEM

Thinking back to when the heating system was installed, how happy were you with the installation process?

Is there something that you didn't like?

Is there something that you particularly liked?

What could have been done better?

Overall, was the installation better or worse than you expected?

Did you talk with the installers?

If yes, did they ask you anything about the installation?

If yes, did you give them any indication? (e.g., where to place the sensors) Why?

If no, did somebody at your place talk with the installers?

Were you given any information about how to operate the system before the installers left or during the commissioning process?

If no, how did you learn how to use the system?

If yes, who was there (Passiv side)?

If yes, who was there (householder side)?

If yes, after living with the system for a while, do you think that they gave you all the information/explanations needed?

If yes, was there something that surprised you?

If yes, did you share the information that they gave you with the other householders?

If yes, how did they explain that the system should be operated?

If yes, did they mention any potential problem of overriding the heating schedule?

If yes, how did they describe the system?

If yes, did they mention any potential environmental benefits of the new system?

If yes, did they mention any potential economical benefits of the new system?

Did you had any further interactions/follow up phone calls, etc. With them since the job?

Has there been any technical failure of the system since our last meeting?

COMPARING THE TWO HEATING TECHNOLOGIES

Can you name any differences between the hycompact boiler and your previous conventional boiler? Can you name another one?

INDOOR CONDITIONS

Can you name any differences in the indoor conditions after installing the system?

Can you explain it in more detail (for each of the differences)?

How do you notice the changes (senses)? Noise, visuals, touch, etc.

Has that affected your activities at home?

Have you tried to do something to change that? How?

Do you think that you've got used to it?

Have you had visitors at home (e.g., family, friends, etc.)?

Have they noticed the change in the system? Why? Because a change in indoor conditions or something else?

CONTROLLING THE SYSTEM

Is there anything different in the way how you use the system compared to your previous system? If they don't interact with the system ask about change in routines, use of secondary heating, discussions with partner, etc.

Can you explain in more detail each of the differences?

Why do you use it in that way?

Where there any people or information sources that helped?

Was it difficult for you to get used to it?

Is there anything different in the way how you use the system compared to when the system was installed?

Why do you use it in that way?

Where there any people or information sources that helped?

Was it difficult for you to get used to it?

Has this changed the indoor conditions?

Does the operation of the system make sense? Explain

Do you think the heating controls are making your life easier or harder compared to your previous system?

How?

Does it conveniently control the indoor temperature for you?

Are they helping you to save money?

Why?

Are they helping you to reduce your environmental impact?

Why?

Have you changed the way how you use your heating as a result of the current energy crisis and Ucrainian war?

Do the heating controls help you to do that?

Do you think you interact more often or less often with the heating system after installing the heating controls?

Why?

Do you now pay more attention to the operation of the system? For example, by constantly checking the temperature sin the app?

Are you on a ToU tariff?

Do you ever shift other electricity consumption (e.g. appliances) at certain times of the day?

Why?

Are the heating controls helping you to adapt to the variable electricity prices?

PREVIOUS DAY ROUTINES

To be more specific, we will discuss now your experience with your heating system yesterday

Did you interact with the app yesterday?

If yes, why?

If yes, when?

If not, does that happen often?

Do you think that changing the settings in the app affects your comfort?

Do you think that changing the settings in the app affects your environmental impact?

Do you think that changing the settings in the app affects your energy costs?

Other than for changing the settings, did you check the app at any time?

Why?

Do you do that regularly?

Did you try to force the boiler to run instead of the heat pump?

Did you touch the wall thermostat or the boiler yesterday?

If yes, why?

If yes, when?

If not, does that happen often?

Did anybody else interact with the system?

Did the heating system provided the indoor conditions that you wanted yesterday?

If yes, all times?

If yes, all places?

If yes, does that always happen, even in cold days?

If not, when? Or where?

If not, do you know why?

What are those conditions?

What were your routines at home?

Is your heating schedule usually adequate for your activities on different days and different times?

If not, is that a problem for you? Is there anything that should change to solve that?

CLOSING

Overall, did the project meet your expectations?

Overall, did the technology meet your expectations?

Would you recommend the system to a friend?

Is there something that you know now that would have been useful to know before the trial?

Thank you very much for your participation. Your answers will help to inform the future development of the Passiv UK heating controls as well as the Sime Compact Hybrid boilers. It will also form a significant part of my PhD research.

10.4. Codes thematic analysis

Examples of the codes used in the second part of the thematic analysis

10.4.1. Comfort-related heating practices

- Lower Temp Heating - Cold rads - Drying clothes
- Lower Temp Heating - Cold rads - Cosiness
- Lower Temp Heating - Cold rads – Competences: Heat blast
- Lower Temp Heating - Cold rads – Competences: Other
- Lower Temp Heating - Steady warmth – Between Heating periods – Competences
- Lower Temp Heating - Steady warmth – Between Heating periods – Meanings: Night expectations
- Lower Temp Heating - Steady warmth – Between Heating periods – Meanings: Morning expectations
- Lower Temp Heating - Steady warmth – Between Heating periods – Meanings: During the day expectations
- Lower Temp Heating - Steady warmth – Between Heating periods – Meanings: Other
- Lower Temp Heating - Steady warmth – Within Heating periods – Meanings: Temp oscillation
- Lower Temp Heating - Steady warmth – Within Heating periods – Meanings: Old boiler expectations
- Lower Temp Heating - Steady warmth – Within Heating periods – Competences
- Lower Temp Heating - Steady warmth – Spatial
- Smart heating controls – Meaning: Unbalanced temperature
- Smart heating controls - Meaning: Shoulder season
- Smart heating controls – Meaning: Learning algorithm
- Smart heating controls – Competences
- Noise – Physical conditions
- Noise – Characteristics noise: Timing
- Noise – Characteristics noise: Sound
- Noise – Meanings: Negative
- Noise – Meanings: Neighbours
- Noise – Know-how: App settings
- Noise – Know-how: Adapting
- Noise – Know-how: Other

10.4.2. Waste-related heating practices

- Competences monitoring waste - App
- Competences monitoring waste - Energy supplier feedback
- Competences monitoring waste – Lack of feedback
- Competences monitoring waste – Monitoring equipment
- Competences monitoring waste – Smart meter
- Competences monitoring waste – Bills
- Competences monitoring waste – No monitoring
- Competences monitoring waste – Heating operation: App
- Competences monitoring waste – Heating operation: Radiators
- Competences monitoring waste – Heating operation: Noise
- Competences know-how waste - Retain control heating times
- Competences know-how waste – Delegate control heating times
- Competences know-how waste – Lost Control of heating times / Resigned
- Competences know-how waste - Lack of trust
- Competences know-how waste - Trusts the system
- Competences know-how waste – Not using the occupancy periods as designed
- Competences know-how waste – Secondary heating
- Competences know-how waste – Understanding heating patterns: longer duration more wasteful
- Competences know-how waste – Understanding heating patterns: longer duration less wasteful
- Competences know-how waste – Understanding heating patterns: Erratic HP
- Competences know-how waste – Understanding heating patterns: Other
- Meanings waste – Relax waste concerns
- Meanings waste – Trade-offs
- Meanings waste – Conflicts algorithm – householder
- Meanings waste – New system helps reduce environmental waste
- Meanings waste – New system helps reduce environmental waste but increases costs
- Meanings waste – New system is wasteful

10.5. Monitoring

10.5.1. Instructions monitoring

Example of the instructions provided to the participants to help them correctly place the temperature loggers in their homes.

Instructions on where to place the temperature sensors in your home

1. Contents of package

In the package you have received from UCL you will find the items listed below. If anything is missing or damaged, please contact us and will we arrange to replace them.

Six **Hobo temperature sensors**. Each sensor has a label with a unique anonymous reference code (for example EI30748) and a room location (e.g., living room, hallway or bedroom). A photograph of a typical temperature sensor is shown here →

One set of **3M Command hanging strips**. These can be used to position a temperature sensor on a wall. These strips are removable and will minimise the risk of leaving any marks on the wall surface. A photograph of a pack of 3M hanging strips is shown here →

2. Which rooms to place the sensors

Please place one temperature sensor in the **main bedroom,** one next to your **thermostat**, one in a **second bedroom**, one in the **living room**, one in the **kitchen** and the other one in another **widely used room** (for example, a studio). In each case, please use the sensor that is labelled up for the specific room or area.

3. Where to place the sensors in each room

Please DO

- ☑ Place the sensors either on a flat surface such as a book shelf, bedside table or cupboard, or use the 3M hanging strips to position the sensor about halfway up on a wall.
- ☑ If using the 3M hanging strips please follow the instructions given on the packet.
- ☑ Please place the sensor where it will be out of the reach of small children or pets.
- ☑ Make sure the the label is facing upwards if placed on a surface, or outwards if it is on a wall.

Please DO NOT

- ☒ **Please avoid placing the sensor next to anything that might be warm** such as a radiator or an electrical device such as a televsion, computer or DVD player.
- ☒ **Please do not place the sensor on a window sill or where direct sunlight might shine on the sensor** during the day.
- ☒ Please do not place the sensor on the floor.
- ☒ Please do not place the sensor behind something else such as a door, curtains or photo frames.

10.5.2. Post-monitoring survey

Example of the survey sent to the participants to check the position of the temperature loggers at the end of the monitoring campaign.

IMPORTANT! Fill this document and put it in the prepaid envelope with the sensors

Sensor MOST USED ROOM 1 (WHICH? ____________________)

1. Has the sensor been in the same exact location within the room the whole time?
   ☐ YES ☐ NO
2. Has the room (or the open plan area) more than one sensor?
   ☐ YES. Which is the other sensor? ________ ☐ NO
3. Is the room heated?
   ☐ YES ☐ NO
4. Is the sensor in a place that could receive direct sunlight sometime during the day?
   ☐ YES ☐ NO
5. Is the sensor less than 1 meter away from a heat source, like a radiator?
   ☐ YES ☐ NO
6. Is the sensor hidden (e.g., behind curtains, in a wardrobe or behind a photo frame, etc.)?
   ☐ YES ☐ NO
7. Which is the approximate height above the floor of the sensor?
   ____
8. How often is the room used?
   ☐ ONCE A DAY OR MORE ☐ ONCE A WEEK ☐ ONCE A MONTH OR LESS

Sensor MOST USED ROOM 2 (WHICH? ____________________)

1. Has the sensor been in the same exact location within the room the whole time?
   ☐ YES ☐ NO
2. Has the room (or the open plan area) more than one sensor?
   ☐ YES. Which is the other sensor? ________ ☐ NO
3. Is the room heated?
   ☐ YES ☐ NO
4. Is the sensor in a place that could receive direct sunlight sometime during the day?
   ☐ YES ☐ NO
5. Is the sensor less than 1 meter away from a heat source, like a radiator?
   ☐ YES ☐ NO
6. Is the sensor hidden (e.g., behind curtains, in a wardrobe or behind a photo frame, etc.)?
   ☐ YES ☐ NO
7. Which is the approximate height above the floor of the sensor?
   ____
8. How often is the room used?
   ☐ ONCE A DAY OR MORE ☐ ONCE A WEEK ☐ ONCE A MONTH OR LESS