Flexibility of UK home heating demand: an exploration of reactions to algorithmic control

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

Abstract

Most future scenarios for decarbonising the UK energy system include a high proportion of homes with electric heat pumps. Shifting current heating demand patterns to the electricity network would increase peak demands. Demand management to reduce this peak can only be achieved if households are prepared to accept flexible running times for their central heating. This thesis investigates what this flexibility looks like from the perspective of the households involved.

The investigation centres on a case study of a trial of hybrid heat pumps (gas boiler and air source heat pump) with smart controllers. The algorithmic controllers aim to satisfy both household requirements for warmth and energy network requirements for flexible demand. A practice theory approach is used to assess design assumptions about what residents want from their heating and how they interact with the controls.

Household requirements are frequently more complex than achieving steady temperatures when the home is occupied. The thermal conditions considered appropriate vary with different activities. In many of the case study homes residents preferred different temperatures at different times of day. A desire for cool bedrooms may limit the potential for preheating during the night ahead of morning peak demand periods.

Residents are concerned not only with temperature but also the running pattern of the heating. Some households noticed unwelcome consequences of changed running patterns (for example, noise at night time) and in some instances the residents did not understand how to adjust control settings to achieve their preferred response.

High levels of manual operation were seen in some homes. A few households were frequently altering setpoints to stop or start the heating, rather than relying on automated, pre-scheduled settings. This mode of operation limits the potential for demand management based on predictable, scheduled heating operation.

Impact statement

Residential space heating accounted for approximately 58 Mte CO_{2e} or 16% of total UK carbon emissions in 2018 (BEIS, 2019). Reducing emissions from heating homes will be an important step towards achieving the UK's commitment to meet the targets in the Climate Change Act and to maintain the UK contribution to international action under the Paris Agreement.

This thesis addresses the challenges associated with a transition from gas boilers to low carbon home heating in the UK. In particular it investigates the demand flexibility which is likely to be required alongside widespread adoption of electric heat pumps, in order to smooth electricity demand peaks and minimise costs for electricity network reinforcement. It describes household reactions to heating demand management and discusses reasons why residents may choose to "opt out" of taking part in demand response.

The case study for the investigation is a field trial of hybrid heat pumps with smart controllers, an option for decarbonisation advocated by the Committee on Climate Change (CCC, 2018). This thesis considers flexible heating demand from the point of view of the households concerned and discusses limits to flexibility encountered among the trial participants. These findings are relevant to UK energy policy to encourage flexible, low carbon heating.

The research has been supported by PassivSystems Ltd, a supplier of smart heating controls. The company collaborated closely with the research, providing data and access to interviews. The findings about what households aim to achieve with their heating controllers have been shared with PassivSystems employees and the investigation has led to specific recommendations for improvements in controller interfaces and design. Some of the findings have already influenced product development and been incorporated in recent design iterations.

Results from the work have been shared in a seminar with policymakers at the Department for Business, Energy and Industrial Strategy. Findings have also been presented at several academic conferences focused on energy and social science including EASST 2018 and Energy and Society 2018. A paper presented at the European Council for an Energy Efficient Economy (ECEEE) Summer Study 2019 (Hanmer C., Shipworth D., Shipworth M., Johnson C. (2019) *Load shifting with smart home heating controls: satisfying thermal comfort preferences.* ECEEE Summer Study 2019 Proceedings pp. 1377-1386) was aimed at an international audience of policymakers and academics.

The contributions to knowledge provided by this investigation include:

- New quantitative methods for analysing temperature setpoint data from heating controllers.
- Integrating social practice theory and adaptive thermal comfort approaches to provide a new perspective on residents' interactions with their heating systems.
- Analysis of the new relationship created when energy network requirements influence patterns of operation of heating in the home.

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Chapter 1

Introduction

1.1 Background

A widespread transition from gas boilers to low carbon home heating in the UK is required to meet carbon emissions targets. This transition is likely to involve large scale electrification of heating, with roll-out of electric heat pumps (CCC, 2016, 2019b).

Electrification of heating will lead to significant increases in electricity demand. In order to minimise the necessary grid reinforcement costs there is a need for flexible demand which can be moved in time away from peak periods (Torriti, 2015). Demand Side Response (DSR) to avoid peaks in electricity demand could be provided by households using algorithmic heating controllers which alter the times the heating operates. Households which transition to heat pumps with algorithmic controllers providing DSR must therefore adjust to different heating operating patterns. This DSR involves changing patterns in time of both heating operation and of temperatures in the home and will introduce a disconnect between the times households require heating and the times the heat pump (or other heat source) is operating. Further background on heat pumps and DSR is provided in the literature review in Chapter 2.

This investigation looks at changes in heating control from the point of view of the householders involved, asking how flexible home heating demand is in practice. To enable households' participation in demand response, an algorithmic heating controller must provide both a temperature profile over the course of the day and a pattern of heating operation which are acceptable to the residents. This means that it is important to understand what outputs households aim to achieve from their heating system.

1.2 Introducing the investigation

In this section I introduce the aim of the research, the research questions and the structure of the thesis. I also outline the key features of the algorithmic heating controllers used in the case studies for the project and introduce the design assumptions behind the algorithms. A key strand running through the thesis is the exploration of how far these assumptions (about what residents want from their heating and how they will interact with it) reflect the realities of households in the case studies. Further background on algorithmic control is provided in Chapter 2 and more detail on the controllers used in the case studies in Chapter 4.

1.2.1 Aim and scope of research

The aim of the research is to explore the factors influencing householders' willingness to accept a demand response algorithm which decides when their heating operates.

Objectives

- Develop theoretical framework for analysis of case study interview data, and for combining findings from quantitative and qualitative analysis.

- Develop quantitative methods to analyse temperature setpoint data data from heating controllers, to support investigation of residents' actions and preferences.

- Conduct interviews with households taking part in trial of hybrid heat pumps to discuss how they operated their heating before and after the trial began, and to explore their reactions to the new heating system and how they adapted to an algorithmic controller.

- Interview a group of householders with boilers operated by algorithmic controllers to provide a contrasting case study with a different heating system and a different level of understanding of the control system.

- Draw conclusions about factors limiting flexibility of heating demand, and make recommendations for control design to encourage flexibility, and for energy policy to support a transition to flexible, low carbon heating demand.

The research centres on a trial of hybrid heat pumps with algorithmic controllers providing demand response to network requirements. Recent reports from the CCC (CCC, 2019a, 2018) highlight the potentially significant role of hybrid heat pumps with algorithmic control. The focus is on the interactions between residents and the heating technology in their homes rather than on purely technical aspects of low carbon heating.

The scope is geographically constrained to domestic heating in the UK. Section 2.4.1 explains how patterns of heating use are specific to the UK's climate and history of building and heating technologies.

1.2.2 Freedom trial

The Freedom trial of hybrid heat pumps, which forms the main case study for this investigation, took place in 75 homes in South Wales during the 2017-18 heating season. In all the homes in the trial a conventional gas boiler was replaced by a hybrid heat pump (combining an air source heat pump and gas boiler). The project aimed to investigate "the network, consumer and broader energy system implications of high volume deployments of hybrid heating systems" (Freedom Project, 2018).

PassivSystems Ltd were project managers for the trial and supplied the smart heating controllers which were installed with the hybrid heat pumps. The company supported the research for this PhD, providing part funding and access to interviews and data from controllers.

1.2.3 Algorithmic control

Energy network requirements to manage electricity and gas demand were indicated during the Freedom trial by time-variable tariffs. The control algorithm developed by PassivSystems incorporated these tariffs in the calculation of lowest cost operating patterns. The residents specified the times they wanted to be warm and the controller ran the heat source for the appropriate amount of time *ahead* of the period when warmth has been requested to ensure the requested temperature was reached at the beginning of the period. (I use the term “preheating” as shorthand for this type of control which involves the heating running before the time the residents have specified they want to be warm.)

In contrast to operation with a standard thermostat and timer, when the heating only starts to run at the beginning of the scheduled period, the algorithmic control introduces a disconnect between the times the heating operates and the times the residents have specified they want to be warm. This represents a major change for households accustomed to a gas boiler which only runs during times they select.

Using algorithmic control enables a heat pump to run efficiently with a steady, low temperature output and to gradually warm up the building. Households which replace a boiler with a heat pump or hybrid heat pump are likely to find their home is warmer during the night after the change since the heat pump is likely to run for several hours during the night in winter, to ensure the home is warm when the occupants wake up.

In order to optimise running costs the algorithm must be able to predict residents’ temperature requirements over the course of the day. The scheduled times and temperature setpoints entered by the residents in the controller are used by the algorithm to set target temperatures for the optimisation. If residents override the schedule and operate the heating manually this cannot be incorporated in the optimisation as the algorithm has no “visibility” of when these unpredictable requests will be made in the future.

1.2.4 Design assumptions

In her widely cited paper on the relationship between designers and those who use the products they have designed, Akrich points out that "when technologists define the characteristics of their objects, they necessarily make hypotheses about the entities that make up the world into which the object is to be inserted" (Akrich, 1992, p.207). In the case of heating controllers, the set of hypotheses - or assumptions - used in the design of the controller about why and how people operate their heating controls can be envisaged as a model of the residents "built into" the controller.

The stated aim of the PassivSystems control algorithm design for the Freedom trial is to provide the "lowest cost operating strategy to meet specified comfort levels" (Carter, unpublished report, July 2018). This statement implies a number of assumptions about what residents want the algorithm to do on their behalf. The identification of "lowest cost operating strategy" as the goal of the algorithmic optimisation of running patterns explicitly assumes that cost is the parameter that the algorithm should optimise and that minimum cost should be prioritised over any other goals.

By ensuring that the specified temperature is reached for the whole of the heating request period, the algorithm is in effect translating "comfort level" into a constant air temperature measured at the thermostat. Unfamiliar aspects of the operation which the residents have not specifically requested include the heat source running outside the heating request periods and high temperatures preceding the start of the heating request period.

The households which are prepared to accept algorithmic control for heating demand management are likely to have the following characteristics:

- Set a heating schedule (and update it in advance if there is a change in routine). This allows the algorithm scope to respond flexibly to requirements several hours in the future, selecting the lowest cost running pattern.

- Rarely or predictably make manual adjustments to temperature setpoints. If the algorithm cannot predict future requirements it cannot optimise the running pattern to deliver them.

- Are not concerned by a change in the pattern of temperature over the day, for example higher temperatures because of preheating during the night.
- Are not concerned by the "disconnect" between times heating is requested and times heat source runs. These residents have no issues if the heat source runs outside the times heating is requested, or does not run during these periods, as long as their requested temperature is achieved.
- Are prepared to delegate decisions about when the heat source runs to the algorithm.

Households which do not match these characteristics may not respond to requests for demand response, and if a substantial proportion of homes fall into this category, this will limit the potential demand flexibility available. This thesis investigates how far these assumptions hold in the context of the Freedom trial, and explores situations where the assumptions do not match the actual preferences of households.

1.2.5 Research Questions

The research questions for the investigation were developed to explore potential discrepancies between design assumptions and the preferences of residents, and to establish factors important to households which may limit the flexibility of their heating demand.

If the control algorithm does not interpret residents' wishes accurately, the decisions it takes may lead to resistance from the household. This leads to the first research question: **RQ1 What output do households want from their heating systems?**

As well as asking what people want from their heating, designers also need to understand how they interact with the heating controller, to ensure that they are able to get the responses they want. If residents are not able to operate a new type of controller to achieve a satisfactory response from their heating system this is also likely to create resistance to adopting the new technology. This leads to the second research question: **RQ2 How do residents interact with their heating system to get their required outputs?**

The third research question arises from the first two, using the case study to examine what residents' reactions to change reveals about their preferences for heating outputs and their ability to achieve the conditions they want with a new heating system: **RQ3 How do households react to a change in heating system characteristics?**

1.2.6 Structure of thesis

Chapter 2 provides the context for the investigation, introducing the need for a transition to low carbon heating in the UK. The significance of electricity demand management following electrification of heat and the role of smart, algorithmic heating controllers in enabling demand flexibility is explained. This chapter also introduces concepts of thermal comfort and reviews research on household experience of heating systems. Chapter 3 introduces the theoretical approach (Social Practice Theory) used in the investigation, providing a review of the relevant literature. Chapter 4 outlines the approach used for the mixed methods case study investigation. The main case study of the Freedom hybrid heat pump trial is outlined and two other cases of homes with smart heating controllers are described.

Chapters 5 to 7 present the findings of the investigation. Chapter 5 focuses on the temperature aspects of what people want from their heating and explores residents' reactions to changes in daily temperature profiles following the installation of a hybrid heat pump. Chapter 6 moves on to other goals residents have for their heating system, in particular their desired operating patterns. Freedom trialists' reactions to the change in running pattern associated with a hybrid heat pump with algorithmic control are discussed. Chapter 7 considers the relationship between the household and the energy network, applying concepts of social worlds and boundary objects to examine heating demand flexibility from the perspectives of households and energy network organisations. The role of control design in reconciling these different goals is discussed.

Chapter 8 is a general discussion of the findings from all three results chapters, including reflections on the benefits and limitations of the theoretical framework used for the investigation. This chapter outlines the contributions to knowledge from the investigation. Chapter 9 summarises the findings and provides recommendations for control design and energy policy based on the findings of the investigation.

1.3 Notes on language

1.3.1 Homes

I use the term home to describe a building in which people live. I intend this term to include those living in flats and maisonettes as well as those living in houses. I deliberately do not use the more technical term “dwelling” since it seems to me important that in a social science study of homes we should not forget that these are buildings in which people live.

1.3.2 Households and residents

I use the term resident to refer to one person who lives in a home, and the collective terms residents or household to refer to everyone who lives there. I have avoided the used of the term “occupant” which is frequently used in building physics and thermal comfort literature to refer to people in any type of building, because it seems to me to have inappropriate connotations of uniformity and passiveness. Shipworth (2013) points out that the widespread use of the term “occupant” to describe a person in a building has a simplifying, de-humanising effect which “probably arises from the tradition of defining ‘occupancy schedules’ within models . . . Such schedules remove variability and standardize human influences” (Shipworth, 2013, p. 251).

The terms resident or household remind us that people are likely to have a very different relationship to their homes than to other buildings such as offices, shops and schools which they may also occupy at different points in the day.

1.3.3 Heat sources

This study considers two main types of heating equipment – boilers and heat pumps – for which I use the collective term “heat source”. I consider a hybrid heat pump which combines heat pump and boiler as a combination of two heat sources.

The heat sources give rise to energy demand – from gas or oil fuel for a boiler and electricity for a heat pump. When discussing demand patterns I am referring to the energy supply – gas or electricity – unless I explicitly identify I am referring to heat demand. I avoid the use of the term “demand temperature” to refer to the temperature setpoint in a controller to avoid confusion with a possible third type of demand.

1.3.4 The need for a new heating control terminology

I have described how algorithmic control leads to a disconnect between heating operation times and times when residents specify they want to be warm. This creates a need for a new terminology about heating operation. In the UK it is normal to say “the heating is on” during periods when the timer is set to request boiler operation, even though the boiler will in fact “cut in and out” once the temperature reaches the thermostat setpoint. With a conventional system, the boiler will not run outside the specified timed periods.

Preheating, when the heat source operates ahead of the times set for warmth, confuses this distinction between when the heating is “on” or “off”. The heat source may in fact stop running before the beginning of the heating request period, in contrast to a conventional heating system when the beginning of the scheduled period would be described as the time “the heating comes on”. This means that detecting active central heating use as defined by Shipworth et al. (2010): “active central heating use is defined as times when the heating system is actually supplying heat to the dwelling” [p.55] would no longer be same as detecting the times the residents have requested warmth, as it was in their study of systems with conventional thermostats.

In this thesis I describe the period when residents have requested warmth as the “heating request period” which is defined in 4.5.5. Rather than writing about times heating stops or starts, or is switched on or off, I use phrases such as “start of heating request period".

Chapter 2

Context for the investigation

2.1 Introduction

This chapter introduces the context for the investigation and provides an overview of relevant literature about heating technology and the energy system. I start by discussing thermal comfort and factors which can influence this. I then introduce the adaptive thermal comfort research tradition, which considers the actions people take to manage their thermal environment.

In the second part of the chapter I describe the gas central heating systems which are used in a large majority of British homes and outline how the intermittent running patterns followed by many households lead to fluctuations over the day, both in temperature in the home and in national gas demand. I then outline the need for electrification of home heating and the unfamiliar heating technologies this involves. I describe the challenge of managing peaks in electricity demand, and the requirement for flexible heating demand. Likely changes in heating control technology are introduced and the changes in operating patterns that result from moving from a standard thermostatic controller to algorithmic control are outlined.

I finish the chapter by summarising research which has been carried out on resident reactions to different types of heating technologies and identify the research gap which this investigation aims to fill.

2.2 Thermal Comfort

There is general agreement that heating should provide comfort, as is shown in the following quotes:

"Heating systems ... [are] principally required to maintain comfortable conditions for people" CIBSE (2005, p.1-1)

"The primary function of an HVAC system is generation and maintenance of comfort for occupants" Howell et al. (1998, p.1.1)

My starting point is the widely used ASHRAE definition of thermal comfort "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2017) (I revisit different definitions of comfort in 2.2.2). There is a long tradition of thermal comfort research in which engineers, architects, physiologists and other researchers have investigated people's satisfaction with their thermal environment. This offers many insights relevant for my question about what people want from their heating system. This section starts by outlining the influential thermal comfort model introduced by Fanger. It then moves on to describe the adaptive thermal comfort approach, which considers how people use both heating and other options to obtain satisfactory conditions.

2.2.1 Fanger's Predicted Mean Vote

P.O. Fanger (1934-2006) is a central figure in the history of thermal comfort research. Thermal comfort was a well-established research field when Fanger started his work in the 1960s, but his introduction of a heat balance approach to derive a predictive comfort equation was ground-breaking and continues to be extremely influential half a century later. His text book *Thermal Comfort* (Fanger, 1970) is by far the most highly cited publication in the thermal comfort field (Rupp et al., 2015).

While previous research had investigated thermal comfort at different temperatures and relative humidities, Fanger was the first to derive a generalisable equation based on six factors (air temperature, radiant temperature, relative humidity, air velocity, clothing level and metabolic rate). He started by deriving an equation for heat exchange between the person and the environment based on the physics of convection, conduction and radiation. The resulting “comfort equation” indicates how the properties of the environment (air temperature, radiant temperature, relative humidity, air velocity) combine with factors affecting individual physiology (clothing and metabolic rate) to “create optimal thermal comfort for persons under steady state conditions”[p.42].

Fanger introduced the predicted mean vote (PMV) index to cover situations where the conditions for “optimal thermal comfort” are not satisfied based on this comfort equation. The calculated PMV is the thermal sensation on the ASHRAE seven point scale which ranges from -3 (cold) to +3 (hot) with 0 being neutral (neither too hot nor too cold). Fanger derived a relationship between mean reported thermal sensation and the six variables in the comfort equation based on empirical findings from experiments in climate chambers. During these experiments the subjects cast thermal sensation votes on the seven point scale. Clothing, activity and environmental variables were carefully controlled. It is important to note that Fanger’s methods establish the mean thermal sensation within a group and that it does not imply that every individual will be satisfied if the PMV is neutral. Large numbers of subjects were tested to give the results statistical validity and Fanger derived an equation to calculate the predicted proportion of occupants who are dissatisfied (Fanger, 1970, p.128).

Fanger’s findings are based on results from people in steady-state conditions in a climate chamber. Thermal comfort research has traditionally focused on static conditions and more recent work assessing responses to changing conditions (Schellen et al., 2012; Schweiker et al., 2013) has been in controlled experimental settings, and does not reflect the complex diurnal fluctuations in the temperature in a typical UK home described in Section 2.4.1.

Fanger’s derivation of mean sensation votes for large numbers of occupants is a practical solution for those designing buildings (such as offices and hospitals) with many occupants who will have little individual control over their environment. Fanger was very clear that his work was focused on the needs of the designers of HVAC equipment for conditioned buildings, writing “thermal comfort is the ‘product' which is produced and sold to the customer by the heating and air conditioning industry" (Fanger, 1970, p.15). De Dear points out "Fanger's model is undeniably an ingenious solution to this complex problem, but the enormous success of the model is probably due mainly to the way in which the problem was conceived in the first place, and how the format of Fanger's solution matched perfectly the requirements of thermal comfort practitioners, namely the HVAC engineering profession" (de Dear, 2004, p.38). The focus on the needs of designers who are sizing equipment is a natural one given the requirements of the industry, but it has also served to embed what de Dear (2004) characterises as an "engineering" approach to thermal comfort, in which building occupants are regarded as passive recipients of a product (an environment at a constant, satisfactory temperature) and assumed to have thermal requirements which do not change over time (as long as clothing and activity level are constant).

2.2.2 Defining Thermal Comfort

My starting point was the ASHRAE definition of thermal comfort but there are a number of issues with this definition as a basis for research. Fanger was clear that "that condition of mind which expresses satisfaction with the thermal environment" is a subjective assessment by individuals. Hellwig (2015) offers "subjective indifference to the environment" as a definition of thermal comfort. Expressing satisfaction and being indifferent are clearly two different responses.

The challenges posed by evaluating thermal sensations are discussed by Auliciems (1981) who points out that the ASHRAE comfort definition "clearly contains an affective component" [p.114] but this component of emotion or feeling is not present in the ASHRAE sensation scale which simply asks whether the respondent is warm or cool, not whether they are satisfied. This leads him to highlight the issues of "imprecise semantic usage" in thermal comfort research. This reservation is echoed in Halawa and van Hoof's (2012) review of the strengths and limitations of the PMV model. They discuss evidence that thermal neutrality (taken by Fanger as the optimum) is not necessarily the respondent's ideal state.

Shove (2003) traces definitions of comfort through history, showing how a term that was originally applied to a state of mind and relationships between people (e.g. comforting a bereaved friend) acquired a material dimension. She describes how, based on the work of Fanger and others, comfort was turned into a measurable attribute, something that was to be provided to building occupants, who were conceived of as passive recipients.

It is clear from the literature that thermal comfort is both subjective and hard to pin down as a concept. An individual's ideal thermal state, a state with which they express satisfaction, and a state to which they are indifferent may represent three different temperature ranges.

2.3 Adaptive thermal comfort

2.3.1 Introduction to ATC

Humphreys and Nicol (Nicol et al., 2012, 1994; Humphreys, 1978, 1995) have long advocated an adaptive approach to thermal comfort. A key tenet of this approach is the principle that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol et al., 2012, p.8). Adaptive thermal comfort focuses not on whether people are satisfied, but on what actions they take to mitigate dissatisfaction. In climates with cool or cold weather, these actions can include operating a heating system. People who are thermally uncomfortable will make behavioural adjustments, such as changing their clothing or posture, as well as interacting with heating controls and building fabric (for instance opening windows or drawing curtains). This view of thermal comfort as a dynamic process in which occupants are actively engaged gives a different perspective to Fanger's concept of thermal comfort as a static product of the HVAC industry, received passively by the occupants. Adaptive thermal comfort offers many insights particularly relevant for the situation in homes. Tweed et al. (2014, p.2) point out: "the key difference between the home and other environments is that householders are usually in charge of their own comfort". The residents are usually able to start and stop the heating, set the temperature level, open and close windows etc., in a way that occupants of conditioned offices are not.

The adaptive thermal comfort approach recognises that the environment constrains what people can do and may limit whether they can achieve their thermal desired state. Humphreys et al. (2015) give a long list of possible constraints "wealth of the occupants, the climate, the design of the building, the cost of fuel, the cost of clothes, the requirements of other people, the socially correct dress, the controllability of the heating system ... whether the activity is fixed or may be varied ... The list is virtually endless" [p.89]. Hellwig (2015) adds occupants' limited knowledge and a limited responsiveness of the building and its systems to the list of possible constraints.

The ASHRAE RP-884 adaptive model project is an important milestone in the codification and dissemination of the adaptive approach to thermal comfort. It was the basis for two important and frequently cited journal papers (de Dear and Brager, 1998; Brager and de Dear, 1998). As it stood in the 1990s, ASHRAE Standard 55 -1992 *Thermal environmental conditions for human occupancy* described methods for determining acceptable indoor conditions based on the PMV model. It was recognised that this could potentially drive unnecessary energy use if occupants would in fact be comfortable in a wider temperature range, as suggested by the adaptive thermal comfort approach.

The report of the RP-884 project (de Dear et al., 1997) outlines the approach taken to adaptive thermal comfort and traces the translation of these concepts into an "adaptive model" for inclusion in ASHRAE Standard 55 (ASHRAE, 2017). The authors emphasise that the adaptive model is complementary to, rather than contradictory to, the static heat balance model of thermal comfort. Fanger's model allows for an alteration of clothing and metabolic rate, while de Dear et al also include psychological and physiological adaptations as well as a wider range of behavioural adaptation.

Section 1.2.2 of de Dear et al. (1997) outlines a conceptual model of adaptation and is an important articulation of the proposition that there are three main categories of adaptation:

- Behavioural adaptation. Three subcategories of modifications people might make (either consciously or unconsciously) are listed:

  - Personal adjustment including adjusting clothing, posture, activity, moving location, eating or drinking.
  - Technological or environmental adjustment - interacting with HVAC equipment and the building fabric (e.g. windows and shading).
  - Cultural adjustments such as scheduling (e.g. siestas) and dress codes.

- Physiological adaptation as a result of exposure to particular thermal conditions. Two subcategories are identified: genetic adaptation and acclimatisation (over a period of days or weeks).
- Psychological adaptation. The report states “thermal perceptions are directly and significantly attenuated by one’s experience and expectations of the indoor climate”.

Brager and de Dear (1998, p.85) put forward an “adaptive hypothesis” that: “satisfaction with an indoor climate is achieved by matching the actual thermal environmental conditions prevailing at that point in time and space with one’s thermal expectations of what the indoor climate should be like”. Behavioural adaptation involves changing the thermal environment (of the individual or of the building) to bring the thermal conditions closer to the desired state. Psychological adaptation, on the other hand, involves the occupants changing their expectations, adjusting their ideas about satisfactory conditions to something closer to the actual conditions.

This two-way adaptation, both changing the thermal environment but also changing how it is evaluated, suggests that what people want from their heating depends on the context. It may change over time and when the heating system configuration changes.

2.3.2 Expectations

An important example of research in the adaptive thermal comfort tradition that suggests that expectations as well as behaviour play a role in thermal comfort is de Dear et al.’s (1991) report of two separate studies in Singapore, on air-conditioned offices and naturally ventilated high-rise residential buildings, in which detailed environmental measurements were taken at the same time as recording thermal sensation votes. Respondents in both locations were mainly sedentary for the hour before being interviewed. Thermal neutrality for the air conditioned offices was at an operative temperature of 24.2°C while for the naturally ventilated homes it was 28.5°C. When the responses were calibrated using the PMV model (i.e. the results were compensated for differences in clothing level, relative humidity etc. between the two environments), the predicted neutral temperature in the residential setting was about 2 degrees lower than that actually observed. This led the authors to conclude “these data suggest that thermal perceptions are significantly attenuated by expectations” (de Dear et al., 1991, p.264). They point out that long-term residents of Singapore have established expectations of indoor climate at home and at work and suggest these expectations are context-specific and that expectations “appear to form the benchmarks for thermal perception”. This leads them to a statement of the principle that thermal comfort is not “a simplistic stimulus-response system” [p.259]. This has important consequences for my investigation as it suggests that the reactions of residents are not determined by the thermal conditions, but are influenced by each individual’s thermal history and expectations linked to a particular location and time of day.

A further study that supports the case that expectations of conditions for a particular location are influential in the evaluation of thermal comfort is Oseland’s (1994) work comparing thermal sensation for the same (English) subjects at home and at work which found “the respondents chose room temperatures in their homes which were significantly lower than those in their offices”[p.11]). Environmental data logging and thermal sensation questionnaires were carried out with subjects at work and at home on the same day. Oseland found that although there were significant differences between the air and radiant temperature in the two settings (and hence differences in the predicted sensation votes from the PMV model) the subjects rated their thermal sensation as similar. Oseland considered other variables which, based on Fanger’s equation, could influence the comfort vote. He found no significant difference between the office and home situation. Since a previous phase of the work had involved reaching higher temperatures in the same homes, the lower temperatures were not a result of inadequate heating systems. Oseland's results suggests that expectations are likely to be an important factor in thermal comfort in the home, where occupants have developed expectations of the domestic environment based on a lifetime's thermal experiences.

Thermal comfort research has been predominantly focused on offices and other public buildings, but there is also an active tradition of investigating comfort at home in different countries. In addition to the studies of Oseland (1994) and de Dear et al. (1991) I have already mentioned, Nicol (2017) describes the wide range of indoor temperatures evident from plotting "cloud" charts of mean daily internal temperature against mean daily external temperature in several countries. Studies looking at thermal comfort in the context of temperature fluctuations during the day are rare but Hong et al. (2009) compared comfort and temperature in 2,399 UK homes at 07:00 and 20:00. They found that the neutral temperatures derived from the data differed from those predicted by the PMV model. Higher neutral temperatures were observed in the evening than in the morning, and this could not be explained by activity or clothing. Tweed et al. (2014) asked residents in five Welsh homes about their comfort three times a day alongside monitoring indoor temperature. They found diverse time-varying patterns in the different homes. They concluded that householders develop the skills to create thermal conditions they consider acceptable, and that these acceptable conditions are not the same as those that would be predicted by conventional PMV calculations.

Kim et al. (2016) describes an Australian study of 42 homes in which participants were polled about their comfort level at different times of day using a phone app. A periodic smartphone questionnaire asked about adaptive strategies such as opening windows, using fans and supplementary heating. The researchers aimed to build a model of adaptive behaviour but found that they had not identified a driver that make residents more tolerant of cooler than neutral conditions. Their statement on the factors they had not measured indicates the challenge of gathering information on the many possible adaptive actions: "conditions that couldn't be captured in our study might have played a role: such as using blankets, moving closer to warm radiant source ... exercising, cooking and concerns on energy bills".

2.3.3 Feedback

Feedback can be defined as information taken from one stage in a process and reintroduced to modify the process at an earlier stage (Fisk, 1981, p.3). The recognition of the importance of feedback between building occupants and their environment can be traced to the early stages of the development of the adaptive concept. Nicol and Humphreys (1973) describe the body's interaction with the thermal environment as a self-regulating system with feedback loops. The ASHRAE RP884 report authors point out that conceiving of the occupant as an "active agent" interacting with the environment implies the existence of feedback loops in which sensations of thermal discomfort lead to behavioural or expectation adjustments, which in turn affect the thermal sensations of the occupant. The three feedback mechanisms identified (two of these are shown in Figure 2.1) reflect the categories of adaptation listed in 2.3.1: behavioural adjustments (to indoor climate, clothing or activity), psychological adjustments (in which "expectation and habituation are influenced by one's current thermal experience or one's longer history of experiences with both the indoor and outdoor climate") and acclimatization ("an unconscious feedback loop that affects physiological thermoregulation setpoints") (de Dear et al., 1997).

Hellwig (2015) describes how the feedback between occupant and environment includes the occupant's evaluation of the thermal sensation against their expectations. She points out that the desirable conditions vary with time, internal state and activity: "an environment that is suitable on one day or for one activity may not be in another instance". (Hellwig, 2015, p.311). This highlights the dynamic aspect of changing thermal requirements. Humphreys and Nicol (1998) also stress the dynamic relationship implied by feedback.

Humphreys et al. (2015)'s description of the system with feedback considered by Adaptive Thermal Comfort research is an important influence on this investigation. The idea that residents of a home, the building, its heating system form an

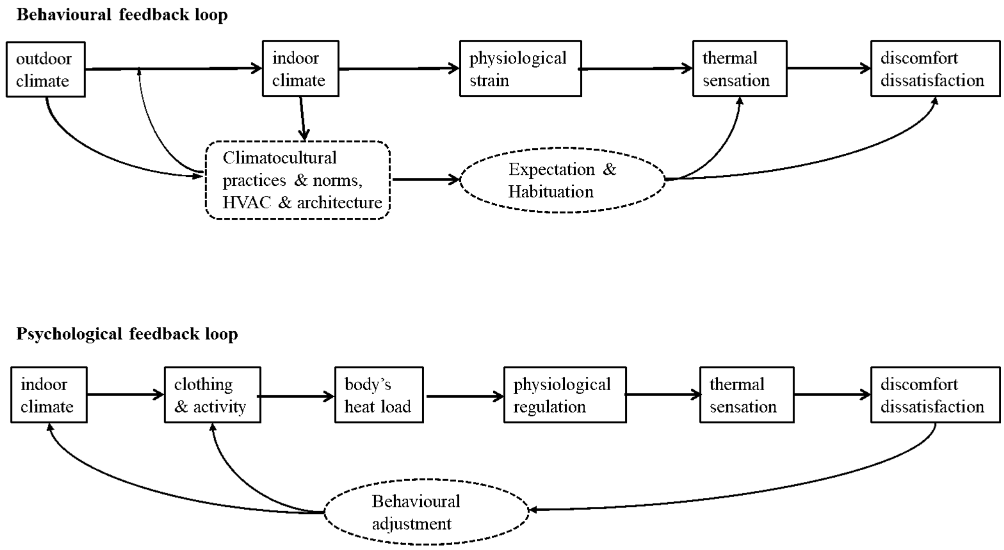


Figure 2.1: Feedback loops from de Dear et al (1997, pp.10,13)

adaptive system with multiple feedback loops is crucial to the analysis in Chapter 6

2.4 Context for electrification of heating

The next section summarises literature which sets the scene for this investigation. I start by describing the gas central heating systems which are used in a large majority of British homes. I introduce the intermittent running patterns followed by many households and how these lead to fluctuations over the day, both in temperature in the home and national gas demand.

I then introduce the need for electrification of home heating and the unfamiliar heating technologies this involves. Options for the electrification of heating, and the requirement for flexible heating demand to minimise future grid investment costs are introduced. The challenges of managing peaks in electricity demand and the need for demand management are introduced. This moves some of the responsibility for system flexibility from supply and operation companies to the electricity consumers in their homes.

2.4.1 Gas heating in the UK

The predominant type of heating in the UK is central heating from a gas boiler: 90% of homes have central heating and 91% of these are fuelled by natural gas (Palmer and Cooper, 2014). During the winter heating season, it is very common in UK homes to operate space heating intermittently, running the boiler for a few hours in the morning and the evening, but not at night or in the middle of the day (Huebner et al., 2015).

Rudge (2012) provides a historical background for the prevalence of intermittent heating in the UK in her account of the historical context for fuel poverty in Britain. She identifies the traditional use of open coal fires (the most usual form of heating before the conversion to North Sea gas) together with a high proportion of poorly insulated homes (which lose heat quickly) as the main reasons why homes were only heated for part of the day. She speculates that the British habit of shutting down heating systems at night is related to the unpredictability of the next day's weather. Rudge draws a contrast with countries with colder winters where the tradition was to use closed stoves to heat airtight homes, providing a steady temperature through the day. Differences in climate and historical heating practice lead to a situation where "the British are still in the habit of closing down heating systems at night, which many overseas visitors find hard to understand" (Rudge, 2012, p.8).

Intermittent operation of the heating system leads to temperatures in the home which vary during the day. Plots of internal temperatures during the day frequently show a pattern of peaks and troughs rather than a steady temperature (Huebner et al., 2015; Kane et al., 2015), implying that many households are accustomed to a dynamic, constantly changing thermal environment at the times when they are in the home.

The intermittent pattern of boiler operation is reflected in gas demand patterns, leading to significant peaks in the gas demand in the morning and evening. These peaks in demand are not an issue for the gas network as they are met by allowing the pressure in the gas supply network to fluctuate, with the volume of the supply pipework acting as a buffer. Wilson and Rowley (2019) describe how the variable "linepack" (amount of gas in the high pressure pipelines) allows supply to be matched with demand. The buffering in the gas supply network provides flexibility to deal with the significant ramp in demand which occurs on cold winter mornings.

The scale of the fluctuations in demand supplied by the gas network is illustrated by Wilson et al.'s (2018) analysis of peak demand in the 2017-2018 winter period. This occurred with the "beast from the east" cold weather on 1/3/18. The peak demand on the gas network of 214GW was more than four times the peak on the electricity network of 53GW (occurring on the same day). The change in demand on this extreme weather day was an increase of 116GW in the three hours from 5am to 8am (i.e. an increase of more than twice the *maximum* electricity demand).

The current situation, with intermittent operation of heating leading to varying temperatures in the home and causing large fluctuations in energy demand, is made possible by the flexibility of the gas supply system. In the next sections I explain the need for electrification of heating, and why some of the responsibility for flexibility in the energy system is likely to move from the fuel supply system to the households using heating.

2.4.2 The need for a transition to low carbon heating

Residential space heating accounted for approximately 58 Mte CO_{2e} or 16% of total UK carbon emissions in 2018 (BEIS, 2019). Reducing emissions from heating homes will be an important step towards achieving the UK's commitment to net zero greenhouse gas emissions by 2050.

Energy systems modelling suggests that it will not be possible to reach 2050 carbon reduction targets without a very substantial shift away from gas heating to lower carbon heat sources, for example electric heat pumps or district heating from a low carbon heat source. The scenarios also show that converting the existing building stock to low carbon heating is an extremely important part of this transition, implying that the majority of households will have to change their heating system. For example Delta-ee (2012) identifies 22 million homes currently using gas heating which require lower carbon heating systems, and predicts that homes built between 2011 and 2050 will only be responsible for 2% of heating carbon emissions in 2050

Multiple scenarios have been proposed for future heating technologies. Most of these imagined futures involve a significant role for electric heating, in particular air and ground source heat pumps (Leveque and Robertson, 2014). This implies a significant increase in the use of electricity for heating.

A series of recent reports from the UK's Committee on Climate Change (CCC) outline both the urgency of the decarbonisation challenge and the options available to tackle it. The CCC is an independent, statutory body established founded under Climate Change Act 2008 to advise the Government on both setting, and progress towards meeting Carbon Budgets. The Carbon Budgets are five year caps on emissions which are set in law once they have been accepted by Parliament .

The 2016 report *Next Steps for UK Heat Policy* (CCC, 2016) sets out the scale of challenge posed by the high proportion of emissions from heating and how it will be necessary to largely eliminate these emissions by around 2050 to meet the targets in the Climate Change Act. The report goes on to say that progress in decarbonising heat has stalled and that action is required immediately, stating that "deployment of low-carbon heat cannot wait until 2030" [p.7]. The report identifies several options for low carbon heating, pointing out that the most suitable heat source for a particular building depends on location, space available and other factors.

The 2018 publication *Hydrogen in a Low-Carbon Economy* (CCC, 2018) reported on further work to assess two options for low carbon heating: electric heat pumps and using hydrogen as a fuel. The report strongly recommends hybrid heat pumps, an option that allows a future combination of electric and hydrogen heating. (hybrid heat pumps are described further in 2.4.4.) The report concludes: "The path to near-full decarbonisation by 2050 now entails near-term deployment at scale of 'hybrid' heat pumps in buildings on the gas grid, with hydrogen boilers contributing mainly as back-up to meet peak demands on the coldest winter days" [p.11].

In *UK housing: Fit for the future?* (CCC, 2019b) the CCC again stresses the urgency of a transition to low carbon heating, stating: "deployment at scale of 'hybrid' heat pumps in buildings on the gas grid should start soon (up to 10 million by 2035)" [p.13] and pointing out "deployment of heat pumps remains very low at around 160,000 heat pumps, with only around 18,000 units sold in 2016" [p.28].

2.4.3 Heat pump characteristics

This section describes different types of heat pumps and how their characteristics differ from gas boilers, introducing the features that are likely to be unfamiliar to households accustomed to gas boilers.

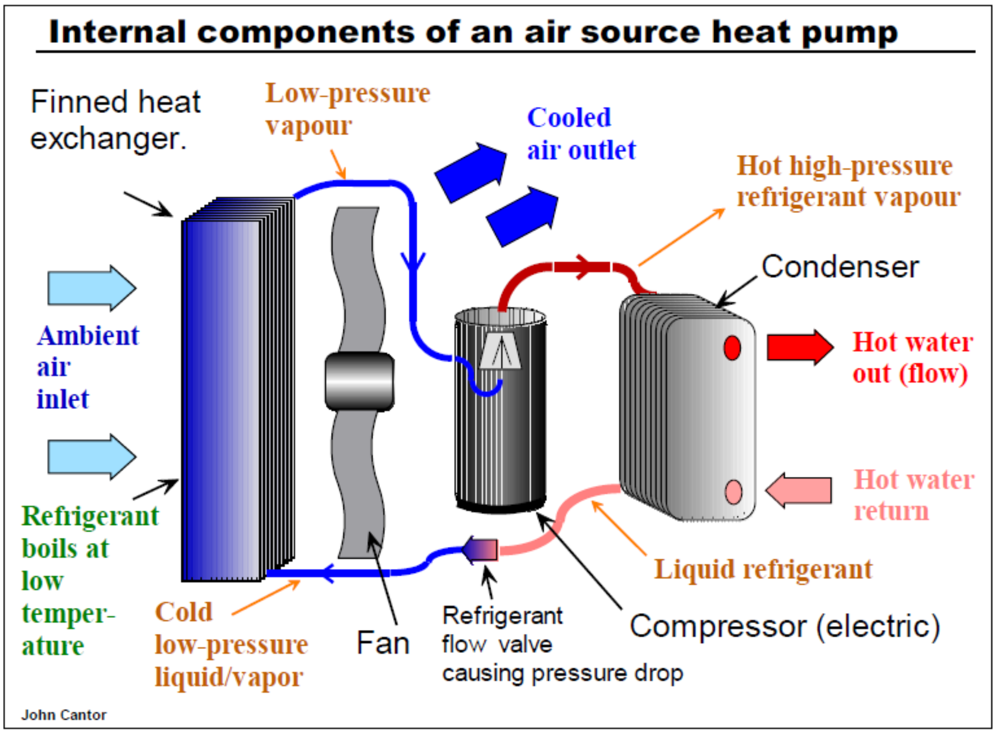


Figure 2.2: Schematic of heat pump components (source Cantor (2011))

Heat pumps transfer heat from a low temperature source to the heated space by pumping refrigerant round a circuit with two different pressure levels. Low pressure refrigerant evaporates, taking in heat from the source. It is then compressed to a higher pressure at which it condenses, releasing heat into the space to be heated. Most heat pumps installed in the UK heat water to circulate through radiators or underfloor heating pipework.

There are two main types of heat pump: ground source heat pumps take heat from the ground while in air source heat pumps the refrigerant is evaporated through heat exchange with outside air (EST, 2013). In contrast to a gas boiler, both types of heat pump require equipment outside as well as inside the house. An air source heat pump incorporates an outside unit with evaporator and fan while a ground source heat pump uses pipes buried in the garden.

Heat pumps (both air source and ground source) have different output characteristics to gas boilers. The efficiency varies depending on the temperature difference between heat source and heat sink. Cantor (2011) explains that a heat pump operates most efficiently when it supplies hot water to heat emitters at 35-40°C. This is a lower temperature than the 50-70°C supply temperature usual with a gas boiler (supplying radiators). This lower temperature means that the house does not heat as rapidly as it does with a boiler system. A heat pump has to run for a longer time period than a boiler to heat up the house.

Cantor explains that heat pumps achieve the best efficiency and highest carbon savings when they supply low level heat continuously; the use of boost heating or supplementary heating reduces heat pump efficiency. Lowe et al. (2017b) describe a situation which seems counter-intuitive to those familiar with gas boilers: running the heat pump steadily can consume less electricity and supply more heat than running it intermittently for a shorter overall time period. They explain "for heat pumps with good part load performance, it is possible in principle to shift from intermittent to continuous heating and simultaneously increase annual heat demand, and reduce electricity consumption and CO_2 emissions" (Lowe et al., 2017b, p.15).

2.4.4 Hybrid heat pumps

Hybrid heat pump systems combine many of the advantages of both boiler and heat pump. There are several possible configurations of hybrids (Element Energy, 2017), but the type of hybrid heat pumps outlined in CCC (2018) and considered in this investigation consists of a heat pump in parallel with a gas boiler, operated with a common control system.

Hybrid heat pump systems offer two ways to manage electricity network peaks: flexible use of the heat pump by shifting the electricity demand to an earlier time and switching fuel between electricity and gas. The hybrid system can utilise the flexibility and energy storage capacity of the gas network during periods of high demand for heat or power (such as cold weather periods and midweek evenings).

The gas boiler allows rapid response to instantaneous requests for heat. Hybrid systems can be retrofitted around existing heating systems, retaining the existing radiators and also the existing boiler (CCC, 2018; Element Energy, 2017). These features lead the CCC to suggest “this more incremental approach to switching to heat pumps is likely to be considerably more acceptable to the public than replacing the boiler with a heat pump ” (CCC, 2018, p.12).

CCC (2018) points out that to use a hybrid heat pump most efficiently (minimising cost for residents), a sophisticated control system is required to decide which heat source to run at which times. The controller has an important role to play in reconciling the flexibility needed to manage electricity network peaks with meeting the heating needs of individual households.

A hybrid heat pump’s potential to switch between using electricity and gas provides an extra level of demand flexibility compared to a stand-alone heat pump. In the future it is likely that homes will have an increasing role as an “infrastructure junction” (Späth and Rohracher, 2015) between different energy networks (e.g. the house supplies electricity from PV panels or from a storage battery). The ability of a hybrid to switch between different fuel sources to heat the home could contribute to this new role of households as flexible energy nodes.

2.4.5 The challenge of demand peaks

Section 2.4.1 described how the gas supply system provides buffering so that customers can be supplied reliably even at times of rapidly increasing demand. Unlike the buffered gas network, the electricity supply system has to match supply and demand second by second, which means that the electricity network must be designed to supply short term demand peaks (Strbac, 2008). A transition to electric heat pumps in many homes would have a significant impact on these peaks (Redpoint, 2013). Shifting current heat demand patterns to the electricity network would dramatically increase peak demands and require significant investment to increase the capacity of the electricity supply system (both electricity generation and transmission/distribution networks) (DECC, 2012). CCC (2016) explains that future electrification of heat implies substantial costs for reinforcements to the electricity system to meet the additional demand. The CCC’s central estimate for electricity demand in 2030 (which includes 2 million heat pumps and also increasing demand from electric vehicles) is around double today's level (CCC, 2019b).

A transition from gas boilers to electric heat pumps would not lead to the pattern of gas demand being reflected exactly in the current pattern of additional electricity demand. Love et al. (2017) describe how heat pump demand has less variation than that from gas boilers, with a lower peak:mean demand ratio, but they also show how a new morning peak in electricity demand starts to appear as the number of heat pumps increases, based on modelling of a 20% deployment of heat pumps. This implies that the morning peak in electricity demand will become increasingly significant as heat pump penetration increases.

2.4.6 Heating demand side management

"Demand side management" (DSM) is the general term used to cover a variety of techniques to modify electricity demand (on the customer side of the electricity meter), both reducing the overall load and shifting it to different times. "Demand Side Response" (DSR) is a subset of DSM. DSR is a term that covers moving the demand to a different point in time, but not necessarily reducing overall demand. Another term used frequently is "load shifting" i.e. moving electrical loads from peak periods to other times when the load on the network is not so high (Torriti, 2015).

Electric heating loads can take part in DSR by running at times of low overall demand to heat up the thermal mass of the building (Bruninx et al., 2013). Providing the building is warmed sufficiently in advance, the heating can be switched off during periods of high electricity demand, without impact on the residents since the space is already warm.

Demand management benefits network operators and electricity suppliers by making networks easier to manage and allowing additional flexibility in balancing demand and supply. DSR to avoid peaks in electricity demand is valuable at different points in the system (Charles Rivers Associates, 2017):

- For electricity suppliers DSR provides the ability to manage their customer load and to match supply and demand without having to purchase expensive extra electricity at times when demand is higher than expected.

- For Distribution Network Operators (DNOs) it can be used to reduce congestion on local electricity distribution networks, thus avoiding additional investment to increase local capacity or remove bottlenecks.

- For Transmission System Operators (National Grid in Great Britain) DSR is a way to manage national peak electricity loads and also to integrate an increasing share of intermittent renewables. DSR is one of a number of options (which also includes electricity storage) to minimise the amount of extra capacity required in the system and hence reduce the costs of system reinforcement.

DSR benefits the network, but if it reduces overall costs it is also in the long-term interests of energy users. The costs for DSR can be divided between system costs and participant costs (Torriti, 2015, p.22). If the reduction in electricity system (generation, transmission and distribution) investment costs as a result of flexible demand is greater than the extra investment by households required, the households should see a benefit in lower overall cost of heating.

Consumers can be encouraged to shift the times they use electricity by special tariffs which reward them for changing when they use power. A "Time of Use" (ToU) tariff sets different costs for different blocks of time in the day. Another option is "real-time pricing" with prices based on the fluctuating wholesale market half-hourly price. Apart from the long-standing "Economy 7" and "Economy 10" tariffs designed for electric storage heaters, there are currently few ToU tariffs available from suppliers, and little public awareness of these options (Frontier Economics and Sustainability first, 2012).

2.4.7 Smart girds and smart homes

The flexible demand patterns involved in Demand Side Management can be placed in the wider context of discussions about the smart grid, and this thesis draws on relevant literature on this topic. The definition of a smart grid given in Naus et al. (2014, p.436) is that it is "characterised by the active management of both information and energy flows, in order to control practices of both distributed generation, storage, consumption and flexible demand".

The smart grid vision involves a more active role for homes in the energy system, as locations for energy generation, demand management and storage rather than households simply acting as passive consumers. Torriti (2015, p.1) characterises the concept of the smart grid as a vision of a future energy supply system with two way flows of energy and information, going on to say "a vital role in their future smart grid will be played by flexible consumers". Strengers (2013) questions visions of what she designates a "smart utopia", pointing out that it is based on a specific view of an energy consumer which she labels "Resource Man" who is rational, motivated by cost saving and prepared to engage with new technology. She provides evidence to support her statement that "the Smart Utopia excludes, ignores or seeks to eradicate the vast majority of human experience and energy's role within it". Strengers offers an alternative approach based on the recognition that smart energy technologies are entangled in everyday activities, which is further described in Chapter 3.

A related concept to smart grids is 'smart homes' which Hargreaves and Wilson (2017, p.1) define as "a generic descriptor for the introduction of enhanced monitoring and control functionality into homes". They highlight a need for more studies of how householders actually use Smart Home Technologies (SHTs -a category which includes smart heating controls) in real life settings, writing that "most SHT research has given no consideration to smart home users at all" [p.3].

2.5 Heat flows in a building

The previous section introduced the changes required to heating systems. Before moving on to describe changes to heating control it is necessary to introduce some concepts from building physics which are important to my discussion of patterns of temperature and how these change when the heat source changes. This section briefly outlines how the heat flow from a heating system causes a varying profile of temperature over time inside the building. This simplified and summarised account is based on Fisk (1981).

The fuel supplied to a heat source (gas to a boiler, electricity to a heat pump) is converted to a temperature inside a home in a series of steps. The first step is conversion of fuel to heat, for example burning gas in a boiler. In the "wet" heating systems which predominate in UK homes, the combustion is used to heat water, which is then circulated through radiators or other emitters. The radiators warm rooms by a combination of convection and radiation. The rate at which heat is transferred from the radiators depends on the temperature at which the water is supplied. Solar gain and other heat sources in the house add to the heat flow into the house.

Heat is lost from the house to the outside through two main routes: heat flowing through the walls (at a rate determined by the thermal conductivity) and through air movement (as a result of ventilation or air inleak). The rate of heat loss will be influenced by the external temperature. Actions by residents such as opening and closing doors, windows and curtains can make a significant difference to heat flows.

The dynamic properties of the heating system and the home determine how varying heat flows translate into patterns of temperature. For this investigation of the flexibility of heating demand in time there are several points to note about the relationship between patterns in time of heating operation and the resulting temperature:

- There is a time lag introduced by the thermal mass of the building. When the heat source starts to run, the temperature will rise at a rate influenced by the thermal properties of the building.

- A second time lag is introduced by the rate of heat transfer from the radiators, which depends on the radiator temperature and surface area.

- If one heat source (e.g. a boiler) is replaced by another with different characteristics (e.g. a heat pump) which supplies hot water to the radiators at a different temperature, then the rate at which the temperature in the home rises will change.

2.6 Heating control

This section introduces different types of heating controller, setting the new type of control associated with DSR in the context of the historical development of heating controls. Different generations of equipment are described and the assumptions about their users that are made during controller design are identified.

2.6.1 Thermostats and timers

Three methods of heating control are commonly found in UK Homes:

- switching on and off at the boiler
- using a thermostat
- using a thermostat combined with a timer

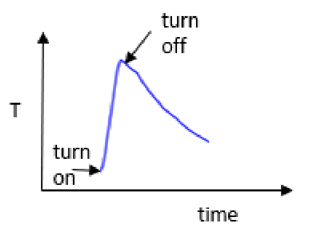
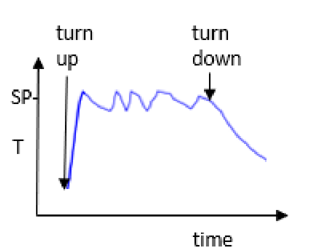
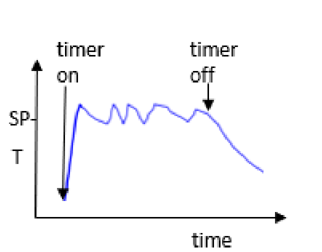
Type of control	Description	Temperature pattern
No thermostat	Switch on and off at boiler. Temperature rises when boiler switched on and falls when switched off.	
Thermostat only	Set desired temperature. Temperature rises to setpoint then boiler cuts in and out to maintain temperature. Boiler stops and temperature drops if setpoint reduced.	
Thermostat and timer	Set desired temperature and times heating should operate. Temperature starts to rise at beginning of period, then boiler cuts in and out to maintain temperature until end of requested time period, then temperature drops.	

Figure 2.3: Temperature patterns resulting from different standard control modes SP setpoint T temperature

Figure 2.3 shows these three different control cases and typical temperature patterns that result from these. Residents who operate their heating simply by switching the boiler on and off will experience rising temperatures when the boiler is running and falling temperatures when it stops.

The simplest form of equipment to maintain a constant temperature is a thermostat. Peffer et al.'s (2011) account of history of heating control points out "the basic function of the typical residential thermostat - to set a target temperature, see the current temperature, and control the equipment accordingly - has remained constant over the past sixty years". They describe the "ubiquitous Honeywell Round, which emerged in 1953 and is still available today" [p.2530]. The limitation of this type of manual control is that the house will only start to warm up once the thermostat has been turned up, with the time to reach the requested temperature varying depending on the starting temperature, outside temperature and physical characteristics of the house and heating system.

The most common heating controller in a British home is a thermostat (usually in a hall or living room) together with a timer to enable scheduling of running times (Kane et al., 2015). The EFUS study of 2,616 nationally representative homes in the UK in 2011 found that 90% of heating systems had this kind of control in 2011 (BRE, 2013). Even when a timer is present not all households will use it. The EFUS study found that 10% of homes had a controlling timer but did not use it. The remaining 80% of all homes with a timer control which they reported using often combine timed operation with some manual operation (BRE, 2013).

Lomas et al. (2018) define a category of "standard controls" that comprises the three options already mentioned as well as thermostatic valves on radiators (TRVs). TRVs can be used to control the temperature in individual rooms. It is rare to use these as the main method of control. The usual configuration is that the heating controller operates the central heating as a single system for the whole house, with residents occasionally adjusting TRVs in individual rooms (Kane et al., 2015).

Meier et al. (2011) describe the increasing uptake of programmable digital timers, with integrated thermostat and timer, with a trend towards thermostats being designed and marketed as "a new category of consumer electronics" [p.1892].

Lomas et al. (2018) identify two other control types: smart controls, which are discussed in the next section, and "non-smart advanced heating controls". The latter category incorporates energy-saving variations on timer-thermostat control which include weather or load compensation and time-proportional integral control. For the purposes of this comparison, these can be grouped with the standard thermostat and timer system since they only operate the heating during the periods for which heating is requested and do not involve preheating ahead of these times.

2.6.2 Introducing algorithmic control

Peffer et al. (2011) describe the introduction of more sophisticated controllers that use algorithms to decide when to run the heating. An algorithm is a series of instructions. Fry explains that while this definition could be used to describe many types of instructions (for example a recipe) "usually algorithms refer to something a little more specific…they take a sequence of mathematical operations .. and translate them into computer code" (Fry, 2018, p. 7-8). She goes on to describe how algorithms are "fed with data, given an objective and set to work on calculations on how to achieve their aim". This calculating ability gives algorithms the potential for autonomous decision-making. Some algorithms are designed to use machine learning, building a model based on the data they receive which improves with experience as the amount of data available increases.

Algorithms in heating control open up possibilities for running heating more efficiently and providing improved comfort for residents. For example algorithmic control can be used to heat pump at the most efficient operating point. As described in 2.4.3, this is likely to involve running the heat pump at a steady low output for a long time ahead of the period for which warmth is required, to take advantage of the improved performance of the heat pump at a low delivery temperature. Figure 2.4 shows how the pattern of operation (and rate of increase of temperature) are likely to differ between a heat pump and a boiler with pre-heating. This preheating ensures that the home is heated to the desired temperature for the whole of the period specified by the residents. This type of algorithmic control is often described as "model predictive control" (MPC) (Lomas et al., 2018). The PassivSystems controller introduced in Section 1.2.3 is an example of this type of controller.

This type of preheating is not the only way in which machine learning can be applied to home heating control. Scott et al. (2011) describe another kind of learning, about when the residents are present in the home, using occupancy sensing and occupancy prediction to control home heating.

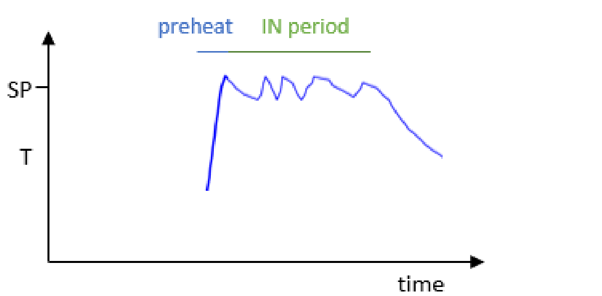
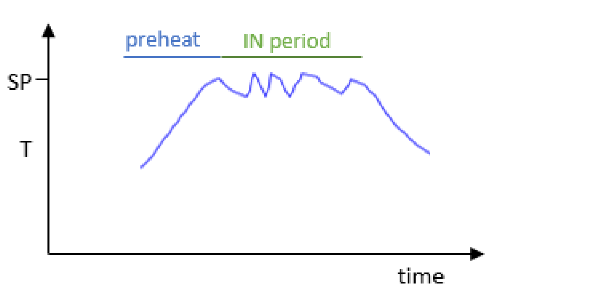
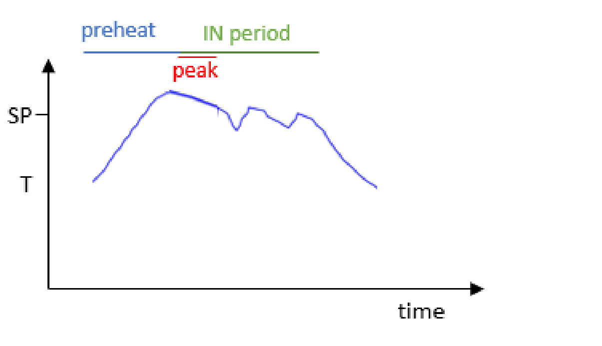
Configuration	Temperature pattern
Boiler	
Heat pump (longer preheat period)	
Heat pump with Demand Side Response (no heating in peak period)	

Figure 2.4: Temperature profiles resulting from algorithmic control with preheating

Algorithmic control can also take network requirements into account, if a suitable data signal is available. In order to signal peak electricity demand periods to households, information about how electricity prices vary with time of day can be sent to the algorithm. A time of use tariff, with higher electricity prices at peak times when electricity network congestion is expected and lower price at times demand is low, can be incorporated in an algorithm that minimises overall running costs. The algorithm can evaluate the cost savings of shifting operation to times when electricity is cheapest while still ensuring that the residents' specified IN temperature is reached.

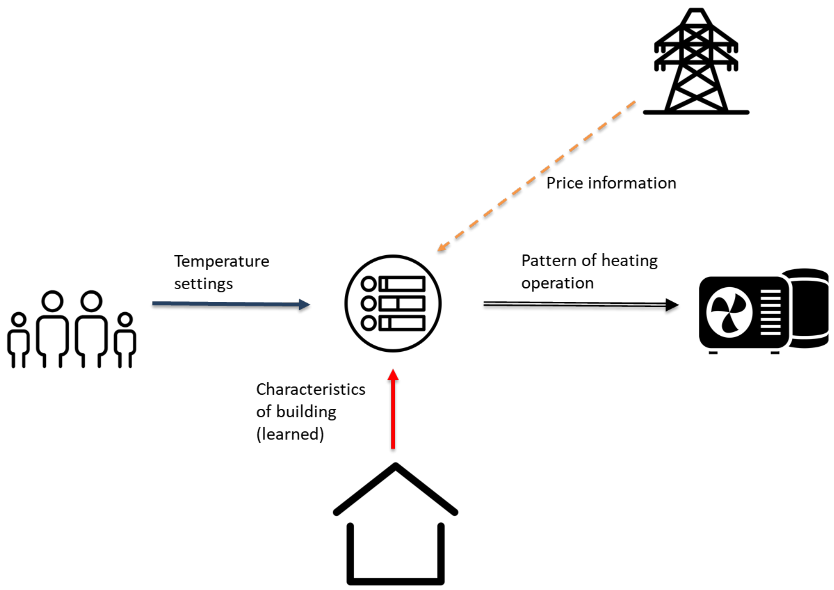


Figure 2.5: Information flows to algorithmic controller

Figure 2.5 indicates the data inputs to the algorithm. The temperature settings requested by the residents are combined with the learned characteristics of the building and the heating system to generate a signal telling the heat source to run or not to run. The price information from the network is an extra input which the algorithm takes into account when calculating the lowest cost running pattern over the day.

Figure 2.4 shows how the preheating period can be moved to an earlier time to avoid a peak demand period. It is likely that the morning peak in electricity demand will become a concern for the electricity network as there is increasing electrification of heating (Love et al., 2017). A price signal encouraging running during the night when overall demand is low and avoiding the peak morning period is likely to lead to demand shifting so that more electric heating runs during the night.

With a hybrid heat pump, information about gas and electricity prices opens up two possibilities for the control algorithm to provide DSR:

- switching between running the heat pump using electricity and running the boiler using gas, depending on calculations about which is the lowest cost option

- shifting electricity consumption by the heat pump to an earlier time to take advantage of time-varying electricity prices

To take advantage of this cost optimisation the residents must delegate to the algorithm decisions not only about when to start the preheating, but also about which of the two heat sources to run. This represents a significant change from the usual situation of operating gas boilers with gas tariffs that do not vary with time. In UK homes on the gas network, there is currently no energy supply network influence on the times when the boiler runs. In the case of a heat pump or hybrid heat pump with an algorithm that optimises based on variable energy prices, the price signal from the energy network is directly influencing the running pattern of heating equipment in the home.

Many advanced heating controllers are described as “smart” (Lomas et al., 2018). Algorithmic controllers and smart controllers are overlapping categories with algorithmic control a key feature of many heating controls branded as smart. A typical smart controller optimises heating operation to match customer specifications (e.g. minimise cost) using algorithms. Smart controllers also provide non-algorithm based features such as information on energy use, and the opportunity to operate the controls remotely from a phone app (Hargreaves and Wilson, 2017; Yang and Newman, 2013).

2.7 Review of literature on household experience of heating

This section surveys literature on household experience of heating controls, new heating systems and new patterns of energy demand. The main focus is on academic and other work in the UK since it is likely that reactions to change will depend on the previous history of heating in a particular country.

2.7.1 Household reactions to heat pumps

The literature on UK householders' reaction to heat pumps is not extensive. Owen et al. (2012) found that lack of understanding of heat pumps among their interviewees led to suboptimal control (residents who were not running the heat pump consistently for long periods). They also reported concerns about disturbance from the fan running on the air source heat pump evaporator unit. Wrapson and Devine-Wright's (2014) investigation of the uptake of low carbon heating systems described complex combinations of heating technologies in rural homes. Judson et al. (2015) interviewed residents in the North of England who had heat pumps installed. They found that the change in the heating technology led to a need for rearrangement of practices and routines in the home because of the change in heating response time.

The Energy Saving Trust heat pump trial (EST, 2013) monitored actual performance of heat pumps in 83 homes in phase 1 and followed up with phase 2 in 43 homes, including interviews with householders. Caird et al. (2012) describe consumer experience of these trials. They found that the most common problem reported was a lack of understanding. Noise was also a concern from some of their those who responded to their questionnaire. Comparing data on heat pump performance with questionnaire responses, they found that better performance was correlated with residents who said that they had a good understanding of the technology and who operated the heat pump continuously.

It is straightforward to understand that the longer a boiler runs the more fuel it consumes and the greater the energy bill will be. The concept that running a heat pump for a long time continuously is actually less expensive and more environmentally friendly than to run it in short bursts is difficult to grasp for those who are accustomed to operating boilers. Judson et al.'s (2015) account of residents' reactions to a trial of heat pumps describes how "switching to uninterrupted use contrasts with the 'blasts' of heat experienced when gas boilers fire up … and can be disconcerting for users"[p.36].

The RHPP (2015-2017) study of heat pump installations receiving government incentives included interviews with 21 households (Lowe et al., 2017b). 18 of these said they were satisfied or very satisfied with their heat pump but the report authors comment “the case studies revealed the rich complexity of the notion of satisfaction, which included the level of thermal comfort felt, running costs, ease of use, environmental impact, technical integrity, noise levels and controllability of the system” (p.23). The monitoring for the RHPP study revealed a very wide spread of different patterns of use.

There is little published literature on residents’ reactions to hybrid heat pumps. Shepherd (2019) reports on satisfaction surveys of five homes with hybrid heat pumps in Lincolnshire. The project report from the Freedom project which forms the case study for this investigation (Freedom Project, 2018) includes a brief section on consumer acceptability. Stumpf et al. (2018) describes work on strategies for providing explanations of smart heating which formed part of the project.

2.7.2 Studies of demand flexibility

The major focus of current academic work on demand flexibility is on electricity use for appliances. Work by Torriti and by Grunewald and his collaborators has focused on describing the activities behind patterns of electricity demand, not on reactions to changes in patterns (Grunewald and Diakonova, 2018; Torriti et al., 2015). Satre-Meloy et al. (2019) look at intra-day variations in electricity consumption and emphasise the importance of considering consumption as a function of time of day. Powells et al. (2014) investigated the flexibility of timing of electricity demands from appliances such as cookers and washing machines. They found that time of use pricing had a limited ability to engage practices in the home, with performances of solitary practices such as doing laundry easier to shift in time than practices such as cooking and eating the evening meal which involve several overlapping individual schedules.

The literature on heating demand in the home is mostly concerned with overall heating energy use rather than patterns of demand during the day. For example Gram-Hanssen (2010) investigated reasons for different heating demand in similar homes in Copenhagen. The only investigation of DSR for heating in UK homes found for this literature review is outlined in Sweetnam et al. (2019) and Fell (2016) who describe a trial of demand management in properties with heat pumps. They spoke to residents of eight homes trialling an algorithmic controller retro-fitted to an existing air source heat pump. They encountered respondents who were unhappy with increased late night and daytime temperatures and disturbances due to overnight heating and noise. Sweetnam et al. (2019) point out that most academic literature is based on theoretical models, which assume standard user behaviour. They identify a need for more research on DSR for heating from the household point of view.

Grunewald and Diakonova (2018) outline the mechanisms that provide the flexibility to respond to incentives, and point out that flexibility is not free but involves non-monetary as well as financial costs to the households involved. They identify three elements to the additional requirements to achieve flexibility: redundancy, operational tolerances and skills. Their discussion centres on electrical appliances but can be applied to hybrid heat pumps. These provide a good example of redundancy, since two heat sources (a boiler and an electric heat pump) are required, and, although the overall system can be optimised, the cost is higher than for a standard boiler alone. Hybrid heat pumps require operational tolerance in terms of the residents' acceptance of a changed pattern of operation and temperature delivery. The new understanding required to operate a heat pump efficiently are outlined in Section 2.4.3.

Grunewald and Diakonova's point that shifting loads will have an impact on consumers suggests that it is important to understand the impact of shifting heating loads on the households involved. Their statement that "flexibility is found to be deeply bound up with practitioners, even in cases where automation is thought to take full agency of response management" [p.65] points towards some key theoretical considerations for the investigation which are outlined in Chapter 3.

2.7.3 Research on thermostats

Shipworth et al. (2010) investigated whether central heating controls reduce energy consumption and, based on reported thermostat settings and actual measured temperatures, found no evidence to show this is the case. There was also a significant discrepancy between reported hours of heating running in the day (mean 9.4 hours on weekdays) and the value inferred from temperature profiles (mean 8.2 hours). Shipworth et al. found that households adjust temperature setpoints fairly frequently, a finding echoed by Tweed et al. (2015) and ETI (2014).

Research on user interactions with their controllers has tended to focus on whether the assumptions used in building simulation models correctly represent actual patterns of use. Huebner et al. (2015) describe a method for inferring thermostat setpoint temperatures from measured temperatures in the home based on the assumption that a rising or steady temperature means that heating has been requested. Analysing data from 248 homes in the CaRB study, the authors describe daily temperature profiles which fall into four clusters, three of which show considerable variation over the day. This challenges the frequent modelling assumption that one standard pattern of operation fits all homes. Kane et al. (2015) discuss how to characterise heating operation patterns based on temperature data. Analysis of temperatures in 249 dwelling in Leicester led them to conclude that 51% were heated for two periods each day and 33% were heated for only one period. Bruce-Konuah et al. (2019) inferred "manual override behaviour" from temperature profiles, identifying variables that influence the probability of the residents in ten homes overriding the normal schedule to run the heating for longer periods.

Little work has been published on the way people actually set their heating controls based on setpoint data rather than inferring from measured temperatures. Morton (2016) had access to actual setpoint data in a group of 12 homes. Her thesis on the subject of interactions with heating controllers investigated the duration of manual and scheduled use of the heating system. She found that in winter there was a wide range of ratios of manual to scheduled use in the houses, varying from no manual operation in one home to 100% in another.

Another strand of research has focused on usability of heating controllers and residents' understanding of how their heating system works. Stevenson et al. (2013)

investigate usability of control interfaces and in a series of reports building on the work of Kempton (1986), Revell and Stanton (2014, 2016, 2018) look at mental models of heating systems, aiming to extract the picture users have of how their heating system operates.

Policy-related research in recent years has focused on controllers as an item of consumer choice. For example a report for DECC, *What people want from their heating controls?* (Rubens and Knowles, 2013) used interviews and diaries to investigate how heating control requirements vary for different households. They identified five different "user types", highlighting the diverse motivations and patterns of heating use in different households.

2.7.4 Research on smart heating control

The literature on household reactions to smart heating controllers in not extensive. Sweetnam et al. (2019)'s discussion of reactions to a heat pump trial has already been mentioned. This trial involved fitting algorithmic controllers in a group of homes with heat pumps. Hargreaves and Wilson (2017) describe trials of British Gas Hive and RWE Smart Home systems. They discuss the negotiations, conflicts and resistances generated as these technologies were domesticated.

Yang and Newman (2013) discuss the reaction of 23 US users to the Google Nest "learning thermostat". They found that "while the Nest was well-received overall, the intelligent features of the Nest were not perceived to be as useful or intuitive as expected, in particular due to the system's inability to understand the intent behind sensed behavior" [p.1].

A number of reports, from the Energy Systems Catapult, in particular Batterbee (2018) and Lipson (2018) discuss the challenges of providing low carbon heating, including the innovative control strategies required. The focus is on opportunities both for new smart control products and for new services from energy retailers, identifying the customer needs these should meet. Batterbee (2018, p.7) points out that "consumers care about far more than just air temperature setpoints".

2.7.5 Research gap

This literature review has identified a need for research on household reactions to new forms of heating systems and heating control. In particular very little work has been identified describing household's reception of algorithmic control to enable DSR, or reactions to hybrid heat pumps.

The CCC (2018, p.16) emphasises that the UK general public has a low awareness of alternatives to natural gas heating and that "there is a limited window to engage with people over future heating choices, to understand their preferences and to factor these into strategic decisions on energy infrastructure".

This statement of the importance of understanding heating preferences sets the scene for this investigation of understanding what people require from low carbon heating systems, in the context of a UK trial of hybrid heat pumps.

Chapter 3

Social practice theory

3.1 Introduction

In Chapter 2 I introduced the need for flexible heating demand and the role of algorithmic control in delivering this. I showed how control algorithms depend on interpreting user requests and include assumptions that the residents will not object to changes in patterns of operation. This highlights the importance of understanding what output the residents actually want from their heating system, and how they react to a change in the pattern of output.

In this chapter I introduce the main theoretical approach used in the investigation of these questions, social practice theory. This places individual actions in a wider social context, and explores the meanings and purposes that motivate the actions. Social Practice theory can be used to investigate motivations for operation of heating and how these are linked to what is happening in the home.

Different practices carried out by the residents and the organisations supplying energy to the home intersect at the heating controller. I relate the role of the heating controller in overlapping practices to concept of social worlds and boundary objects.

3.1.1 A different approach

Social practice theory crosses the boundaries of philosophy, sociology and cultural studies (Røpke, 2009). It takes social practice (as opposed to individuals, social systems, or technologies) as the central topic of enquiry (Shove and Walker 2014). Schatzki (2010b, p.73) states " its organization is the property of the practice .. and not a property of the individuals participating in it". Practice theory offers an alternative to various dualisms in social theory, crossing the boundary between structure and agency (Giddens, 1984), individual and social (Shove et al., 2012), mind and body (Reckwitz, 2002a), society and nature (Ingold, 2011), stability and change (Shove et al., 2012). Of particular importance to this investigation is how practice theory overcomes another dualism - that between people and technology. Chiu et al. (2014, p.577) set out the case for the practice perspective transcending "the separation of 'technology' and 'people"'. Shove and Spurling (2014, p.118) describe how " it is through practices that socio-technical systems become embedded in the routines and rhythms of everyday life".

Different definitions of practice are found in the literature, but all of these have in common a focus on what is actually done. Schatzki (2002) variously describes a practice as a "set of doings and sayings", a "bundle of activities" and an "organized nexus of actions". Reckwitz (2002a) explains that "a practice represents a pattern which can be filled out by a multitude of single and often unique actions reproducing the practice".

The section on the practice of showering in Shove (2011) offers a light-hearted example of the application of practice theory. A video shows how two individuals incorporate taking showers in their daily lives, demonstrating how the practice has multiple meanings which change with the practitioner, location and time of day. Martin showers in the early evening as this is an important part of his "going out ritual" before he leaves home to meet friends. Ali takes multiple showers in the day - at home to wake up, then again at work to cool off after her journey and following a run at lunch time. She then showers again to freshen up after her trip home. These examples are used to illustrate how "Martin and Ali create and reproduce and sustain specific versions of normality". A key aspect of this description of practices relevant for my investigation is the importance of the timing of practice, both the duration of each performance of the practice and at what point in the day it occurs.

Shove et al. (2012) discuss how changes in practices come about as elements of the practice, including their material configurations and meaning, change over time. In the example of the practice of showering, the increasing availability of technology (bathrooms with showers and instant hot water) has influenced how increasing numbers of practitioners have been recruited to the practice over time (Shove, 2003). It is not simply technology that influences the spread of the practice. Gram-Hanssen (2007) discusses how teenagers develop showering practices under the influence of their peer group.

3.1.2 Energy and practices

An important statement of a principle followed in this investigation is from Shove and Walker (2014): "energy is used, not for its own sake, but as part of, and in the course of, accomplishing social practices". Shove et al. (2012) claim that "understanding energy is first and foremost a matter of understanding the sets of practice that are enacted, reproduced and transformed in any one society, and of understanding how material arrangements, including forms of energy, constitute dimensions of practice."

Practice theory offers a framework to link heating with other practices in the home, with interactions among household members, and with the wider social context.

3.1.3 Research on energy and practices

In recent years, practice theory has been widely applied to include social science thinking in the investigation of energy demand. Practice theory has been used in the UK and other countries:

- To suggest new approaches to energy policy. Shove (2010) criticises the dominance of the ABC paradigm (considering individual Attitude, Behaviour and Choice as a basis for behaviour) in environmental policy in the UK, putting forward practice theory as an alternative which explains the limited success of interventions which are based on a "language of individual behaviour and personal responsibility" [p.1271] and offers alternative ideas for policy centred on practices. Shove's paper sets out the key tenets of her practice approach:

"social theories of practice on the one hand, and of behaviour on the other, are like chalk and cheese. Whereas social theories of practice emphasise endogenous and emergent dynamics, social theories of behaviour focus on causal factors and external drivers. Likewise, people figure in the first case as carriers of practice and in the second as autonomous agents of choice and change" [p.1279].

- To present new ways of looking at how people use energy, for example Strengers (2013, Chapter 1) argues for an analysis of smart grids using "an alternative *ontology of everyday practice*, in which smart energy technologies, and energy itself, are entangled in everyday activities" [original emphasis]. Practice theory encourages the study of how energy is used as a consequence of everyday practices.

- As a theoretical underpinning for studies relevant to energy transitions. For example Nyborg (2015) spoke to families using smart home equipment and Powells et al. (2014) investigated electricity load shifting in the context of practices in the home. Torriti et al. (2015) used practice theory to underpin a quantitative discussion of how different practices contribute to peak electricity demand.

3.1.4 Is heating a practice?

Galvin and Sunikka-Blank (2016) highlight the difficulty of drawing boundaries round practices and challenge what they see as somewhat arbitrary boundaries used by researchers. My approach is that practices must satisfy Morley's (2014) definition that they are "activities with which people engage in their own right... recognised as such by those who participate in them, and require some time and attention to undertake".

Gram-Hanssen (2010) describes practices of "regulating the indoor climate", including within this definition both operation of heating and adjustment of building fabric (e.g. window opening). Kuijer (2014) also uses practices in the plural when she writes of "practices for staying warm at home". In order to draw a boundary round a set of practices which form the subject of this investigation I am using the actions listed under de Dear et al. (1997)'s category of "behavioural adjustment" which includes not only the actions identified by Gram-Hanssen but also clothing and other personal adjustments. I use Kuijer's terminology to designate these "practices for staying warm at home". I consider the operation of central heating as one of this set of practices. Setting heating schedules and making changes to temperature setpoints are a recognizable set of activities which require attention and so fulfil Morley's definition. Much of this investigation focuses on this practice, but I also consider other practices such as operating supplementary heating that fall within Kuijer's "practices for staying warm at home".

3.1.5 Rhythms of practice

Practice theory can be used to examine patterns in time of energy use. In this investigation I draw on the practice theory literature about the regular rhythms created by practices.

In his discussion of the dynamics of energy demand, Gordon Walker highlights rhythms of energy use which he describes as "the dynamics of repetition and 'beat' over shorter timescales". He identifies daily patterns as "a key scale of rhythmic temporality" (Walker, 2014, p.51) and points out the importance of these rhythms for generating peaks in collective demand. "If we ... scale up the combined practice/energy rhythms of multiple homes, organisations, transport infrastructures and so on, to local,regional or national level spatial units, we see the production of rhythmic 'load profiles' in electricity or gas grids". Section 2.4.5 explains how daily peaks in aggregate demand have a significant impact on the management of energy supply systems. Walker describes how aggregated rhythms "are made up or constituted by the many practices of people and organisations reproducing, over time, similar patterns of coordinated activity" [p.51]. It is this aggregated pattern that is of particular importance when considering the demand on energy networks.

In Shove et al. (2009) Elizabeth Shove writes about "the complex temporal organization of everyday life" [p.1]. She suggests " rhythms are usefully understood as bundles of everyday practices" [p.10], describing how multiple everyday practices are linked together as they are carried out through the day. Shove refers to Zerubavel's work on how temporal cycles are organised by practice. *Hidden rhythms : schedules and calendars in social life* (Zerubavel, 1985) describes three parameters of the timing of situations and events that can be applied to patterns of heating operation:

- Duration: the lengths of periods that people are requesting heating
- Temporal location: when these heating periods take place
- Rate of recurrence

3.1.6 Practice elements

Reckwitz' description of elements of practice is very frequently cited: "a 'practice' (Praktik) ...consists of several elements, interconnected to one other: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge" (Reckwitz, 2002b, p.249).

Shove et al. (2012) simplify Reckwitz' account into three elements: materials, competence (skills, knowledge and technique) and meaning. Meaning includes "states of emotion and motivational knowledge" and is also described as the "social and symbolic significance of participating in a practice"[p.23].

In this study I shall not be referring to elements but rather to the subtly different "linkages" proposed by Schatzki, which are outlined in the next section.

3.1.7 Concepts from Schatzkian practice theory

This section introduces a set of concepts from Schatzki's approach to practice theory which are particularly relevant for this investigation.

3.1.7.1 Arrangements and prefiguration

Unlike other theorists (Reckwitz, 2002a; Shove et al., 2012) who include materials as an element of practices, Schatzki considers the physical context separate from the practice itself. In Schatzki (2002) he defines how "an arrangement of things is a layout of them in which they relate and are positioned with respect to one another" [pp.18-19]. He goes on to define an order as “an arrangement in which entities also possess meaning and identity”. He describes how “orders and objects exert a causal impact on activities and practice” [p.107]. In Schatzki (2010a) he has simplified the concept somewhat, dropping the separate category of orders and writing about “material arrangements” (defined as “a set of interconnected material entities”) and describing how the concepts of practices and arrangements are fundamental to his ontology: “social life, that is human coexistence, inherently transpires as part of nexuses of practices and material arrangements” [p.129]. The essential point here (and one also emphasised by Reckwitz (2002b) and Shove et al. (2012)) is that the physical setting shapes practices.

Schatzki’s concept of prefiguration: “ how the world channels forthcoming activity” (Schatzki, 2002, p.44) is a subtle way of examining the influence of the context (both physical and social) on the performance of practices. He writes “the mesh of practices and orders does not simply clear some paths and obliterate others. Rather it figures them as more distinct or fuzzy, more threatening or welcoming . . . ” Schatzki discusses the relationship of prefiguration with constraints “conceived as things that occlude but do not necessarily permanently prevent” [p.226]. In Schatzki (2010b) he describes how context is not determining actions, but is making some more likely than others.

Schatzki’s discussion of how arrangements prefigure actions is valuable for my investigation of how the type of heating system shapes operating practice. It recognises that residents are constrained by what their heating system is able to deliver, but have a range of options within these constraints, some of which are more likely than others.

3.1.7.2 Linkages between sayings and doings

Schatzki does not conceive of practices as made up of elements but instead writes of four “linkages” between the sayings and doings of practices. These provide a focus on the actions of the practice which can sometimes be lost in the Shove et al. (2012) three element approach.

Schatzki’s terminology has been developed over time. In Schatzki (2002) [p.77] he uses the following terminology for four linkages:

- *Practical understandings* - abilities that apply to the actions composing a practice
- *Rules* - explicit formulations and instructions that direct people to perform specific actions
- *Teleoaffectivity* (also referred to as teleoaffective structure) - what the practitioner will do for the sake of their ends given their beliefs, expectations and emotions.
- *General understanding* across a group of practitioners about why and how a practice should be carried out

In Schatzki (2010a) general understanding is combined with practical understanding and teleoaffective structures are renamed normative teoleologies

Schatzki's linkages form the basis of Gram-Hanssen's (2010) framework described in Section 4.2.1. This framework has subsequently been used by a number of energy researchers (Foulds et al., 2013; Behar, 2016; Morgenstern, 2016).

Practical understanding

Schatzki's definition of practical understanding, "knowing how, through the performance of bodily actions, to carry out actions that make sense to perform" (Schatzki, 2010b) is very relevant for considering how people understand the consequences of operating heating controls and how they know what to do to achieve their goals. It should be noted that this practical, bodily understanding differs from the intellectual understanding explored in investigations of mental models (Kempton, 1986; Revell and Stanton, 2014, 2016). A person may physically know how to achieve something (e.g. "if I set the timer to start one hour before I get home, the house will be warm when I arrive") even if they are not able to describe how their heating system is configured.

Rules

Schatzki (2002) identifies rules - "explicit formulations, principles, precepts and instructions that enjoin, direct or remonstrate people to perform specific actions" [p.79] as a linkage holding a practice together. I consider the role of formal instructions on how to operate heating and, in particular, the guidance provided by the instructions on how to set the schedule in a heating controller.

Teleoaffectivity

People carry out the doings and sayings that constitute a practice for the sake of some result. Schatzki uses the term teleology (orientation towards ends) to indicate the motivation behind practices. He uses the term teleoaffectivity (combining teleology with affectivity) to represent what the practitioner will do for the sake of their ends given their emotions and beliefs (Schatzki, 2002). This has a great deal in common with Shove et al.'s (2012) "meaning" element. I use the term "goals" as shorthand for the concept of teleoaffectivity.

Schatzki is clear that the motivations may not be logical or rational: "not everything that makes sense to people to do is sensible, intelligent, or appropriate from their own perspectives"(Schatzki, 2010a). He highlights desire, emotion, belief and perception as determining what it makes sense to do in a particular situation (Schatzki, 2010b).

Schatzki highlights the normative aspect of what makes it makes sense to do (Schatzki, 2002, p.80). He describes how normative perceptions of a practice - based on historical experience of carrying out the practice and seeing how others carry it out - influence, but do not determine, individual performances of a particular practice.

Lowe et al. (2017a, p.4) suggest that "what distinguishes Schatzki's theory from others' is that social practices are processes with trajectories". Section 2.5 described how a change in the heating setpoint leads to a pattern of temperature extending over time. People setting heating controls have to think about their goals for temperature in the future, and how they can achieve them. Shove and her collaborators also follow how practices change over time but the explicit incorporation of goals for the future in Schatzki's theory is particularly useful for my investigation of how people operate their heating systems.

General understanding

In his discussion of the practices of the Shaker community producing herbal medicines which form the core of Schatzki (2002), Schatzki described the general understanding that the Shakers had of their work, and how this "sense of common enterprise" motivated their production processes. This concept can be applied to general understandings of the purpose of flexible demand held by those involved in energy supply, who have shared objectives for a future of decarbonised energy and recognise the importance of DSR to match supply and demand. In Chapter 7 I investigate how far this general understanding is shared by households.

3.1.8 Pickering and "the mangle of practice"

My analysis also draws on a strand in practice theory represented by the work of Andrew Pickering. In his studies of sociology of science, Pickering describes "the reciprocal coupling of the human and the nonhuman, the interactive tuning of subjects and objects" (Pickering, 2002, p.170). This comes very close to Schatzki's account of the bi-directional shaping between people's actions and the objects around them when he describes how "practices affect, give meaning to, use and are inseparable from arrangements while arrangements channel, prefigure, facilitate and are essential to practices"(Schatzki, 2011). It also parallels the concept of a dynamic interaction between people and the heated environment considered in Adaptive Thermal Comfort

Pickering recognises that needs are not fixed but vary depending on a person's experience of what they can get. He quotes Herrnstein Smith (1988) : "What we speak of as a subject's 'needs', 'interests' and 'purposes' are not only always changing, but they are also not altogether independent of or prior to the entities that satisfy or implement them... there is a continuous process of mutual modification between our desires and our universe" (Pickering, 1995, p.54). A parallel can also be drawn with Shove's (2003) discussion of increasing expectations of thermal comfort over the last century and how this has been translated into design requirements.

An example of the "mangle of practice" given by Pickering (1995) is the development of a scientific instrument used in particle physics - the bubble chamber.

He follows the work of Glaser (who developed the bubble chamber from the cloud chamber) in a series of steps in which a set of failed iterations led to both innovations in design and modifications to Glaser's original goals. Glaser had hoped to develop an instrument to detect particles in cosmic rays but Pickering recounts how a series of physical and social "resistances" led him to change his objective to work with beams from particle accelerators.

Pickering's discussion of interactive tuning makes it clear that the people involved have agency. They do not simply accept the limitations represented by physical obstacles but will work to improve the situation, "mangling" both the equipment and their goals as they do so. In this process of "resistance and accommodation" people both adjust the technologies they are using and accommodate to them. This concept of resistance which can be overcome, rather than a hard constraint, can be used to consider how households adjust to heating DSR over time.

Pickering's description has much in common with Schatzki's practice theory. In both there is a stress on the goals of practices, and an insistence that these goals form part of the practice (Pickering (1995) describes the goals as being "in the plane of practice"[p.20]). Pickering's statement: "the language of constraint is the language of the prison ... my usage of resistance has none of these qualities" [p.65] is very similar to Schatzki's discussion of constraints and prefiguration.

3.2 Boundary objects and the social worlds framework

The role of technology (and objects in general) in social practices is an important aspect of the theoretical approaches I have described. Sometimes one object plays a role in many different practices. In the case of the algorithmic heating controller delivering DSR, it is taking part not only in households' practices of staying warm but also in the set of energy industry practices involved in matching supply and demand to ensure a continuous supply of electricity to these households. Two sets of practices with their different goals and practical understandings intersect at the heating controller.

In order to investigate the overlap of the practices of these different groups I draw on concepts of social worlds, and the boundary objects between them - objects which allow several social worlds to work together even though they have different goals. I aim to use this theoretical approach to consider the different social worlds of a group of households providing flexible demand and the organisations involved in supplying energy to their homes.

3.2.1 Social worlds

Anselm Strauss's influential paper on "A social world perspective" (Strauss, 1978) defines social worlds as "universes of discourse". He clarifies this definition:

> Though the idea of social worlds may refer centrally to universes of discourse, we should be careful not to confine ourselves to looking merely at forms of communication, symbolization, universes of discourses, but also examine palpable matters like activities, memberships, sites, technologies, and organizations typical of particular social worlds. (Strauss, 1978, p.121)

Strauss goes on to state: "In each social world, at least one primary *activity* (along with related clusters of activity) is strikingly evident ... Technology (inherited or innovative modes of carrying out the social world' s activities) is always involved" [p.122].

Based on Strauss's identification of activities as central to social worlds, Clarke and Star (2008, p.115) offer "groups with shared commitments to certain activities" as a description of social worlds. This is the definition I use in my discussion of the social worlds linked through a smart heating controller in Chapter 7.

3.2.2 Boundary objects

Star and Griesemer (1989, p.16) introduced the concept of a boundary object in their frequently-cited paper discussing the activities of the zoological museum director Joseph Grinnell. They described how Grinnell aligned the work of amateurs, farmers and animal trappers with the scientific objectives of zoological research by creating boundary objects such as maps and standardised forms to record specimen collection.

Star and Griesemer (1989, p.16) define boundary objects as “scientific objects which inhabit several intersecting social worlds . . . and satisfy the informational requirements of each of them”. A key feature of boundary objects is that they allow two social worlds with different goals to work together in a situation where “consensus is not necessary for cooperation” [p.388]. Bowker and Star (1999, p.16) explain that, to succeed as a boundary object, an object must be “plastic enough to adapt to local needs”. The flexibility to meet different sets of goals allows different groups to work together even though they do not have the same objectives. Star (2010) discusses the “interpretive flexibility” of boundary objects. She gives an example from Star and Griesemer (1989, p.16) of how the same map may be interpreted and used in different ways by tourists, zoologists and geologists.

Star and Griesemer’s (1989) list of the different ways in which boundary objects can be used to manage conflicting views includes the use of “versatile, plastic, reconfigurable (programmable) objects that each world can mould to its purposes locally”[p.404]. In Chapter 7 I examine whether an algorithmic heating controller can be moulded to the purposes of both households and energy networks, and to what extent it allows cooperation between these different social worlds.

The definition of a boundary object is hard to pin down, indeed their ability to be interpreted in different ways is one of their defining features. In Chapter 7 I use the characteristics identified by Star and her co-authors as a guide to assessing whether the controller is acting as a boundary object:

- Does it enable cooperation without consensus?
- Can each world mould it to its own purposes?
- Does it satisfy the information requirements of both social worlds?

A theme in Star’s studies has been the process by which successful boundary objects are standardised and eventually become a part of infrastructure. She traces how boundary objects such as forms for describing diseases develop into methodological standards which are embedded as infrastructure. I draw on these ideas in my discussion in Chapter 7.

The boundary object concept has been widely applied across a huge range of disciplines and subjects. In the energy field it has been applied to energy systems models (Taylor et al., 2014), energy performance certificates (Willan, 2019) and to energy meters (Lovell et al., 2017; Poderi et al., 2014). My literature search has not identified any discussion of smart heating controllers as boundary objects.

3.3 Comparison of approaches

Social practice theory concepts run through the three chapters in which I describe my findings, providing a framework for the reasons residents select particular actions, recognising that these are influenced by practical understanding and goals. I also draw on adaptive thermal comfort in Chapter 6 and discuss intersecting social worlds in Chapter 7.

There are many connections between the practice theory approach and the adaptive thermal comfort concepts described in Section 2.3. They have in common a focus on what people do rather than what they say about their feelings or intentions. Both approaches suggest that the response to the thermal environment is both physically and socially shaped. The technology available affects both what people can do and also what they wish for.

Adaptive thermal comfort recognises cultural influences on expectations, while practice theory frames these expectations as socially-shared understandings and meanings which form part of a practice entity. Adaptive thermal comfort's discussion tends to frame expectations in terms of individual psychology based on previous experience in the same (or a similar) place. Social practice theory adds a future focus to the motivation for heating operation, highlighting the goals people are aiming to achieve with their heating.

The social worlds concept also emphasises activities and the technologies that make these possible, but moves the focus from the practices themselves to groups of people each with their own distinctive practices. Ideas about boundary objects provide a framework for examining how sets of practices in distinct social worlds intersect.

Pickering's concept of the mangle, in which actions and goals are constantly adjusting in response to one another, sums up a theme from both practice theory and adaptive thermal comfort: that goals (and how people achieve them) are dynamic, changing over time. Humphrey's statement that "the desired state need not be constant, and in practice is not constant... We should therefore expect comfort to be sought by making a set of successive attempts to satisfy continually varying desires and needs" (Humphreys, 1994, p.60) can be linked with Pickering's point that "needs" are continually modified. In the context of home heating, the conditions that people desire are influenced by their experience of the conditions they can achieve.

Chapter 4

Research methodology

4.1 Introduction

This chapter outlines my overall approach to the mixed methods, case study-based investigation. I begin by discussing how theory was used to shape my analysis and outline my reasons for choosing particular methods. Section 4.3 explains the case study approach used and introduces the individual cases. This is followed by descriptions of the qualitative analysis of data from interviews and the quantitative analysis of data from heating controllers. The approach used to link accounts in the qualitative data with patterns in the quantitative dataset is described in Section 4.6

The methodology relates to the three research questions:

RQ1 What output do households want from their heating systems?

Section 4.4 explains how the theoretical frameworks introduced in Chapter 3 are used as a basis for qualitative analysis of residents' goals when operating their heating. Section 4.4.1 introduces semi-structured interviews, and explains why this method was chosen for in-depth exploration of the reasons residents chose particular controller settings. Section 4.5 outlines the quantitative methods used to analyse the controller data and relate these to residents' goals when operating their heating.

RQ2 How do residents interact with their heating system to get their required outputs?

The interviews also explore residents' practical understanding of how to get what they want from their heating controller. Section 4.5.5 describes how quantitative data on setpoints are used to analyse patterns of interaction with the heating controller. I explain how manual changes in setpoints are used as a indication that the residents want to change the output from the heating system.

RQ3 How do households react to a change in heating system characteristics? The installation of hybrid heat pumps with algorithmic control in the Freedom trial case study (described in Section 4.3.2) allowed investigation of residents' experience of changes. Interviews explored their reactions, asking about what differences they noticed.

4.1.1 Influence of the researcher

In this section I reflect on my role as a researcher and how my own first degree and professional training as an engineer may be influencing my research methods and findings. As an engineer trained in thermodynamics and engineering control, I have found my experience of commissioning and operation of controls for chemical plants directly relevant to this study of the control of heating in homes.

Engineers tend to have a pragmatic approach to problem solving and I have evaluated different possible theoretical approaches based on which seem best suited to tackle my research questions. Rather than alter the research questions when I found that more than one theory was required to answer them, I decided to draw on two different theory areas and draw practical links between them. My focus is on applying the theory rather than theory development.

As an engineer engaging in social research I have frequently faced challenges of reconciling different world views. When dealing with physical data I take a realist view that there is an independent external reality (Ritchie and Lewis, 2003). As I consider data from interviews I am conscious that social research has to deal with a variety of subjective individual realities, and that as a researcher I have an impact on the social world I am investigating. My approach resembles Maxwell and Mittapalli (2010)'s combination of "ontological realism with epistemological interpretivism" which they base in the philosophy of critical realism.

Attempting to bridge the gap between different traditions raises multiple practical as well as philosophical questions. One example is the dilemmas that have come up over the writing style for this thesis, such as whether I should write in the first or third person.

Another factor which I am conscious could be shaping my findings is my relationship with PassivSystems, the company who are part-sponsoring my PhD. The access to interviewees and controller data provided by the company has been essential to the research. I was given many opportunities to interact with the PassivSystems employees responsible for developing the heating controllers described in this thesis. Over the course of four years, with frequent conversations and e-mail exchanges, I have built up my understanding of the work of the designers. In particular I have frequently discussed my findings and the practical implications of my work with my main contact at the company, Edwin Carter.

Throughout the PhD both I and my PassivSystems contacts have been conscious of my need to maintain academic independence. The company has had the opportunity to review output to correct errors and misconceptions but they have not tried to alter or suppress findings that might be perceived negatively.

Felt et al. (2017, p.170-172) describe four different types of engagement between companies and researchers. In this framework my research sits somewhere between critical engagement (a scholar operating principally in an academic context, but influencing product development) and corporate engagement (researchers embedded in technology companies).

4.2 Applying theory

Chapter 3 introduced Social Practice Theory (SPT) and Section 2.3 outlined the Adaptive Thermal Comfort (ATC)approach. In this section I describe how these theories have shaped the approach I have taken to this investigation. I draw on the theories to provide a conceptual framework of the key aspects to consider, and the relationships between them. This provides me with categories to use and questions to ask in gathering and analysing empirical data. The theoretical framework also provides an interpretive lens to frame the reporting of findings and conclusions.

An important basic principle for the investigation which arises from ATC and

SPT is that the investigation should focus on what people actually do - their practices - as opposed to their attitudes or values (Shove, 2010). In interviews I did not ask about what people might do in hypothetical situations but asked about what they actually do each day. My quantitative analysis focused on setpoint changes as these represent actions taken by residents to achieve their heating goals.

4.2.1 Theoretical framework

In order to apply the theoretical concepts outlined in Chapter 3 to develop interview questions and coding categories, I drew on two frameworks from the relevant literature. This section describes Gram-Hanssen's analytical framework derived from practice theory, and how I combine this with the conceptual model of Adaptive Thermal Comfort in de Dear et al. (1997).

Gram-Hanssen (2010)'s framework of "practice elements" (illustrated in Figure 4.1) was developed from the Schatzki "linkages" described in 3.1.7.2. This framework was originally developed for a study of energy use in Danish homes and has since been used in analysis by a number of other energy researchers (e.g. Foulds et al. (2013); Behar (2016); Morgenstern (2016)) I considered using an alternative framework based on the widely-used "three elements of practice" (Shove et al., 2012) but decided that the Gram-Hanssen categories were most relevant for this investigation of heating operation. Section 3.1.7 outlines my reasons for finding Schatzki's linkages particularly appropriate when considering the goal-setting involved in heating operation. Gram-Hanssen's inclusion of Schatzki's categories of rules and know-how provides a helpful distinction between formal instructions and practical experience, which is not found in the Shove et al. (2012) "competence" category.

Drawing on Schatzki's description of the ways the "doings and sayings" of a particular practice are linked, Gram-Hanssen identifies four practice elements, illustrated in Figure 4.1

- Know how, embodied habits: Gram-Hanssen equates this to Schatzki's concept of practical understanding.

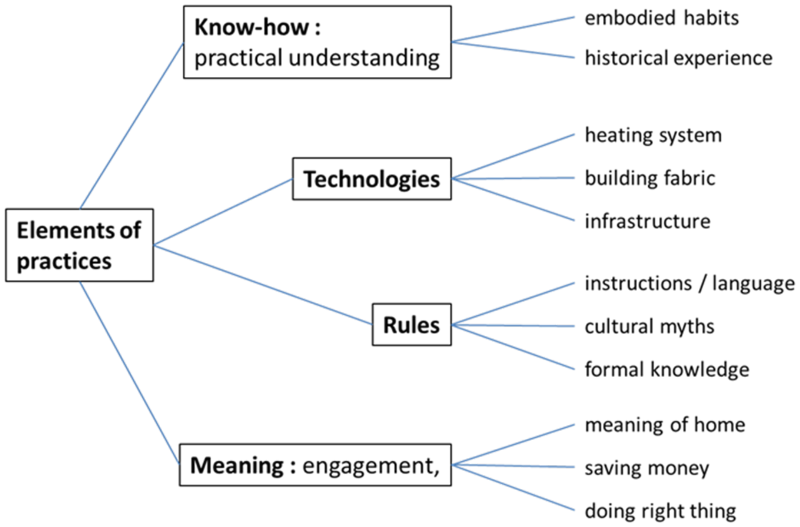


Figure 4.1: Practice elements based on Gram-Hanssen (2010)

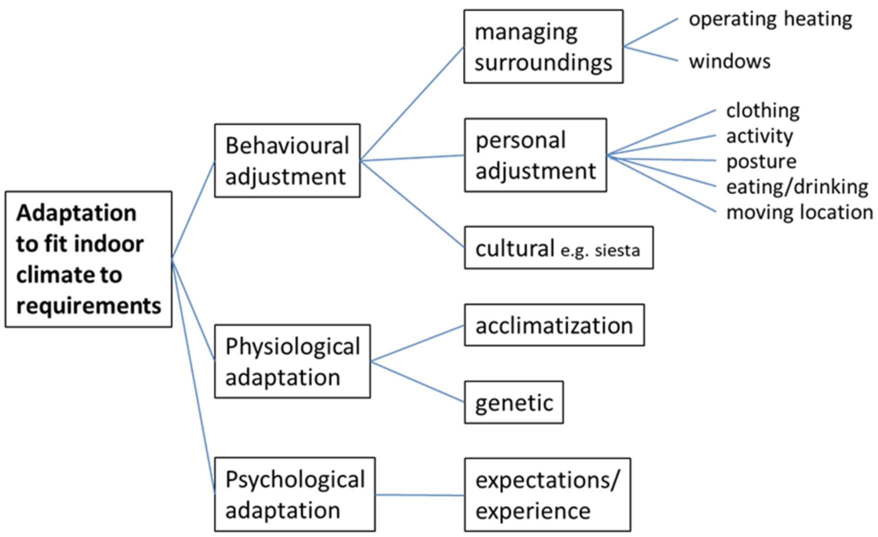


Figure 4.2: Conceptual model of adaptation based on de Dear et at (1997)

- Technologies: this element recognises how the physical environment influences practices. This inclusion of the physical context diverges from Schatzki who considers objects (including technologies) as arrangements outside practices. Gram-Hanssen includes the fabric of the building and the district heating infrastructure as well as the heating system in home heating "technologies".

- Rules, institutionalised knowledge – a category in which Gram-Hanssen includes both formal technical knowledge and instructions and also "cultural myths" about the best way to operate heating.

- Engagements, meanings. This element recognises that practices are goal-oriented and influenced by normative views and moods. It draws on the concept Schatzki (2002) labels as "teleoaffectivity".

As discussed in Section 3.1.4, Gram-Hanssen does not include the full range of actions to manage surroundings included in the de Dear et al. (1997) conceptual model. Figure 4.2 shows the options for behavioural adjustment outlined in this model, including personal adjustment actions, which are not included in Gram-Hanssen's framework.

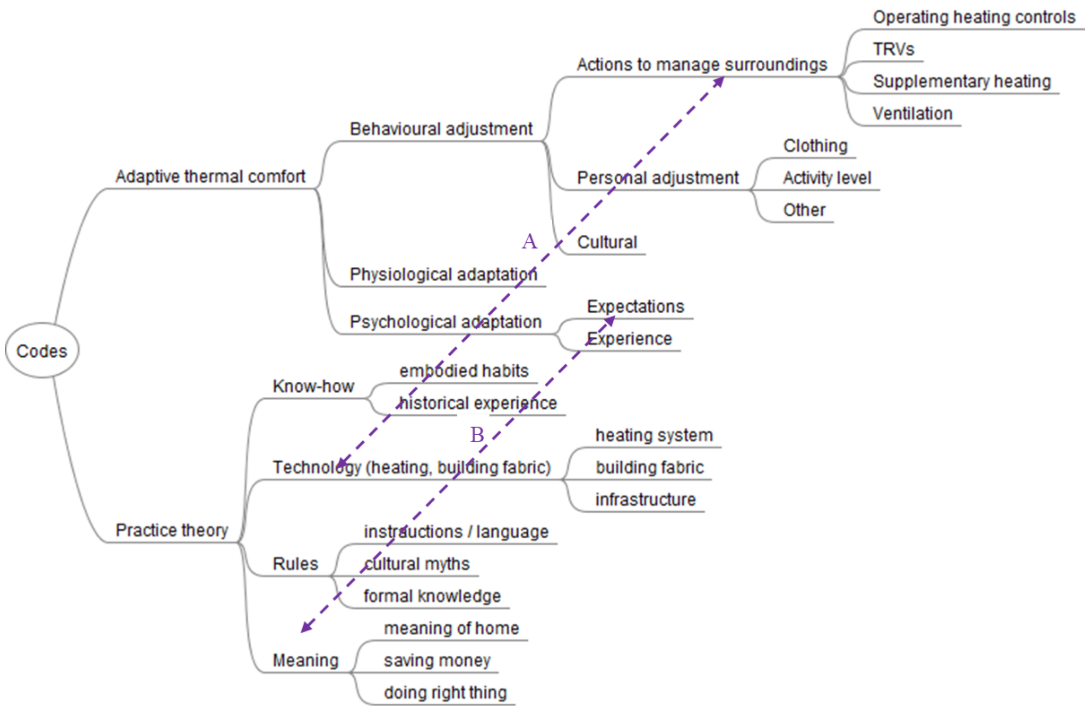


Figure 4.3: Combining the two frameworks

Figure 4.3 shows how I combined the two frameworks into a structure for coding. There are two clear links between the de Dear et al. (1997) (ATC) and Gram-Hanssen (SPT) framings, identified by arrows A and B in the diagram:

A. Between actions to manage surroundings in the ATC model and technology in the SPT framework. When using these categories for coding I included accounts of *what* people actually did with technologies under actions to manage surroundings in the ATC frame, and reasons they gave about *why* they did this under technology in the practice theory frame.

B. Between meanings in the practice theory framework and expectations in the ATC model. The psychological expectations which influence the occupants' assessment of their environment in the ATC model contribute to the meanings about the right thermal conditions included in the practice theory framework. I coded statements about wishes for particular temperatures at particular times under ATC expectations while the reasons given for these expectations were coded under practice theory meanings.

Other parts of the two frameworks are complementary rather than linked directly. The SPT framework allows coding of dimensions not explicitly included within the ATC model, such as knowledge about how to operate the heating system and formal and informal rules about this. The ATC personal adjustment category allows the inclusion of bodily actions (such as moving location) which are not easily incorporated in the practice framework technology category

Section 4.4.3 goes into more detail about the practical experience of interview coding and extra categories that were added to the coding framework during analysis.

4.3 Case study approach

Case study investigation is a well-established approach to answering "how" or "why" questions about a contemporary set of events over which a researcher has little or no control. (Yin, 2009). Flyvbjerg (2006) makes a strong case for the benefit of the in-depth exploration of complexity made possible by case study investigation, providing context-specific knowledge rather than what he sees as a "vain search for predictive theories" [p.224]. Flyvberg points out that even a single case study is valuable if it shows that a relationship which is thought to be generally true is false in one particular case.

This investigation draws on data from:

- A trial of hybrid heat pumps in 75 homes

- A database of data from a smart heating controller in over 3,000 homes
- The homes of a group of 11 PassivSystems employees

Each group of homes is treated as a separate case. The homes in each case all have the same type of heat source and heating control, and the cases are distinct from one another as each has different combinations of heating and controller type.

4.3.1 Introducing the case studies

This section describes the three different groups of homes which form case studies for this investigation. The designation of the cases has two elements e.g Freedom-Hybrid. The first term indicates the group of homes involved (in this example, those taking part in the Freedom trial) and the second the heat source in these homes (in this case a hybrid heat pump).

The central case study is the homes involved in the Freedom hybrid heat pump trial. Quantitative data from heating controllers were available from all 75 homes in which a hybrid heat pump was installed, the group I have designated **Freedom-Hybrid**. I also interviewed some of the trial participants in their homes. Figure 4.4 shows how the interviews overlapped with the Freedom-Hybrid quantitative data.

I visited seven households when their home was being considered for inclusion in the trial - a group of interviews I have designated **Freedom-Boiler**. Only qualitative information is available from the residents in Freedom-Boiler homes, as there was no monitoring data available for the time before the heat pump was installed. Two of these homes were considered unsuitable for a hybrid installation so did not proceed in the trial.

I spoke again to residents in four of the Freedom-Boiler homes which did proceed with the trial after my visit. These interviews with homes after their heat pump was operational are included in the Freedom-Hybrid case. (I was unable to contact the fifth household for a follow-up interview). I also visited residents in an additional seven homes for the first time after the new heating system had been commissioned. This means I have a total of eleven Freedom-Hybrid interviews in homes with a hybrid heat pump running, with 4 of these homes falling into the before installation case as well.

Figure 4.4 shows the overlap between the two cases.

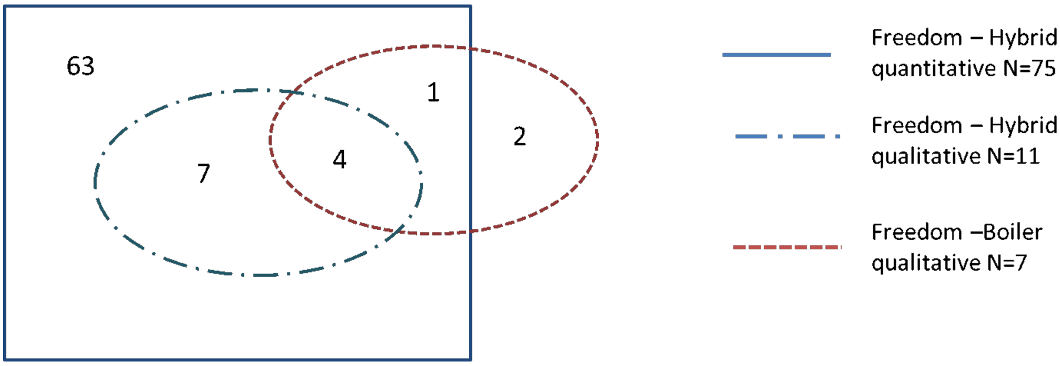


Figure 4.4: Freedom groups for quantitative and qualitative analysis, showing overlap of Freedom-Boiler and Freedom-Hybrid cases

The third case, designated **Customer - Boiler** is made up of PassivSystems customers with controllers operating conventional oil or gas boilers. Quantitative data were available from controllers in over 3,000 homes. The analysis for this investigation focused on 771 of these homes, which were using a standard PassivSystems controller without the "optimum start" preheating algorithm enabled (see 2.6.2). This group of homes with gas boilers and without algorithmic control provided a contrast to the Freedom-Hybrid case of hybrid heat pumps with algorithmic control.

The final case is the group of PassivSystems employees and former employees with PassivSystems controllers operating oil or gas boilers with algorithmic control enabled. I have designated this group **Expert - Boiler** to reflect their more detailed understanding of heating control, even through members of the group had diverse roles in the company, not all of them technical. Interviews were carried out, either by telephone or at PassivSystems offices, with 11 members of this group. Quantitative data from heating controllers were available from this case. The data were used to inform the interviews, but not for statistical analysis, so I have designated this as a qualitative case.

Case		Description	N (Qual)	N (Quant)
Freedom - Boiler		Freedom trialists before start of trial, running boiler with standard thermostat control	7	
Freedom - Hybrid		Freedom trialists during trial, running hybrid HP with algorithmic control	11	75
Expert – Boiler		PassivSystems employees running boiler with algorithmic control	11	
Customer - Boiler		Homes with Passiv controller running boiler, preheat algorithm not enabled		771

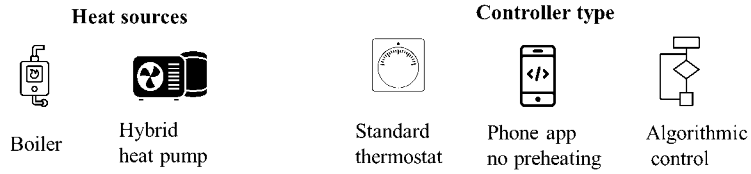


Figure 4.5: Overview of cases

4.3.2 Freedom cases

4.3.2.1 Overview of the Freedom trial

The Freedom project was a £5.2 million initiative funded under the Ofgem Network Innovation Allowance. The Freedom project partners were:

- Wales and West Utilities, a gas Distribution network Operator (DNO).
- Western Power Distribution, an electricity DNO.
- PassivSystems Ltd who supplied the smart controllers and acted as project managers.
- Delta-ee, a consultancy specialising in distributed energy markets and equipment, who led the analysis of customer engagement.
- Imperial College, who carried out energy systems modelling.
- City University who analysed controller usability and adoption strategies.

The project took place in 75 homes in the Bridgend area in South Wales during the 2017-18 heating season. The project aimed to investigate “the network, consumer and broader energy system implications of high volume deployments of hybrid heating systems" (Freedom Project, 2018). The trial included a total of 40 social homes and 35 private homes, in and around the town of Bridgend and the Llynfi Valley. The recruitment process was different for private homes and social tenants:

- Homeowners were recruited by a variety of advertising techniques (including public meetings, Facebook adverts and word of mouth from installers). The benefit was that they would have a new heating system installed free of charge to replace their existing system.
- Social tenants were recruited via their Housing Association which contacted them to ask if they were willing to participate in the trial. The benefit was the replacement of their existing boiler.

Figure 4.6: Breakdown of homes in Freedom trial from Freedom project (2018)

All the households were operating a gas boiler before the trial, which was replaced by a hybrid heat pump connected to the existing radiator system. The hybrid system combined an air source heat pump (rated at either 5kW or 8kW) with a "combi" gas boiler. To run the new heat sources a PassivSystems smart controller was installed. This controller ran the "predictive demand control" algorithm described below. This algorithm decided when to run the heat source and selected whether to run the boiler or the heat pump. The control strategy was to run the hybrid heating system at least cost to the householder.

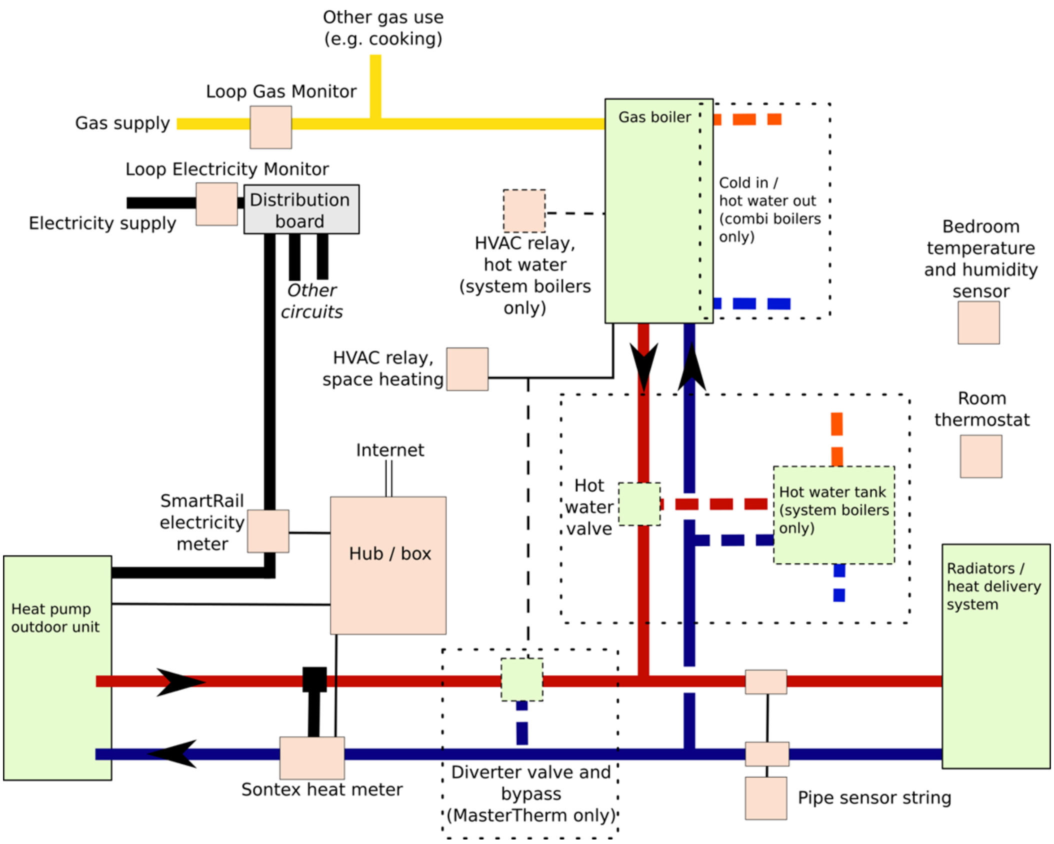


Figure 4.7: Configuration of hybrid heat pump from Freedom project (2018)

The Freedom project partners carried out a number of planned interventions during the trial to investigate the impact of different electricity pricing patterns on the aggregated gas and electricity demand across all the homes in the trial. Various patterns of tariffs were simulated by pushing different electricity to gas price ratios to the controllers. All these trials involved preheating but the tariff pattern (as well as the external temperature that day) influenced the length of the preheating period and the mix of boiler and heat pump running. In interviews I did not attempt to distinguish resident responses to short term changes in tariff patterns but concentrated on the participant's reaction to the major change in operating patterns that resulted from the implementation of algorithmic control with preheating.

4.3.3 PassivSystems algorithmic controller

The PassivSystems “ontime comfort” feature was initially developed for the control of conventional oil or gas boilers. The residents specify when they want to be warm (by setting IN / OUT and ASLEEP periods in the controller, and the temperature they want to reach) and the controller runs the heat source for the correct amount of time *ahead* of the start of the IN period when warmth has been requested.

Based on information about internal and external temperature, the PassivSystems controller develops a model of how quickly the house heats up, learning from experience so that it can calculate how long, for a given outside temperature and starting internal temperature, it will take to heat the house to the requested setpoint.

In the Freedom trail the controller calculated lowest ccost running patterns for the heat pump and boiler elements of the hybrid heat pump. Using algorithmic control with a heat pump enables the heat pump to run efficiently with a steady, low temperature output and to gradually warm up the building. Energy network requirements to manage electricity and gas demand were indicated by time-variable tariffs which the control algorithm incorporated in the calculation of lowest cost operating patterns.

It should be noted that the designers are operating within physical constraints. The controller can only trigger the heating system to add heat to the building, not to take it away. It can trigger an increase in temperature but there is no way to control to achieve cooler temperatures. The heating system cannot respond instantly to deliver a step change in temperature, but will increase the temperature at a rate which is constrained by the properties of the heating system and the building fabric.

4.3.3.1 Contacting trial participants

My university, UCL, was not a formal partner in the project. Both Delta-ee and City University required access to participants for interviews and focus groups. These facts combined to restrict the amount of access I was allowed to interview trial participants, since the project team prioritised interviews linked to formal project deliverables and were wary of interview fatigue among participants.

4.3.3.2 Interviews in private homes

Three different companies, each associated with a different heat pump manufacturer, installed the new heating systems. At the start of the trial in September 2017 it was agreed that I could liaise with the two companies who were carrying out installations in private homes to arrange interviews. A separate process for contacting tenants in social housing in the trial was agreed in November 2017.

In late September 2017 I carried out interviews in 10 private homes. The installer had previously checked with the householder if they were happy to talk to a university researcher. Three of these homes already had the hybrid heat pump installed and the interviews are included in the Freedom - Hybrid case. In 7 instances I visited at the same time the installer was surveying a property to see if it was suitable for the trial. Data from these interviews are included in the Freedom - Boiler case. Two of these homes did not proceed with an installation so they do not form part of the Freedom - Hybrid case.

Of the eight private households that I spoke to in September 2017 I was able to contact six a second time, by telephone, to ask follow-up questions about their experience of running the hybrid heat pump.

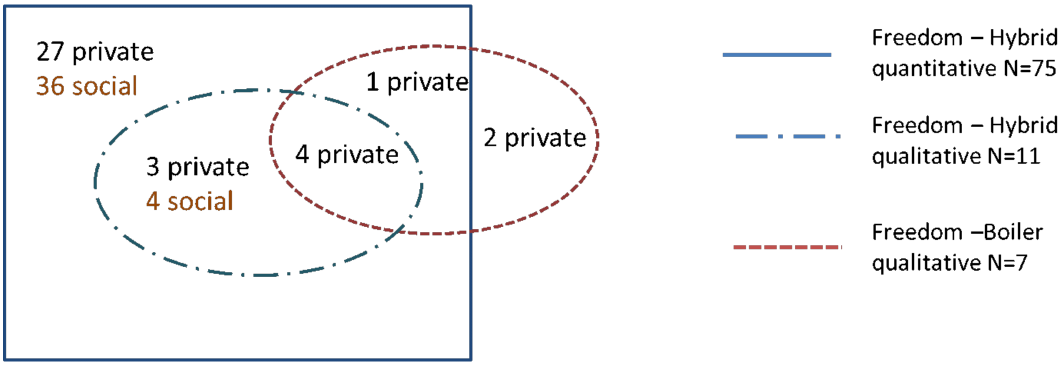


Figure 4.8: Freedom groups for quantitative and qualitative analysis, showing distribution of privately owned and social housing

4.3.3.3 Interviews in social homes

A different process was followed in arranging for interviews in social housing participating in the trial. All the social tenants in the trial were contacted by PassivSystems in November 2017 and asked to volunteer to take part in my research. Four

Pseudonym	Interview 1	Interview 2	Install date	House type	Demographic
Debbie and Ken	27/09/2017	24/04/2018	Nov 17	Detached 4 bed 1995	2 adults 2 children
Ed	28/09/2017	02/05/2018	Sep 17	Detached 4 bed 1990s	2 adults 2 children
Frank and Jill	28/09/2017	16/03/2018	Oct 17	Semi 1960s	2 adults
Rachel and John	28/09/2017		Sep 17	Detached 3 bed 2005	2 retired adults
Nick and Jen	28/09/2017	03/04/2018	Sep 17	detached 5 bed 1960s	2 adults 1 child
Leslie and Dean	28/09/2017	20/03/2018	Oct 17	det bungalow 5 bed 1980s	2 adults 2 children
Jean and Rhys	29/09/2017	23/04/2018	Oct 17	mid terrace 3 bed 1889	2 retired adults
Bill	29/09/2017	N/A	Not suitable for hybrid	Semi 3bed 1899	2 adults 1 child
Jane and Owen	29/09/2017	N/A	Not suitable for hybrid	semi 3 bed 1950s	2 retired adults
June	29/09/2017		Oct 17	detached 4 bed, c1980s	2 adults
Susan	28/11/2017		Aug 17	2 bed flat 1980s	1 adult retired, 1 adult working
Linda	28/11/2017		Sep 17	3 bed semi c1980s	1 adult, 2 children
Tracey	29/11/2017		Sep 17	3 bed end terrace c1980s	2 adults 2 children
George	25/01/2018		Jul 17	3 bed semi 1960s	1 adult not working

Table 4.1: Freedom case interviews

responses were received and these interviews are included in the **Freedom - Hybrid** case. In two cases the householder was unhappy with the hybrid operation and may have been motivated to speak to me to make sure their concerns were recognised. The other two interviewees were both very positive about the new system. This provided a range of reactions to the hybrid installation but was clearly only a small sample from the 40 social homes in the trial. At the project manager's request (because of concerns about interview fatigue impacting on project deliverables), I did not contact these tenants a second time.

Figure 4.8 shows a modified version of Figure 4.4, distinguishing the social and private homes in the cases

4.3.3.4 Ethics and data protection

UCL Bartlett School of Environment, Energy and Resources (BSEER) procedures for ethics approval were followed. The BSEER Ethics Director approved the ethics application on 25 August 2017. Data protection for the project was covered by the Customer Engagement Plan (CEP) prepared for Ofgem with PassivSystems designated as the data controller. The CEP outlined the procedures for management of personal data such as addresses and telephone numbers collected in the project. It required all personal information to be deleted at the end of the trial.

The data collected for this PhD were covered by UCL Data Protection Registration, reference no *Z6364106/2017/08/73 social research* dated 18/8/17. Interview data were given an identification number to link it to controller data for a particular house. Quotations and other information were anonymised, with participant names substituted by pseudonyms. Care was taken that any information that could be used to identify the participant was removed. Personal information (contact number and address) which was required for interviews was stored in a password protected file on an encrypted laptop and was deleted at the end of the trial.

All interviewees received an information sheet (Appendix A) and were asked to sign a consent form (Appendix B) before the interview started.

4.3.4 Customer - Boiler case

PassivSystems supplied data from homes which are using the company's controller with a gas or oil boiler. These data were completely anonymous, with no information on the location, type of home or demographics of household available, but it was known that the homes were geographically spread over the whole of Great Britain.

Once the data had been cleaned (see 4.5.3) information from around 3,100 homes was available for the period of interest (winter 2017-2018 to allow comparison with the Freedom trial).

Many of these homes had the "optimum start" preheating algorithm enabled. The method described in Section 4.5.4 was used to identify 771 homes with no preheating (i.e. they were not using the algorithmic feature of the controller, but were operating the heating in a conventional mode when the heat source only runs during the IN period). These homes form the Customer-Boiler quantitative case study.

4.3.5 Expert- Boiler case

This group comprised members of PassivSystems' "Beta test group" who all had PassivSystems controllers installed to operate their oil or gas boiler and had agreed to participate in trials and research. All were current or former PassivSystems employees, with a wide range of both technical and non-technical roles in the company. Interviews were carried out, either by telephone or at PassivSystems offices, with nine members of this group in December 2016 or January 2017. I spoke again to eight of these employees in Spring 2019 and also to two additional employees who had recently had a PassivSystems controller installed. All the members of this group had activated the "optimum start" feature, so were experiencing preheating ahead of IN periods.

Data from interviews and from heating controllers from this group were covered by UCL Data Protection Registration, reference No *Z6364106/2016/12/18 social research* dated 8/12/16. BSEER ethics approval was granted on 8/2/16. All interviewees received information about the interview by e-mail and were asked to sign a consent form (Appendix C) before the interview started (telephone interviewees were asked to confirm consent).

Pseudonym	1st interview date	2nd interview date	House type	Demographic
Richard	15/12/2016	14/03/2019	3 bed semi c 1750 6 bed detached c1850	2 adults / 2 adults 1 child
Tim	15/12/2016	06/03/2019	4 bed detached1750	2 adults
Rita	05/01/2017	06/03/2019	3 bed end terrace 2012	2 adults 1 child
Matt	15/12/2016	06/03/2019	5 bed detached c1530	2 adults 2 children
Vic	05/01/2017	06/03/2019	2 bed mid terrace c1850s	2 adults
Luke	04/01/2017	06/03/2019	4 bed detached 1990s	2 adults 2 children (both moved away by 2nd interview)
Ben	04/01/2017	06/03/2019	2 bed semi 1990s	2 adults 1 child
Ron	04/01/2017	06/03/2019	3 bed semi 1930s	1 adult
Jim	26/11/2018	21/02/2019	3 bed end terrace 1910	2 adults
Phil	21/11/2018	11/02/2019	2 bed terrace 1880	2 adults
Caroline	09/01/2017		3 bed end terrace	2 adults 2 children

Table 4.2: Expert - Boiler case interviews

Figure 4.9 shows how the Customer-Boiler, Expert-Boiler and Freedom-Hybrid cases are all within the universe of those with PassivSystems controllers, but there is no overlap as each case has a distinctive combination of control equipment and heat source.

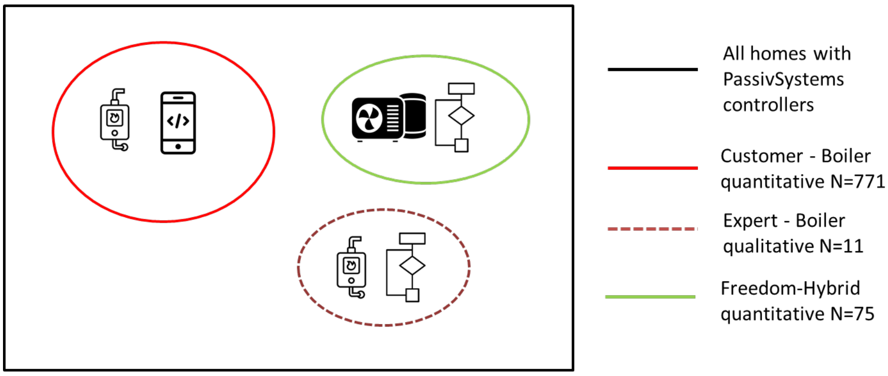
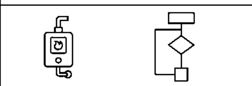
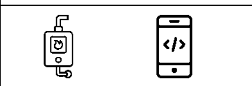


Figure 4.9: Cases within the universe of homes with PassivSystems controllers

Case		**Description**	**N (Qual)**	**N (Quant)**
Freedom - Boiler		Freedom trialists before start of trial, running boiler with standard thermostat control	7	
Freedom - Hybrid		Freedom trialists during trial, running hybrid HP with algorithmic control	11	75
Expert – Boiler		PassivSystems employees running boiler with algorithmic control	11	
Customer - Boiler		Homes with Passiv controller running boiler, preheat algorithm not enabled		771

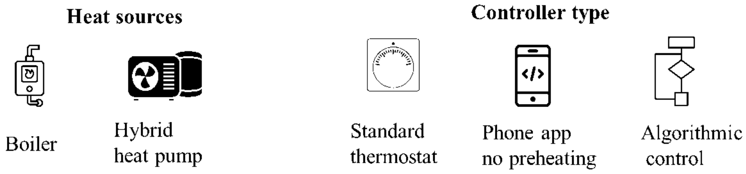


Figure 4.10: Summary of cases

4.4 Qualitative analysis

Chapter 3 outlined the theoretical background to this study of the actions people take to keep warm and how and why they take these actions. It described how the research questions about what residents want from their heating systems and how they interact with the system to achieve their desired output can be linked to practice theory concepts of goals and practical understanding.

Residents' perspectives are crucial to understanding how heating is used in their everyday life and their reasons for the actions they take to control the heating. A qualitative approach was chosen to explore in depth the respondents' understanding of how their heating system behaves and the goals behind particular patterns of operation of heating. This is in line with Miles and Huberman's (1994) statement that "a main task [of qualitative research] is to explicate the ways people in particular settings come to understand, account for, take action, and otherwise manage their day-to-day situations" [p.7].

4.4.1 Interviews

Semi-structured interviews was the technique chosen for investigating the reasons behind residents' patterns of operation of their heating. Researchers with a practice-based approach to investigating home energy use (such as Strengers et al. (2014); Powells et al. (2014); Gram-Hanssen (2010)) have demonstrated the benefits of interviewing people in their homes. Interviews allow in-depth exploration of daily practices and visiting the home gives the researcher a clear picture of the physical context not necessarily picked up in telephone interviews (Robson, 2002).

Hitchings (2012) raises a potential criticism that everyday practices are so habitual that an interviewee many not be able to comment on them. In his paper titled *People can talk about their practices* he gives examples of individuals who were very happy to talk about their use of heating and, once they had grasped the researcher's interest in this mundane subject, were very articulate in answer to his questions. Like Hitchings I found that respondents were willing to talk about heating use and rarely said they did not know the answer to any of my questions. Semi-structured interviews allowed me to ask open-ended questions and to identify factors important to the interviewee that I had not anticipated. It also added time depth to the investigation, as interviewees explained how their current practices related to past experience and described changes in their household situation over different timescales.

4.4.2 Developing interview questions

An interview guide (Appendix D) was developed using the theoretical framework described in 4.2.

At the start of the interview information to provide house fabric (house age and size) and demographic (household members and working patterns) was gathered using a series of closed questions. The categorisation of dwelling type and age was based on the categories used in the CaRB dataset which in turn was based on the English House Condition Survey 2006.

The remainder of the interview was semi-structured based on a pre-determined set of open questions.
The questions explored:

- Heating control operation, knowledge and motivation
- Household routines and how these related to heating operation patterns.
- Temperature preferences including whether these varied with time of day or among household members.
- Use of supplementary heating, window opening and clothing to maintain thermal comfort.
- Awareness of physical properties of home and heating system, exploring their practical understanding.

For Freedom trialists interviewed after the hybrid heat pump had been installed, I also asked about:

- Reactions to the new system, and any changes they had noticed.
- The controller settings they had chosen.

- What actions they took if they wished to diverge from the schedules set in the controller.
- Building on the studies by Caird et al. (2012) and Fell (2016), I probed about reactions to different patterns of operation and of temperature delivered, in particular the change in night time temperature.

In six Freedom homes I spoke to two adults, in the remainder I spoke to a single adult but, when applicable, asked them about the preferences of their partner who was not present. Talking to both members of a couple gave insights into differences of opinion and occasional disagreement over information (for example one husband said his wife ran the heating in the middle of the day but she corrected him, saying that she only switched it on when the children were at home). For the six interviews in which I only spoke to one of two adults living in the home, I was conscious that the person not present might have given a different account. However, questions about the preferences and views of the absent household member often led to detailed descriptions of the differences in opinions and compromises reached.

In some of the Freedom interviews I encountered residents who were unhappy or facing problems. With their permission, I passed on details of the problem to the project team. My role was not to solve problems or to advocate for the project but I did provide explanations when the interviewees expressed puzzlement. Interviewees' reactions to my explanations form part of the analysis for this project since these reveal points which residents find hard to understand.

As far as possible in the interviews I aimed to avoid leading questions. I was aware that interviewees might have ideas about the "right" answer from an energy efficiency perspective and that "social desirability bias" might influence what they said to me (de Vaus, 2013). When I suspected this was the case I added a code to the relevant section of the transcript.

I was not able to access quantitative data from controllers in the homes of the Freedom-Hybrid interviewees until after the first time I interviewed them when I asked their permission to access the data. My analysis of controller data informed my second interviews with this group, as I was able to ask them about any unusual features of their operating patterns and any operational problems I had identified from the data.

I had access to controller data for the period leading up to my second interviews with the Expert - Boiler group so I was able to ask about the details of the routines I had identified in these data. When interviewing this group I also included a question about whether their job influenced how they used the controller.

4.4.3 Experience of coding

Recordings of the interviews were transcribed and NVivo 11 software used for coding, using the coding structure shown in Appendix E. This is based on the theoretical framework described in 4.2.1.

Extra coding categories were added for:

- Reflections on method: aspects that seemed to be shaping answers such as a sense that a respondent was giving "the right answer" or discrepancies between perspectives of multiple household members.
- Collecting reactions to specific elements of the new equipment.

I added a number of codes in addition to Gram-Hanssen's subdivision of the meaning category as I reflected on the transcripts:

- I asked all families with children about the children's routine and noticed that this often affected patterns of heating, so set up a code to highlight instances of this.
- Health reasons for preferring a particular temperature.
- Links with other practices in the home.

4.4.4 Qualitative comparisons

Qualitative comparisons between the Freedom-Hybrid and Expert-Boiler cases were used to contrast practical understanding and reactions to algorithmic control between the two groups. The Freedom interviewees (only one of whom had any specialist knowledge of heating) can be compared with the more knowledgeable Expert group and individual backgrounds taken into account. The analysis in Section 7.6 is based on the very different circumstances of the two groups.

4.5 Quantitative analysis

Section 4.3 describes the two quantitative cases using data from the heating controllers in the Customer-Boiler group of 771 homes with boilers and no preheating and the Freedom-Hybrid group of 75 homes with hybrid heat pumps with algorithmic control including preheating.

Data from the controller only included a subset of the variables which might be expected to influence patterns of heating operation. My aim was to use the data to describe patterns of operation in the case study groups of homes, not to build a predictive model.

The analysis of temperature setpoints in the controller included investigation of both regular, scheduled settings and manual interventions. A manual change to the setpoint is treated as an indication that residents are not happy with their current thermal conditions (or wish to change the conditions in the near future).

Quantitative data from the controllers in homes in the Freedom-Hybrid and Customer - Boiler cases were used to:

- Derive descriptive statistics for the two cases.
- Compare daily profiles of temperature setpoints and temperature achieved for the two cases.

It should be noted that there was no energy data available for the Customer group and only heat pump (not boiler) energy data available for the Freedom - Hybrid group, so it was not possible to analyse patterns of energy use. Data on heat pump power and calls for heat to the boiler were used to establish whether a heat source was running at a particular time, for example when detecting whether preheating was occurring before an IN period.

Patterns in time

An important aspect of the quantitative analysis was analysing patterns in time of both temperature setpoints and temperatures achieved. The focus was on daily profiles, rather than on longer timescales, since it is flexibility to manage fluctuations in demand over the day that was the inspiration for this investigation. At relevant points in the thesis I discuss how quantitative data can be used to characterise "patterns that result from interactions" (Geels and Schot, 2007) between residents and their heating equipment.

Inputs and outputs

The temperature settings entered in the controller can be considered as an input to the heating system which, through a combination of the operating pattern of the heat source and the characteristics of the building fabric, is transformed into an internal temperature profile, which can be viewed as the output of the system.

Section 2.5 outlined how changes in setpoints are transformed into a temperature profile in the home. Figure 4.11 shows this transformation. There are two steps to this transformation: from input to on/off pattern of the heat source, then from heat source to heated space.

This approach highlights how changes in setpoints trigger rises and falls in temperature and inspired the analysis of input setpoints and output temperatures in Chapter 5, in particular the investigation of the impact of different numbers of heating periods in Section 5.4.1. If there is a regular pattern in time in the input during the day, the points when the temperature starts to rise and fall will follow a similar rhythm.

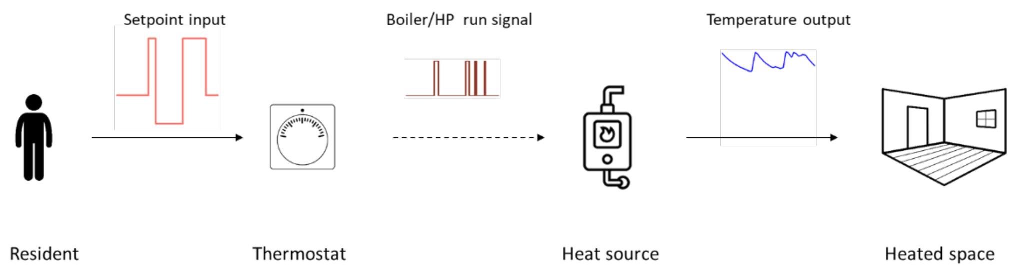


Figure 4.11: How input temperature setpoints are transformed into a temperature output profile

Analysis software

R software was used to read in and process the data. Code development included frequent error checking, in particular using visual inspection of time series and distribution charts and investigating any results that seemed anomalous. Each revision of the R script reverted to processing the original data to minimise the scope for errors.

PassivSystems Controller

The homes in the Expert - Boiler, Customer - Boiler and Freedom - Hybrid cases all had PassivSystems smart controllers. The schedule of the heating can be set up and changed using a smart-phone app. The app can also be used for manual "in the moment" increase or decrease of setpoint temperature. An internet-connected "home hub" contains a Linux processor running the control algorithm. The hub communicates wirelessly with a temperature sensor and the boiler/hybrid heat pump.

There are two generations of communications protocols with slightly different equipment configurations in the home:

- The controllers in the Freedom and Expert Cases all operate using the Z-Wave wireless communications protocol. Z-Wave units have a wall-mounted digital "thermostat" containing a temperature probe and with a dial allowing temperature setpoint to be altered manually by the residents.

- The vast majority of the controllers in the Customer-Boiler group use the Zigbee protocol. Zigbee installations have a temperature probe mounted on a wall and a separate touch-screen unit to allow residents to change settings

A key feature of the controller is that the user sets up an "occupancy schedule", using the mobile phone app to enter times each day under the headings IN, OUT and ASLEEP and what they would like the temperature to be in each of these periods. These terms are capitalised throughout the thesis to indicate the controller occupancy states; these may or may not coincide with the actual times that residents are at home, out, or asleep. Different schedules can be set up for different days of the week. An AWAY option is also available to enter periods when the home will not be occupied.

Preferred temperature setpoints (in intervals of 0.5°C) are set in two ways:

- In the pre-programmed schedule - the time and the temperature for the IN and other periods can be changed in the mobile phone app.
- Manually via the mobile phone app or directly on a thermostat to give a "right now" change in setpoint. This overrides the current setpoint until the end of the current scheduled occupancy period. When the scheduled occupancy changes, the setpoint will revert to the temperature specified for that occupancy state in the schedule.

As described in 2.6.2, the control algorithm learns how quickly the internal temperature rises with different external temperatures and calculates the preheating time necessary to reach the setpoint temperature at the beginning of the IN period. Preheating is enabled in different ways for different groups:

- In the Freedom - Hybrid homes the preheating is always enabled and cannot be overridden or time-limited by the residents.
- In the Expert - Boiler homes the residents have a choice about whether to enable "ontime comfort". If they do so, the amount of preheating will be determined by the algorithm. If they do not enable ontime comfort there will be no preheating.
- In the Customer - Boiler homes with Zigbee controllers there is an option to enable "optimum start". If this option is chosen the resident is then asked to select the maximum amount of time for preheating from 10, 30, 60 or 90 minutes. Zigbee units which do not have optimum start enabled are effectively controlling like a standard integrated thermostat and timer, with no disconnect between the times heating requested and the times the heating runs. Only homes which did not have "optimum start" preheating enabled were included in the Customer-Boiler group. The method for distinguishing these homes is outlined in Section 4.5.4.

Occupancy	Setpoint	Times
IN	19°C	07:00 to 09:00 and 17:00 to 22:00
OUT	8°C	09:00 to 17:00
ASLEEP	12°C	22:00 to 07:00

Table 4.3: Default occupancy period settings

Initially the controller contains default settings which can be altered by the user. These defaults for the Freedom trialists are shown in Table 4.3.

4.5.1 Boiler - Customer data

The controller data from this case formed a very large dataset (over 90,000 files) from over 3,000 homes. The first step was to cut it down to eight weeks starting on the first working Monday in January 2018 to represent the central part of the heating season for that winter, not including the Christmas/New Year period when occupancy patterns were likely to be different. The raw data processing remained challenging - for example there were 35.8 million data points for internal temperature in this period - so the data were broken into chunks to enable processing on a laptop computer.

The following data points were available from the controllers:

- internal temperature (measured at thermostat) - recorded every time it changed by 0.1°C in Zigbee homes, or by 0.2°C in Z-Wave homes.
- external temperature from the nearest Met Office weather station, recorded at approximately 60 minute intervals
- user temperature setpoint (recorded each time it changed).
- call for heat -signal to boiler to supply hot water to radiators. This was either 1 (asking boiler to run), or 0. A data point was generated every time the value changed and also approximately every 60 minutes when the value remains unchanged.
- call for hot water - signal to boiler to supply hot water.

- occupancy state (IN, OUT, ASLEEP, AWAY) - a value of 1 at the point that the occupancy period started. The end of the period was indicated by the start of a period of a different occupancy state.

4.5.2 Freedom project data

Data were supplied from controllers in all homes in the trial from 1/10/17 to 21/4/18. This data were cut down to the same eight week period as the Customer-Boiler data. Once the data had been cleaned and cut down to the eight week period, the number of days with missing data for each home was checked. Homes with less than 20 days of data were removed from the dataset so that long periods of missing data did not affect the analysis (see 4.5.7). At the end of this process data for 56 of the 75 homes in the trial remained.

Data from homes where hybrid operation continued for a second winter were supplied from 1/10/18 to 14/3/19. An eight week period starting on the first working Monday in January was used in comparisons between the two heating seasons.

The controller in homes in the Freedom project was configured to collect additional data. Extra data points used in this investigation were:

- Heat pump power signal - the input electrical power to the heat pump logged approximately every 60s. This was used to detect when the heat pump was running.

- GCR (gas cost ratio) - the ratio of gas to electricity price pushed to the controller. This was varied during the trial to simulate variable tariffs.

- An additional “boiler firing” signal from one particular model of hybrid heat pump used in the trial. This indicated the status of the local controller for this packaged hybrid unit and was used to check whether the local controller was responding to the PassivSystems controller.

4.5.3 Data cleaning

Data were supplied by PassivSystems as csv files for each data point in each home. The data for each home were checked to see if key data were missing (this might have been caused either by an equipment or a communications problem). Many of the important analyses (e.g. mean night temperature, number of manual setpoint changes) were on a daily basis, so days with incomplete data were not included in any further analysis.

A series of checks were carried out for missing data:

- Days without internal temperature data. All days with less than 6 temperature points recorded in the day were removed. This cut off point was chosen to give a balance of not excluding homes with very steady temperatures (the temperature was only recorded each time it changed by 0.2°C) but also eliminating those which only had temperature data for a short section of the day.

- (In the Customer-Boiler data) days when the call for heat was asking for the boiler to run all the time. This could indicate either that the boiler was not running when it received a call for heat signal from the controller, or that it was inadequately sized. In either case, the boiler was not responding as intended to the control signal. This was detected by calculating the total duration of boiler call to heat across each day.

- For some homes in the Freedom- Hybrid case, there were periods when one particular type of hybrid heat pump did not respond to the PassivSystems controller. A result of this fault was that the controller sent a continuous boiler firing signal. Days when this was the case were detected and removed.

4.5.4 Initial processing

As will be evident from the description of the data points, the raw data formed an irregular time series. When detecting events, for example detecting the time the IN period started, this irregular data was used to determine the actual time the occupancy and setpoint changed.

For analysis combining data from a number of homes across a number of days, data points at the same, regular time intervals were required. The irregular setpoint and internal temperature data was converted to a regular dataframe at 10 minute intervals. To do this the R zoo package which carries out linear interpolation between the available data points (Zeileis and Grothendieck, 2005) was used.

In order to find out which homes in the Customer - Boiler case had enabled the "optimum start" feature which allowed preheating, periods when there was a continuous call for heat for a period immediately before the beginning of the first IN period in the day were identified. This indicated that a scheduled IN period was preceded by a period of preheating. The homes with preheating were removed from further analysis of the Customer-Boiler data set, to allow a clear comparison between the homes with no algorithmic preheating in the Customer-Boiler group and the homes in the Freedom-Hybrid case where the preheating algorithm was always operational.

4.5.5 Setpoint changes

The setpoint changes recorded in the controller data can be related to the research question about what people want from their heating system, since a setpoint represents a request for a particular temperature at a particular time.

Shipworth et al. (2010) define "active central heating" as "times when the heating system is actually supplying heat to the dwelling". This definition was intended for systems with conventional control. As explained in 2.6.2, with algorithmic control with preheating the heating often operates ahead of the times residents have requested warmth. A new designation is required to distinguish between the times the heating is operating and the times that the residents have requested warmth. I use the term "heating request period" to refer to the periods when residents have indicated they wish to be warm. For those operating a PassivSystems heating controller as the designers intend, these "heating request" times correspond to the IN times set in the controller schedule.

When processing the setpoint data, it was found that a minority of households were not operating their controllers in the recommended way. For example, they might request warmth during a period when the controller was set to OUT by manually increasing the setpoint temperature to a higher level (e.g. 22°C). In order to include all periods when residents requested warm temperatures as "heating request" periods (whether or not the occupancy was set to IN), a threshold temperature was chosen for each home, with any setpoints above the threshold designated "heating request".

The starting point was to assume a default threshold for all homes of 18.5°C. This distinguishes IN from OUT for those using the default settings of 19°C for IN and 8°C for OUT. However some homes never set an IN value as high as 19°C. A check was therefore carried out to find the most frequently used IN settings. For homes with IN setpoints below 19°C for 20 or more IN periods in the 8 week period, the threshold was adjusted. The new threshold was set at a value 0.5°C below the lowest IN setting used on 20 or more occasions.

In the example shown in Figure 4.12 the threshold was set at 15.5°C. Out of 56 Freedom- Hybrid homes, included in the 2018 analysis, 41 had a threshold at 18.5°C and 15 homes a lower threshold.

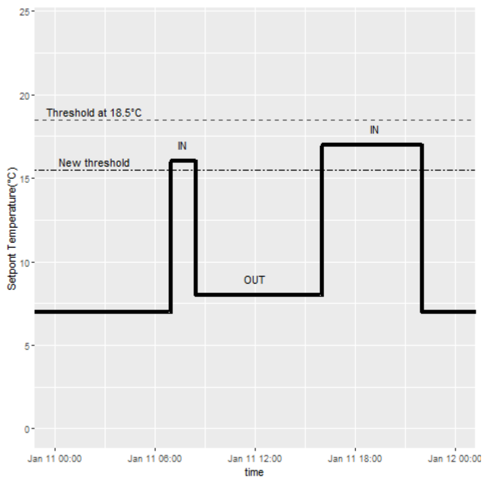


Figure 4.12: Example of threshold detection

Once the threshold was established, each change in setpoint was checked to see if it was:

- Starting a heating request period - i.e. switching from a setpoint below the threshold to one above the threshold.
- Stopping a heating request period - i.e. switching from a setpoint above the threshold to one below the threshold.

- Changing from one setpoint above the threshold to another setpoint also above the setpoint.

4.5.6 Identification of manual changes

For some steps in the analysis it was necessary to distinguish between scheduled setpoint changes which had been pre-programmed into the controller and manual changes “in the moment” using the thermostat or phone app. The method to do this was based on the time (to the nearest second) recorded for the setpoint change. The controller schedule allowed setting at multiples of 5 minutes: 07:00, 07:05 etc. It was assumed that changes at exact multiples of 5 minutes were scheduled and any other changes were manual. This analysis had to allow for delays in the processor - for example a change scheduled at 07:00:00 might be recorded at 07:00:01. A one second delay was allowed for the Z-Wave controllers in the Freedom dataset, based on an analysis of the distribution of the times recorded for setpoint change. This method leaves open the possibility of manual changes which happened to take place at a multiples of 5 minutes or 1 second later being designated as scheduled changes. If the manual changes are randomly distributed in time, the probability that they will be recorded as scheduled is 2/300 (two seconds divided by the number of seconds in five minutes).

4.5.7 Statistical analysis

The dataset was cut down to weekdays from 8 January 2018 to 2 March 2018, and the number of days with missing data for each house in this period was determined. The analysis was carried out for weekdays only since heating operation patterns are sometimes different at weekends (Huebner et al., 2015).

Statistical analysis was carried out on the data for setpoint inputs, for example establishing the mean daily duration of the “heating request” period.

The starting point for this analysis was a dataframe (matrix) with a value for each home on each day for which satisfactory data were available. I have designated the unit of analysis for this analysis the *home-day* as it represents a single day in a single home.

In order to provide statistics for which the unit of analysis was the home rather than the home-day the relevant statistic (mean number of setpoint changes in day, median of setpoint at 08:00 etc.) was calculated based on all the home-days for each home. Analysis was carried out on all the homes in each case, so each case was treated as a population, rather than a sample from a wider population. This means that uncertainty estimates, which assess how far results based on a sample represent a whole population, are not relevant for this analysis.

To compare cases a central tendency value was then calculated across all the homes in the case. This meant that all homes, even those with missing data, were equally weighted. For parameters which showed a non-normal distribution across homes (e.g. number of manual setpoint changes in day), the median was used as the measure of central tendency.

When comparing daily profiles for each case,the mean of the variable under consideration (e.g. internal temperature) across the whole case was plotted. This represents a "typical" profile for the case, a pattern that is particularly relevant when considering the aggregated patterns of energy demand across a group of homes. The typical heating settings for a group of homes are ultimately driving regular patterns in time of heating energy demand. The focus was on the average profile for a winter weekday, not the "1 in 20 years" and other extreme demand cases which also influence network management.

For a number of the calculated results (for example the difference between maximum and minimum internal temperature over the day shown in Figure 5.17), the heat balance described in Section 2.5 leads us to expect that the external temperature will affect the result. In these cases the analysis included plotting the variable of interest against daily mean external temperature. The data for each home-day were gathered into "bins" by rounding the the mean external temperature for each day to the nearest 1°C so that, for example, for the 2°C bin the mean of the variable of interest was calculated for all home-days in the case when the temperature was greater than 1.5°C and less than 2.5°C

Homes with less than 20 days of complete data were not included in the dataset for statistical analysis. This was to avoid biasing the results if the data from homes with only a few days of good data was not typical for the home over the whole period. The missing data in those homes with between 20 and 39 days of data (which were included) was not random in time as there were frequently cases when a number of homes suffered from a common communication or technical problem which meant that the missing data occurred in several homes over the same days.

The possible impact of missing data on the findings was considered. Many of the statistics are derived for a typical winter's day. Only including homes for which data are available for at least half the 40 day period eliminates homes for which data are only available for a short period which may not be typical of the whole eight weeks. The external temperature varied over the period and if data are consistently missing from days that were consistently warmer or cooler than average, this could skew the overall result for the home. Plotting the data at a home-day level against external temperature provided a check that comparisons were not skewed by differences in external temperature.

4.5.8 Quantitative comparisons

Quantitative comparisons were made between Customer-Boiler and Freedom-Hybrid cases were made to:

- Investigate how patterns of temperature setpoints differ for two cases, and for the same case over time (5.2.1,5.3.1,6.5).
- Compare the daily internal temperature patterns from the two cases (5.4.1).

Comparison between these two quantitative cases of groups of homes with different heating equipment is not the same as comparing "before and after" the installation of new heating equipment in the same group of homes. When comparing the two quantitative cases it is important to bear in mind that there is no reason to think the physical characteristics of the homes or the demographic characteristics of the residents are equivalent in the two groups. Any difference between the groups cannot be attributed solely to the difference in heating systems, since other factors may also be influencing the results. If the results for the two cases are very different, this informs investigations of the mechanisms underlying this difference.

4.6 Linking qualitative and quantitative evidence

Working with very different sets of quantitative and qualitative data brings up practical and philosophical questions around the difference between research traditions looking at social phenomena and physical phenomena (Bryman, 1992). The theoretical approaches I have chosen suggest that it is not possible to consider residents' interactions with their controllers without considering both social and technical dimensions. Practice theory sits in the social constructivist theoretical tradition but acknowledges the importance of physical context in shaping practices. As Love and Cooper (2015) point out "physical factors interact with and may be indistinct from social factors". Chiu et al. (2014) advocate for a practice theory approach combining physical measurements and data from interviews "concentrating on accounting for 'doing' rather than merely quantifying individuals' specific behaviours".

The combination of quantitative "monitoring" data and qualitative interview data has been used in other studies of UK domestic energy use. Foulds et al. (2013) make a strong case for the benefits of combining data from monitoring and interviews in their investigation of patterns of electricity demand in a group of Passivhaus dwellings, stating that "qualitative data is central to understanding what the monitoring data mean and what practices they could represent". Tweed et al. (2014) used a combination of interviews, temperature monitoring and thermal comfort surveys to investigate home heating strategies "capturing not just the environmental conditions ... and how they are achieved ... but also why these strategies are employed, what factors influence them and how, when, where and why this might change". In both these cases the study involved a small group of homes and a full set of qualitative and quantitative information was available for each home.

My analysis in Chapters 5 to 7 includes three instances when links are made between trends seen in quantitative data and explanations given in interviews.

- Section 5.2.2.5 links statements made by interviewees about running their heating for longer in colder weather to quantitative findings about variation in length of heating request periods with external temperature.

- Section 6.3.3 discusses how actions to ensure the heating is running mentioned by several interviewees inspired an analysis of manual operation to increase setpoints in the quantitative data.

- Section 7.5.2 aims to quantify the level of cooperation between households and network, inspired by a case of non-cooperation uncovered in an interview.

A general theme of this analysis is the use of information from interviews to suggest reasons that may lie behind patterns in the quantitative data. My strategy is to use qualitative data to identify potential mechanisms behind the phenomena identified in the quantitative data. I am drawing on the concept of mechanisms as defined in Critical Realism. A mechanism is defined as a causal structure that explains a phenomenon (Mingers, 2014, p.54). A mechanism indicates a capacity for behaviour which does not always trigger actions. Bennett (2007) explains "effects are brought about by bundles or configurations of mechanisms, some of which contribute to the effect and some of which push towards counteracting the effect or reducing its magnitude". In other words a number of interacting mechanisms may lie behind a phenomenon visible in the quantitative data, and only some of these may be identified in interviews.

When linking actions visible in the quantitative data for a group of homes with explanations given by a few householders, I cannot claim that the mechanisms identified are the only possible explanation for the actions seen in data from other homes. This does, however, allow me to identify plausible explanations for patterns in the data, and to highlight topics for further investigation in more controlled circumstances, in order to quantify the effect of a particular mechanism.

4.7 Guide to results chapters

Chapters 5 to 7 present the findings of the investigation. Chapter 5 focuses on the temperature aspects of what people want from their heating and Chapter 6 moves on to other aspects, in particular the desired operating patterns. Chapter 7 considers the relationship between the household and the energy network. The links between the research questions and the chapters are summarised below:

RQ1 What output do households want from their heating systems?

- Chapter 5 describes temperature patterns over the day in the home, investigating the temperature setpoints residents ask for and the temperature profile they achieve.
- Chapter 6 explores other outputs from the heating system and residents' goals for particular operating patterns.

RQ2 How do residents interact with their heating system to get their desired outputs?

- Chapter 5 investigates practical understanding of temperature patterns.
- Chapter 6 extends the investigation to knowledge about patterns of heating operation.

RQ3 How do households react to a change in heating system characteristics?

- Chapter 5 discusses the reaction to changes in temperature pattern.
- Chapter 6 discusses the reaction to changes in operating pattern which follow the installation of a hybrid heat pump.
- Chapter 7 focuses on reactions to changes in control strategy and to a new type of interaction with the energy network.

Chapter 5

Temperature patterns

5.1 Introduction

Chapter 2 described the importance of demand shifting and how this will require residents to accept a disconnect between the times the heating operates and the times they specify they want to be warm. It outlined why changes in heating technology and control strategy change the patterns of temperature experienced by residents. In this chapter I explore the change in temperature patterns experienced by a group of hybrid heat pump trialists and their reactions to these changes. Focusing on the daily profile of temperatures in the home I aim to address the temperature dimension of my research questions:

RQ1 What output do households want from their heating systems?

- What patterns of temperature in time do residents aim to achieve?
- What are their reasons for wanting these patterns?

RQ2 How do residents interact with their heating system to get their desired outputs?

- How do residents decide on the timing and temperature levels of setpoints to provide the thermal conditions they would like?

RQ3 How do households react to a change in heating system characteristics?

- How do households accustomed to a conventional gas boiler system react to the change in temperature patterns from a hybrid heat pump with algorithmic control?
- Are residents able to achieve the temperature output patterns they would like with this new heating system?

As I consider the reactions to change, I am considering the effects of two main differences between the old boiler and the new hybrid heat pump system:

1. The disconnect between the times heating is requested and the times the heat source runs which is introduced by the change from standard thermostatic control to algorithmic control.
2. The change from a gas boiler to a hybrid heat pump. The heat pump element of the hybrid supplies hot water at a lower temperature than a boiler. This means that the radiators heat up the building more slowly. The heat pump tends to run for longer periods than a boiler to heat the home to a particular temperature.

Social practice theory provides a framework for the analysis. In particular I relate choices made by residents about temperature setpoints to Schatzki's concepts of *practical understanding* and *teleoaffectivity* introduced in Section 3.1.7.

Teleoaffectivity can be used to consider the goals of residents: what they aim to achieve when they operate their heating system. Section 1.2.4 introduces the assumptions "built in" to the heating controller. In this chapter I explore the thermal conditions which residents aim to achieve in their homes and discuss how far actual goals diverge from those assumed in heating controller design.

The concept of *practical understanding* "knowing how, through the performance of bodily actions, to carry out actions that make sense to perform"(Schatzki, 2010a) is used to investigate how people understand how heating settings translate to the temperature they sense and how they know what actions to take to achieve the conditions they want.

5.1.1 Chapter overview

Section 2.5 explains how a pattern in time of heating setpoint inputs is transformed into a pattern of temperatures in the heated space. There is a time-lag between input and output which depends on the thermal response of the building and the characteristics of the heating system.

In this chapter I discuss the setpoint inputs and temperature outputs in turn. The input pattern of temperature setpoints has two dimensions: the times at which setpoints are changed and the magnitude of the temperature of the settings. I start by discussing the time dimension, drawing on Walker's discussion of patterns of practices in time (Walker, 2014). I then move on to look at temperature settings and how residents choose temperature setpoints to match their goals. Having described the input patterns, I then move on to look at the patterns of temperature in time in the home. I discuss how the Freedom hybrid trial participants reacted to a change in the temperature profile in their home.

Case		Description	N (Qual)	N (Quant)
Freedom - Boiler		Freedom trialists before start of trial, running boiler with standard thermostat control	7	
Freedom - Hybrid		Freedom trialists during trial, running hybrid HP with algorithmic control	11	75
Expert – Boiler		PassivSystems employees running boiler with algorithmic control	11	
Customer - Boiler		Homes with Passiv controller running boiler, preheat algorithm not enabled		771

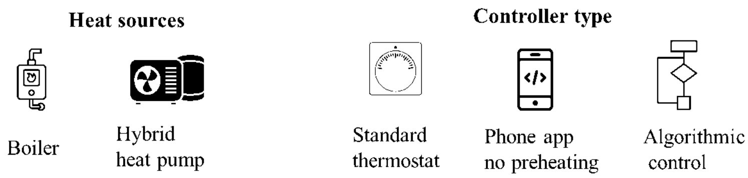


Figure 5.1: Evidence drawn on in this chapter

Throughout the chapter I draw on a combination of evidence from quantitative data (setpoint and achieved temperature) and qualitative data from interviews (discussing setpoint choices and reactions to change). Figure 5.1 shows how qualitative and quantitative data drawn from the four cases studies described in Section 4.3 are used in this chapter. When analysing quantitative data I focus on the patterns of setpoints and temperature achieved over a typical day in the heating season. I use qualitative data to investigate possible reasons behind the inputs and assess responses to changes in output.

5.2 Setpoint patterns in time

This section investigates daily patterns in time of heating operation. I start by discussing quantitative data which shows what times residents have requested heating, investigating both scheduled patterns pre-set in the controller and manual changes to start or stop the heating. I then move on to discuss findings from interviews about why residents choose particular times to operate their heating.

5.2.1 Quantitative data

In this section I discuss the quantitative evidence for patterns of operation in the Customer-Boiler and Freedom-Hybrid groups. Quantitative data about the timing of heating operation provide context for the responses from interviewees about the reasons they choose particular patterns of setpoints in time. It is also a necessary first step before investigating internal temperature patterns, since comparison of differences in output temperature patterns should take into account differences in input setpoint patterns.

5.2.1.1 When are people requesting heating?

The setpoint patterns in individual homes can be explored using quantitative data from the heating controller. Figure 5.2 shows examples of setpoint patterns on individual days in different homes, illustrating variation in the number of heating periods and the start and end times of these periods.

In order to investigate the typical operating pattern on a winter day, I used data from all the homes in each case to calculate the proportion of homes with heating requested at 10 minute intervals through the day, shown in Figure 5.3. As described in 4.5.7, a mean of the means for individual homes was calculated to ensure equal weighting for each home. Homes where there were less than 20 days

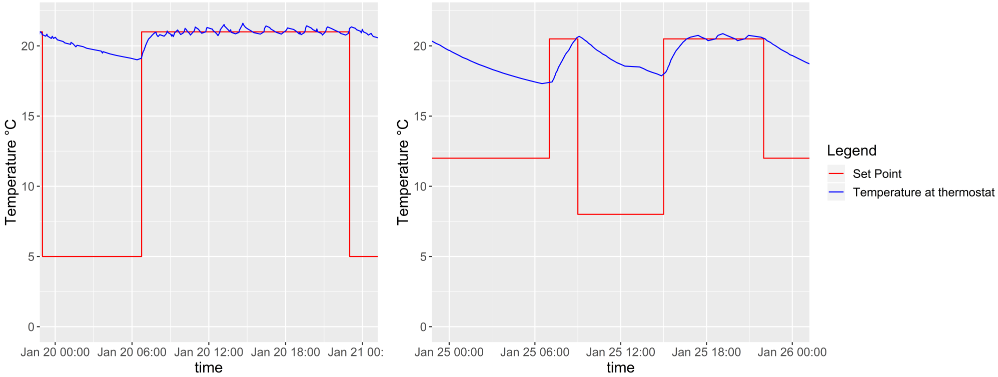


Figure 5.2: Examples of days with one and two operating periods from homes in the Customer-Boiler case

of data available were excluded from the analysis.

Figure 5.3: When do households ask to be warm?
Proportion of homes requesting heating on winter weekdays, plotted at 10 minute intervals. Weekdays, 8 January 2018 to 2 March 2018.

The graph in Figure 5.3 shows clear peaks in the morning and evening for both cases, with a lower proportion requesting heating in the middle of the day, and an even lower proportion at night. The profile of morning and evening heating use which underlies the current daily pattern of gas demand described in Section 2.4.1 is evident in both groups. The proportion of homes requesting heating in the evening is very similar in both cases. Less of the homes in the Customer-Boiler case are requesting heating in the morning but at midday there are more homes in this group requesting heating. Since nothing is known of the actual occupancy patterns in the Customer-Boiler group, it is only possible to speculate on reasons for the differences. Some of the Freedom-Hybrid group may be present but not requesting heating in the middle of the day because they benefit from pre-heating ahead of the evening heating request period.

The co-incidence of morning and evening heating operation in many homes is an example of what Zerubavel calls the "collective beat and rhythm" of social life (Zerubavel, 1985, p.32). As Chapter 2 explains, a key requirement of energy demand flexibility is to decouple the collective rhythms of heating requirements from patterns of energy demand.

5.2.1.2 Number of heating periods in the day

An important characteristic for my analysis is the number of heating request periods in the day, and the time at which these periods start. Section 2.5 describes how the shape of the input pattern, with its step changes in setpoint, is transformed into a pattern of temperature, mediated by the properties of the building. The number of switching points in a day and the time interval between them have an important influence on the temperature pattern. For example, there is a clear difference in the pattern of temperature over the day between the one and two operating period days shown in Figure 5.2.

The timing of switches in setpoint is not only important in individual homes but also for network management. If there is no preheating or load management, a large number of homes requesting the heating to start at the same time represents a significant load on the energy network (Hanmer et al., 2019).

Section 4.5.5 explained how I established the heating requested periods in the day - the times the residents indicated they wanted to be warm (normally representing the times the controller is set to IN). There is a widespread assumption that

British homes are heated for two periods, in the morning and evening on weekdays (e.g. default occupancy in BREDEM model described by Anderson et al. (2002)). Huebner et al. (2015) explain how assumptions about heating operation patterns contribute to assessments of energy saving potential in individual homes, and to building stock modelling. They highlight the value of understanding actual patterns of heating use to use as a basis for prediction of future energy demand. My analysis shows that while two period operation is the most frequent pattern in both cases at 49% of home-days in the Customer-Boiler group and 56% of home-days in the Freedom - Hybrid group, one period operation was also frequent in both cases (30% in the Customer-Boiler group, 24% in the Freedom-Hybrid group). There were also instances of three period operation in both groups. Figure 5.4 shows the distribution of number of heating requested periods in the day (for weekdays). The analysis is on a home-day basis to allow for the homes which did not have a consistent number of periods each weekday.

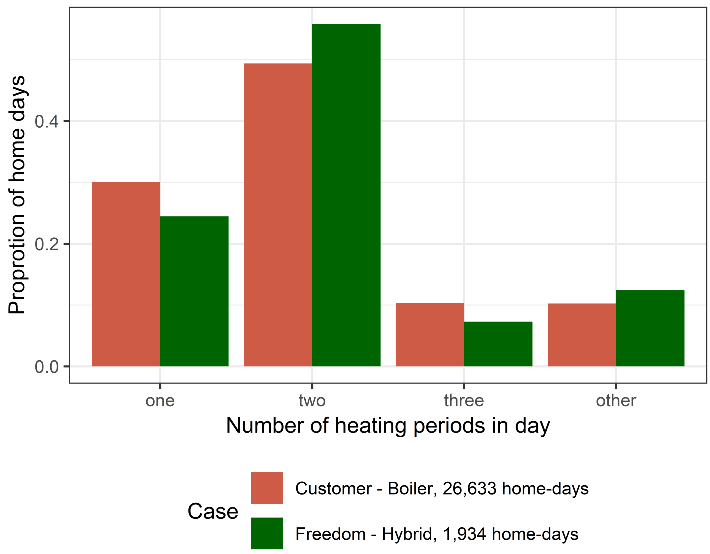


Figure 5.4: How common is two period operation?
Number of heating requested periods in day.
Weekdays, 8 January 2018 to 2 March 2018.

I found that many homes in both cases did not follow a consistent weekday pattern of either always having the same number of heating periods each day. Figure 5.5 shows the number of two period days plotted against the number of one

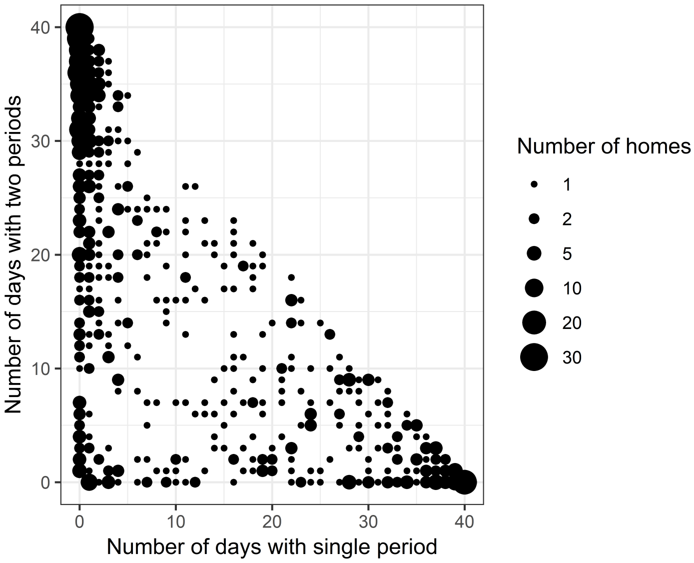


Figure 5.5: How consistent is number of hating request periods in the day?
771 homes in Customer-Boiler Group
Weekdays, 8 January 2018 to 2 March 2018.

period days for each home in the Customer-Boiler dataset. While some homes consistently follow one or two period operation, 52% of the 771 homes have a mix of one and two period operation on weekdays. Section 5.4.1.2 discusses how the temperature profiles experienced on days with single period operation differ from those with two period operation.

Figures 5.6 and 5.7 show distributions of start and end times for heating request periods, plotting the frequency that the switching point falls within a particular 10 minute period. These plots are very far from a smooth distribution. It can be seen that on the hour and, to a lesser extent, the half hour, are the most popular times to schedule heating operation. Zerubavel (1985) in his discussion of the artificial (as opposed to natural) rhythms in our schedules points out “many events in our daily life are scheduled for ‘rounded off’ times such as ‘on the hour”’. For both groups of homes, 07:00 was the most frequent heating request start time and 22:00 the most frequent time the final heating period of the day ended.

5.2.1.3 Heating period duration

Table 5.1 shows the mean length of time each day that heating is requested. A mean is calculated for each home, and then a mean for each case based on all homes in

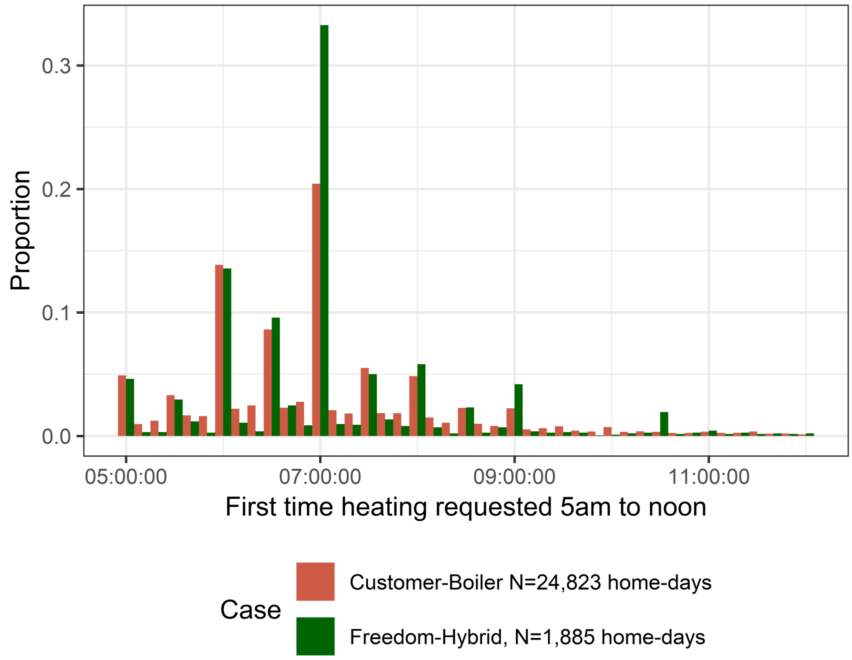


Figure 5.6: How synchronous is the first time that heating is requested in the day? Frequency distributions of start times for heating operation. Weekdays,8 January 2018 to 2 March 2018.

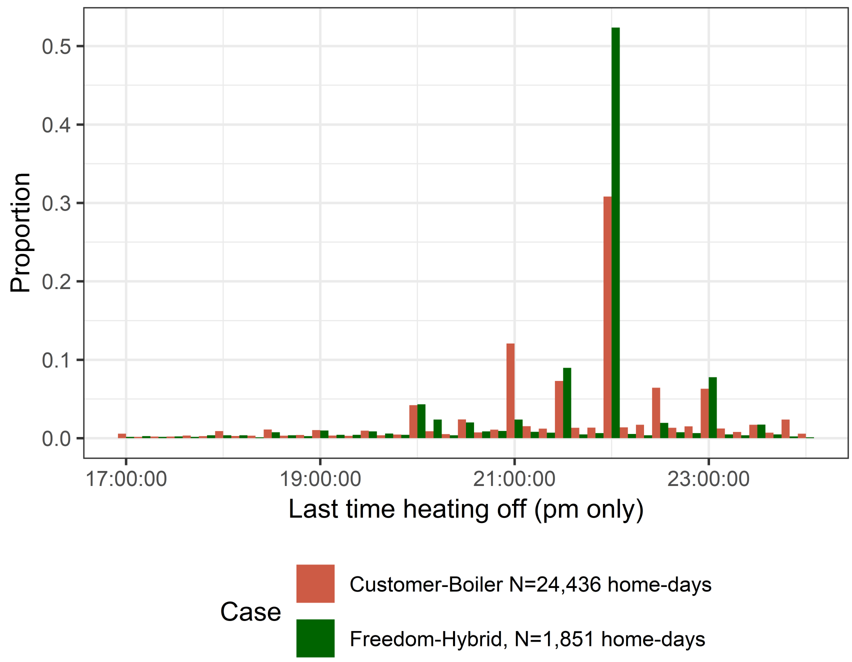


Figure 5.7: How synchronous is the end of the last heating request period in the day? Frequency distributions of end times for heating operation. Weekdays, 8 January 2018 to 2 March 2018.

the case. It shows that on average the total running time is longer in the Customer-Boiler homes than in those in the Freedom-Hybrid case. The duration of the first and second period for days with two period operation is shown in Table 5.2. In both groups the duration of the morning peak is significantly shorter than the evening peak.

Case	N (homes)	Mean duration hours
Customer-Boiler	771	11.07
Freedom-Hybrid	56	9.98

Table 5.1: Typical length of heating requested period
Weekdays, 8 January 2018 to 2 March 2018

Case	N (homes)	Mean length of first of two heating periods (hours)	Mean length of second of two heating periods (hours)
Customer-Boiler	771	2.90	6.42
Freedom-Hybrid	56	3.12	6.02

Table 5.2: Typical duration of first and second heating periods for days with two period operation. Weekdays, 8 January 2018 to 2 March 2018

I investigated the data for length of time the heating was requested at different external temperatures, to see if the shorter request periods for the Freedom-Hybrid case were consistent across different external temperatures. Figure 5.8 shows the heating request duration was plotted against mean external temperature for that home-day. The points were gathered into “bins” by rounding the external temperatures to the nearest 1°C so that, for example, the mean duration was calculated for all home-days when the temperature was greater than 0.5°C and less than 1.5°C.

The request periods for the Freedom-Hybrid case were shorter than those for the Customer-Boiler case across a range of external temperatures. This could be a result of preheating for the Freedom-Hybrid group either removing the need to schedule heating when the home is unoccupied, or providing heat at times when the house is occupied but heating not requested.

Figure 5.8 shows longer running hours in the Customer-Boiler case when the temperature drops below 0°C. This suggests that what households want from their

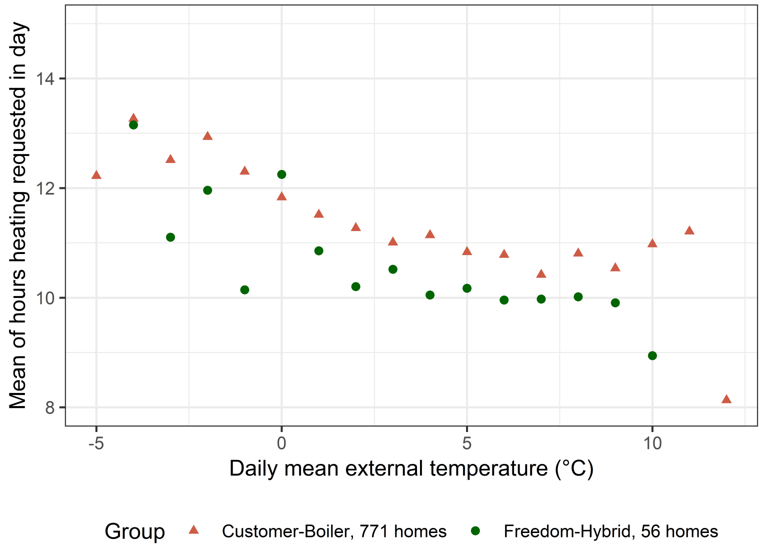


Figure 5.8: Does length of time heating is requested change at different external temperatures? Weekdays, 8 January 2018 to 2 March 2018

heating system varies with external temperature, either because they spend longer indoors in very cold weather, or because they request heating for a higher proportion of the time they spend at home when conditions are cold.

5.2.1.4 Manual operation of heating

In most homes the regular rhythms of the scheduled changes are overlaid by manual operation. In the Freedom - Hybrid group, all the homes made at least one manual adjustment in the period, and only 27 of the 771 Customer - Boiler homes had no manual adjustments. It seems it is extremely rare that a household relies entirely on scheduled settings.

As I discuss in 4.5.5, manual changes are divided into two groups:

- Those that "start" or "stop" the heating
- Adjustments of the temperature during a heating request period, which I have labelled "tweaks".

Figures 5.9 and 5.10 show examples of different ways in which two households in the Customer-Boiler case combined manual and scheduled setpoints on a particular day.

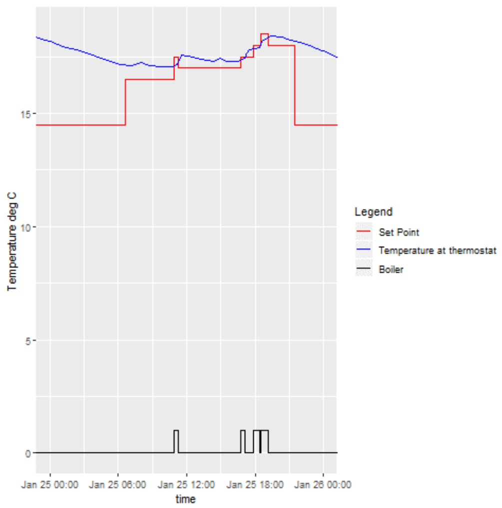


Figure 5.9: Multiple tweaks during a single heating period

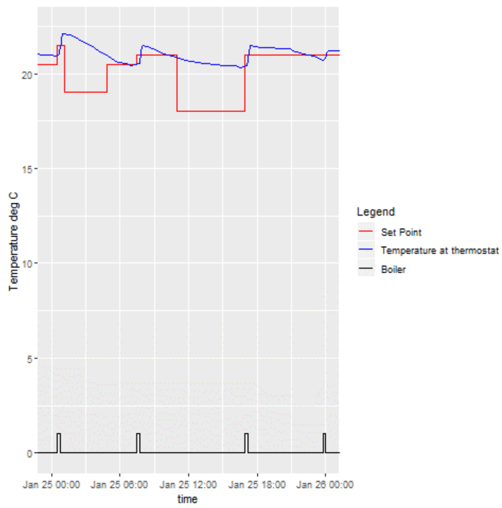


Figure 5.10: Combination of manual and scheduled changes in setpoint

Table 5.3 shows statistics for the amount of manual operation for both of the quantitative case studies. The mean value for each home was calculated and then, since the means for each home did not follow a normal distribution, the median was calculated for each case. In Figure 5.11 it can be seen that the mean number of tweaks for each home follows a different distribution in the two cases.

There is a substantial amount of manual operation with typically more than one manual change a day in both groups This finding concurs with Morton (2016) and Bruce-Konuah et al. (2019) who found evidence of a mix of manual and scheduled operation in the homes they studied.

The median number of tweaks in the day for the Freedom - Hybrid group is approximately double those in the Customer-Boiler group but the number of manual stop/starts is lower. It seems that the Hybrid group rely more on scheduled settings to start and stop the heating but make more manual adjustments during the heating requested period.

	N (homes)	Median of mean tweaks in day	Median of mean manual on or off in day
Customer-Boiler	771	0.29	1.10
Freedom-Hybrid	56	0.81	0.66

Table 5.3: Frequency of manual operation. Weekdays, 8 January 2018 to 2 March 2018

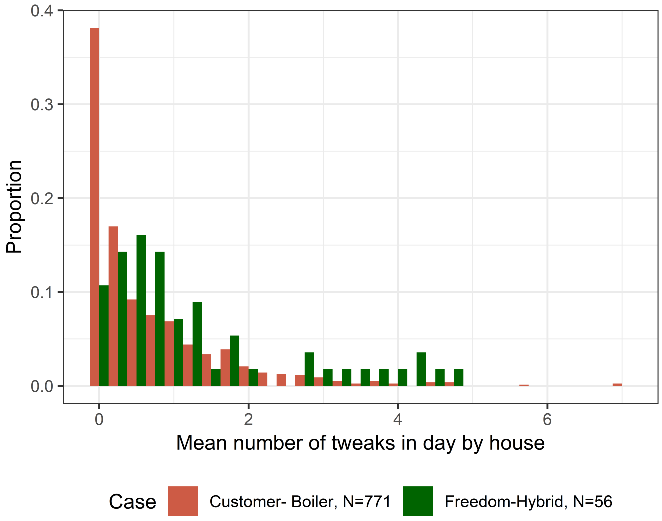


Figure 5.11: Distribution of mean manual tweaks each day for homes in the two cases Weekdays, 8 January 2018 to 2 March 2018

As explained in Chapter 2 the "ideal" DSR household will minimise the amount of manual operation since it is only scheduled setpoint changes that are visible to the algorithm when it is calculating how to move demand away from peak periods. Neither of the two cases demonstrate this ideal behaviour, with the households in the Freedom- Hybrid case making the highest number of manual interventions. In the next section I investigate reasons for manual alterations.

5.2.2 Qualitative data

This section examines the qualitative evidence from interviews about how households decide on the times to start and stop heating. Drawing on the practice theory framework described in Chapter 3, I investigate how these times link to practices in the home, and to the residents' practical understanding of how to operate their heating. I asked the Freedom-Boiler and Expert-Boiler interviewees about how they chose schedules for operating their boilers and spoke to the Freedom-Hybrid interviewees about how they set up the schedule for their hybrid heat pump in the new heating controller.

5.2.2.1 Schedules

Six of the Freedom respondents had set regular heating schedules before the trial, and their responses, together with those from the Expert-Boiler group, illustrate how householders choose the times to set in their boiler heating controllers. Interview respondents linked many of the scheduled settings to patterns of occupancy in the home, in particular getting up in the morning, going to bed at night, and when they left the building to go to work. For example, Susan (Freedom-Hybrid) said "it's on our regular routine, it comes on for 7 o'clock when we get up and goes off at 9 o'clock because often I'm going out by then".

Interviewees often described a combination of manual and scheduled operation of the heating. For example George (Freedom-Hybrid) said "in the evening it'll go off between 10 and 11, if I do go to bed at 10 I'll turn it off, otherwise it'll knock itself off at 11." Tim (Expert-Boiler) described how if his wife gets home earlier than usual in the afternoon she will "do a manual IN". Jill (Freedom-Boiler) said "we always need the heating on in the morning, ….. and then in the evening we do mess around with it a bit in the evening because we're not regular, times we come home". A regular, scheduled pattern is overlaid with manual operation to adjust to changes on a particular day to reflect irregular routines.

In multi-person households the heating schedule sometimes reflected the routine of a particular family member, rather than all the times the house was occupied. Vic (Expert-Boiler) said "in the evenings I'm doing stuff until maybe midnight. My wife normally will be in bed about 9:30. So I prefer it cooler, so the ASLEEP time is more set up for her sleep than mine." Nick (Freedom-Hybrid) works a varying shift pattern but still sets a regular daily schedule in the controller. He explained that his partner "would be in every morning and evening and I don't feel the cold". The link between the schedule and a particular member of the household who is seen as sensitive to cold is discussed further in 5.3.2.3.

5.2.2.2 Manual operation

The Freedom homes I visited had a high proportion of manual operation before the trial. Conversations with fourteen households about their heating before the start of the hybrid heat pump trial established that eight of these were turning the heating on and off manually every day. Six of these households had a programmable timer but did not use it, and two did not have a timer at all. This is a higher proportion than that in the nationally-representative EFUS study (BRE, 2013) which found that 66% of homes with central heating report using a timer.

The respondents described how manual operation of the heating was part of their daily routine in winter. Ken (Freedom-Boiler) said “me or my wife will get up and then we’ll turn the heating on” and that they would turn it off as they left the house in the morning. He explained why they did this rather than setting their timer: “it just kind of works… what’s easiest for us being in and out at different times”. This sense of “what’s easiest for us” was a common theme as people described how they operated their heating manually, often in response to irregular household routines.

Tracey (Freedom-Hybrid), who works variable shift times, when talking about how she had previously controlled her heating said “I don’t bother with timers. I just click it on and off as and when”. This mismatch between irregular daily schedules and setting a fixed pattern for automatic control of the heating is mentioned by Rathouse and Young (2004, p.10), who suggest that programmable timers do not fit with an unpredictable lifestyle.

An unspoken assumption that underlies the absence of scheduling is that the house will start to feel warm soon after the heating is started, so it is unnecessary to plan ahead. When asked whether the house heats up quickly, Ken (Freedom-Boiler) explained “there’s obviously a bit of a delay, but there’s not that much of a lag when the heating goes on” and Tracey (Freedom-Hybrid) said her house heats up quickly. This practical understanding of how the heating delivers a warm space will be discussed further in the next section.

5.2.2.3 Allowing for time lags

Two examples of allowing for a time lag came up in my interview with Ed (Freedom-Hybrid) when he was talking about setting his heating timer before the trial started. In the morning the heating comes on fifteen minutes before they get up “so it’s not ice when we first walk out”. In the evening the heating is on “ till about 7 which is roughly when the kids are bathed, the house then holds its temperature, starts dipping down ready for bed then”. When I checked that he deliberately lets the temperature drop towards the time they go to bed, he said “yes, it’s cooler when we go up for bed time.” Ken (Freedom-Boiler) explained that the time his heating is turned off in the evening depends on the temperature outside: “if it’s peak winter we’d turn it off when we go to bed, at 10:30 , 11, at the coldest times”, but on a mild evening they might switch it off earlier.

These examples show how the respondents’ practical experience of the thermal properties of their homes shapes the way they interact with the heating. This echoes the findings of Tweed et al. (2015) whose investigation of the thermal experience of older people concluded: “occupants can exhibit a fairly sophisticated knowledge of the behaviour of the building” [p.228].

Households are not only operating their heating to reach a warmer temperature at a point in the future, they are also timing operation to control future *coolness.* In order to decrease the temperature they know they have to stop the heating and wait for the house to cool down. Similarly, when they know from practical experience that there is a time lag between the time the heating starts and the time their desired temperature is reached, they will start the heating at an earlier time to reflect this time-lag.

I use the term “workaround” to label the instances when residents use their practical understanding to get a response which is not included in the “script” provided by their heating controller. A standard thermostat with timer control system is not configured for inputs from residents about when they want cooler temperatures, but they nevertheless manage to obtain these temperatures.

5.2.2.4 Links to other practices

When I asked about how timing of heating linked to household routines, several interviewees associated the times they set the heating to particular activities. For example, in several homes the heating was set to operate at times linked to the schedule of children. Five of the fourteen Freedom trial households I visited had children under 16, and in four of these the interviewee mentioned the influence of the children’s schedule on patterns of heating operation. For example, Debbie (Freedom-Boiler) was often in the house in the middle of the day, but did not run the heating until her children came home from school: "it's only really in the morning and the evening that the heating is on at all - just when the children are here really. ... I'd put the heating on just before say now [14:50] when I go to pick them up from school, but it'll be off all day". Leslie (Freedom-Boiler) is also often at home during the day, but runs the heating to match the times the children come home.

For these families, the practice of childcare requires a particular thermal environment. The goals of the practice of staying warm at home are closely linked to those of looking after children.

Another practice mentioned several times in connection with heating requirements was watching television. For example Ron (Expert-Boiler) said "I think I may have turned the heating on a couple of times at weekends if I wasn't out, when I was just lounging around watching telly". He said that on most days he only wanted the heating on in the evening. He does not turn the heating on at all in the morning "if I move around to keep warm then I don't need the heating". Ron associates his requirement for heating with practices with a low activity level, as would be expected from the Fanger PMV equation.

5.2.2.5 Heating norms

Several interviewees mentioned times when they were in the house but not running the heating. This tendency not to run the heating all the time when the house was occupied was also noted by Rathouse and Young (2004) and Rubens and Knowles (2013) . Since it is a common assumption in energy modelling that the home is heated whenever it is occupied (and the residents are not asleep) it is useful to understand the cases when this assumption does not hold.

Susan (Freedom-Hybrid), who is generally in the house during the day, had scheduled an OUT period from 09:00 to 17:00 on her PassivSystems controller. She said "when I'm doing things, cleaning, things like that, I don't need it, it's only if I was sitting ... perhaps in the afternoon, as the afternoon goes on, I might feel a bit chilly". Similar to Ron's explanation of why he used the heating only in the evening, she linked her requirement for heating to low activity levels.

Like Ron, June (Freedom-Boiler) explained she often did not run the heating in the morning, explaining “my husband goes to work really early and I don’t start work until 9:30 and usually I’m rushing round like a mad fool trying to do this that and the other and the heating hardly ever goes on in the morning”.

In these cases there is a clear link between heating requirements and the activity level of particular practices carried out in home, as would be predicted from Fanger’s PMV equation. However, not all the mismatches of occupancy and heating requested identified in interviews could be attributed to activity. In other cases residents were sitting at a desk rather than actively moving around, but they were not requesting heating. When I asked Ed (Freedom-Hybrid), who sometimes works at home during the day, if he had the heating running at these times he answered “typically not ... I might put a jumper on if I need to but it’s comfortable”. Luke (Expert-Boiler) explained that his wife worked from home every day but they had the occupancy set to OUT from 08:30 to 15:30. Caroline (Expert-Boiler) said that when she works from home she only very occasionally puts heating on: “it feels kind of wrong to have the heating on during the day”.

A common theme was that residents did not run the heating when they were in the house in the middle of the day. These interviewees are influenced by their sense of “right” and “wrong” times of day to run the heating which relate to social norms. This can be linked to the normative dimension of teleoaffectivity as described in Schatzki (2002) in which practitioners are influenced by ideas about “oughtness and acceptability”. Susan, Ed and Caroline were setting the schedule in their heating controller to OUT in the middle of the day even though they were actually at home. They had to translate their goals into the language of the control schedule because their preferences did not align with the assumption that residents want heating whenever they are in the house.

Debbie (Freedom-Boiler) and Linda (Freedom-Hybrid) both mentioned that they ran their heating for longer periods when the weather was “really cold”. Both these respondents did not request heating all the time they were at home, but sometimes extended the length of the heating requested period when the external temperature was low. This can be linked to the trend evident in the quantitative data.

Figure 5.8 shows an increase in mean heating request period duration as external temperature decreases. However, increasing the time heating is requested while spending the same total amount of time in the house is not the only plausible mechanism behind this trend. It is also possible that some households spend more time at home in cold weather and that this is their reason for running the heating for longer.

5.2.2.6 Heating goals

I have outlined how interviewees linked heating with other practices but I also found evidence of motivations specifically associated with the practice of staying warm itself. I asked interviewees whether comfort and or saving money was most important to them. Some respondents were very clear that they operated the heating to provide a comfortable environment and would always prioritise comfort over being cold. Others expressed mixed motives. Jill (Freedom-Boiler) was typical of many when she answered " a bit of both, a balance really". She went on to say "I am very conscious of the price, and I will put a cardi on, and thick socks, to save energy and money. It's quite important to me."

In some cases couples described compromises between their individual goals. Rachel (Freedom-Hybrid), referring to differences with her husband, said: "he sees the pound signs ticking away. I'm always nagging about the cold and he's always nagging about the money." In the case of Jill and Frank, it was Jill who was most focused on cost - she commented "he says I'm a cheapskate".

5.2.3 Summary: input patterns in time

In this section I have examined links between the timing of heating requests and practices taking place in the home. RQ1, about the outputs households want from their heating, can be related to my finding that heating goals are not static all the time the house is occupied, but dynamic, changing as the mix of practices carried out in the home changes over the day. The normative sense of what is the "right" level of heating has a dynamic dimension, with some residents not allowing themselves heating in the middle of the day, but taking for granted that they would run the heating in the evening.

Chapter 2 explains the assumption built into the language of PassivSystems controllers that people require heating when in the house and not asleep. Responses from interviews suggest that the actual situation in many households is more complex, and there is not a direct mapping between occupancy and heating requested. Two main reasons for this difference emerged from the interviews: allowing for the house to heat up and cool down, and norms about the right and wrong times to run the heating.

The findings also relate to RQ2, asking how residents interact with the heating controller. Applying concepts from social practice theory highlights how patterns of heating requests are linked to the residents' practical understanding of the response time of the heating system.

A relatively high level of manual changing of setpoints in addition to setting a schedule was both evident in the quantitative data and mentioned by interviewees. This potentially limits the scope for heating demand management. As explained in 1.2.4, the ideal DSR customer minimises manual operation, allowing the control algorithm to select low cost operating patterns to meet the scheduled pattern.

5.3 Temperature setpoints

Having established the patterns of heating operation in time, I now move on to investigate data about the level of temperature setpoints. I use quantitative data about settings to address my question about what output residents want from their heating system, and to explore whether the temperature they ask for varies over time. Interview responses allow me to explore the motivations behind varying temperature settings.

5.3.1 Quantitative data

In this section I discuss quantitative data on scheduled and manual temperature setpoints. My focus is not on the absolute levels of the setpoints but on changes during the day. Section 5.2.1.4 identified that there are more manual "tweaks" in temperature setpoint for the Freedom-Hybrid than the Customer - Boiler case homes in the two quantitative cases had very similar control interfaces (both wall-mounted device/thermostat and mobile phone app) so it seems unlikely that different levels of access to the controls affected the results.

These tweaks are indications that residents are not happy with their current thermal conditions, and so are taking action to change the input to the heating controller. Understanding when these are likely to occur is important for demand management since a manual tweak upwards in temperature setting leads to an instant call for heating energy (1.2.4).

5.3.1.1 Setpoint levels

5.2.2 showed that there are similarities in setpoint patterns in the two cases, but are the temperature levels requested also similar?

Group	**N (homes)**	**Mean of setpoint at 08:00 °C**	**Mean of setpoint at 20:00 °C**
Customer-Bolier	56	20.51	20.85
Freedom-Hybrid	771	20.02	20.55

Table 5.4: Median setpoint when heating requested at 08:00 and 20:00
Weekdays, 8 January 2018 to 2 March 2018.

Table 5.4 analyses the temperature setpoint when heated is requested at two points in the day in the two quantitative cases. The mean temperature setpoint is found for each home and then a mean of these means taken across the group of homes. Only setpoints during heating request periods are taken into account, so the home-days when the heating had not been requested at these times are not included. It can be seen that, for both the Boiler and the Hybrid cases the mean setpoint at 20:00 is higher than that at 8:00, but the difference is greater for the Freedom-Hybrid case.

The next step in the analysis is to examine the pattern in time of setpoint alterations.

5.3.1.2 Patterns in time of tweaks

Data for the setpoint at 10 minute intervals were used to detect whether each point was in a heating request period, and if it was, whether the setpoint has been changed manually since the beginning of that period. Changes of setpoint to a higher value than the initial setpoint (changed up) were distinguished from changes to a lower value (changed down).

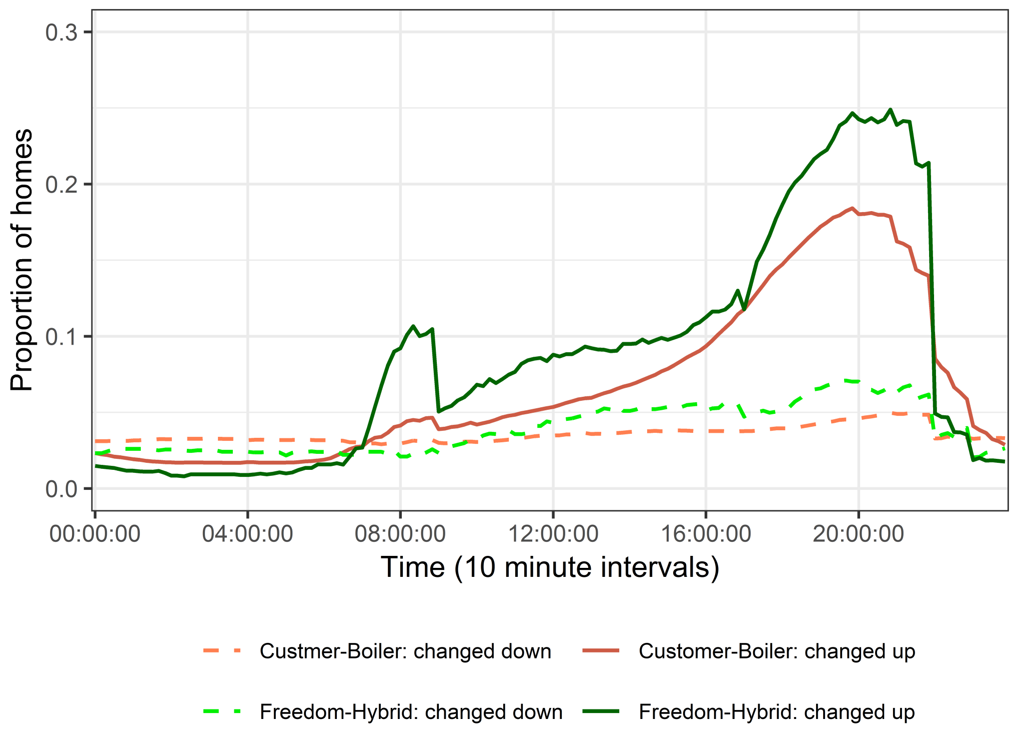


Figure 5.12: At what time of day are residents "tweaking" temperature setpoints? Proportion of homes with setpoint changed since beginning of heating request period. Weekdays, 8 January 2018 to 2 March 2018.

Figure 5.12 shows the pattern of these manual 'tweaks' up over the day. Adjustments downwards are also shown - it is clear in both cases that there are more manual changes upwards than downwards except between midnight and 06:00.

Figure 5.12 shows that as the evening progresses the number of homes in the Hybrid trial where the setpoint has been manually increased during the heating period rises until it reaches a (mean) peak of 25% of homes in the group at 20:50. 53 of the 56 homes with data in the Freedom case had manual increases during a heating request period at some point in the 8 week period. The Boiler group shows a similar trend over the evening, but a lower proportion of homes making tweaks, with a maximum of 18% of homes at 19:50. As discussed in 4.5.8, the two cases are not directly comparable so the difference in the frequency of tweaks cannot be attributed solely to the different heating system. The clear pattern for both cases suggests that many households are regularly adjusting the setpoint because they want a warmer temperature during the evening heating period.

As discussed above, a manual increase in setpoint will trigger an immediate demand for heat. The graphs shows that these additional demands may well occur in the evening peak period. In combination with the higher scheduled temperature setpoints in the second half of the day for the Freedom - Hybrid group, the higher level of manual tweaks in the evening suggests that many residents in the Hybrid case are actively aiming for a higher temperature later in the day.

5.3.1.3 Flexible temperature settings

The designers at PassivSystems were aware that some households preferred a different temperature in the morning than the evening. They designed a feature in the app for the Freedom-Hybrid group which allowed the participants in the Freedom trial to choose different IN setpoints for the scheduled morning (am) and evening (pm) periods. An example can be seen in Figure 5.13: for this home the am IN set point is 16°C and the pm IN setpoint is 17°C.

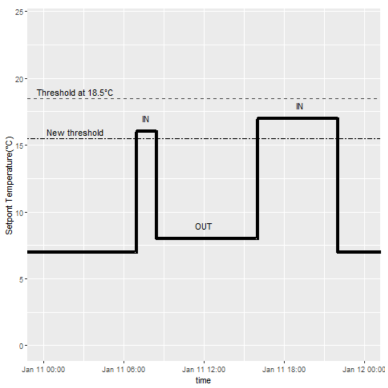


Figure 5.13: Example of am and pm setpoint differences

Of the 56 homes in the Freedom-Hybrid case with data available for weekdays in January and February, 22 set a higher IN setpoint after noon, 5 set a lower setpoint and 22 had the same setpoint before and after noon. Five homes did not have scheduled IN periods in both morning and afternoon.

It might have been thought that allowing the Freedom-Hybrid households to schedule different setpoints before and after noon this would reduce the amount of manual tweaking, since if a higher temperature is regularly required in the evening this can be entered as the pm setpoint in the schedule. However it is clear from Figure 5.12 this did not stop the Freedom-Hybrid households changing the setpoint manually. As shown in Table 5.3, there are more tweaks in the Freedom - Hybrid homes compared to the Customer - Boiler group even though scheduling a different setpoint after noon was not an option for the latter group.

Possibly the residents wish to control the timing of the higher setpoint to a particular time in the afternoon or evening rather than simply from noon onwards. This seems to be an instance where algorithm design to meet a perceived household goal does not actually satisfy the requirements of all the households.

5.3.2 Qualitative data

In Section 5.2.2 I showed how the timing of heating request periods is linked to different practices carried out in the home. In this section I discuss information from interviewees about the level of the temperature setpoint they requested, and whether this varies depending on the practices carried out at different times of day.

5.3.2.1 Time of day

Several interviewees mentioned a difference between temperature preferences in the evening and in the morning. Phil (Expert-Boiler) said: “in the morning generally we’re just not there for very long, it’s pretty hectic and we’re gone, so I don’t need to be super warm”.

Jim (Expert-Boiler) explained his morning requirement: “you just want it warm enough, to it not be, kind of you know that feeling when you just don’t want to get out of bed because it’s freezing outside, that’s all I’m looking for really in the morning, because we hare around and then leave the house anyway”. Nick (Freedom-Hybrid) said “in the morning, because we don’t hang around in the morning, it’s like a milder temperature in the morning, just to take the edge off it, we all get up, shower, and then we’re all off. In the evening we have it a bit warmer”. Ben (Expert-Boiler) contrasted the evening: “it’s that time when we’re relaxed around the TV in the evening, that the temperature goes up by a degree". George (Freedom-Hybrid) is usually at home all day but also has a higher temperature requirement in the evening. When I interviewed him in the morning, he said "I've set it now for 20 and it'll stay that all day and I may knock it up a degree tonight".

These comments reinforce the evidence from quantitative data that there is a widespread preference for higher temperatures later in the day. Rubens and Knowles (2013) also report interviewees saying they wanted higher temperatures in the evening.

Several respondents linked requirements for a higher temperature in the evening to lower activity levels associated with the usual practices at this point in the day. Jean (Freedom-Hybrid) said "I think when you're sitting down in the evening you're needing to be warmer, when you're busy during the day you know." and Jill (Freedom-Boiler) said: "in the morning when I'm rushing round getting ready, I don't feel the cold so much ".

The data show that setting higher temperatures in the evening is not universal and some interviewees gave reasons for wanting higher temperatures in the morning. For example Ed (Freedom-Hybrid) initially chose to set his morning setpoint higher than his evening one. He explained "when we first wake up, when we first get out of bed, that needs to be warm". Vic (Expert-Boiler) explained that his bathroom is in a poorly-insulated extension to the house and often very cold. In order to be sure the radiator is hot when he had a shower in morning he sets the morning setpoint higher than the evening one. "I've still got some heat in the bathroom in the morning coming out the radiators just about when I'm going through the shower". These cases show that the preference for higher temperatures in the evening, while a general trend, does not apply in all homes. Particular combinations of household routines and building fabric properties can lead to varying preferences.

5.3.2.2 Duration

Table 5.2 shows the first heating request period in the day is generally much shorter than the second period later in the day. Phil, Jim and Nick drew a connection between lower temperature preferences in their morning heating request period and the short time they are in the house before they leave for work. Other interviewees also implied that lower levels of warmth were acceptable if they were expecting to leave the house after a short time, compared to periods when they knew they would be in the house for a long time at the end of the day. Statements from interviews suggest that the duration of a heating period can influence temperature preferences for the period.

One phrase that came up in interviews a number of times is "taking the chill off". This seems to imply that the householder is looking for an increasing temperature for a short period rather than being concerned that the temperature reaches a particular level. Tracey (Freedom-Hybrid) used this phrase four times in her interview. Before the Freedom trial she was running the heating manually for short periods. When asked about what times she operated her heating she mentioned "an hour or so before bed just to take the chill off" and said "there's the odd occasion when I'd switch it on about 6, just to warm the house, take the chill off, and then I'd switch it back off". This pattern was not confined to evenings: "on a weekend I may switch it on for an hour. If I'm home you know with the kids, to take the chill off, if we're in the house, in the morning". Tracey's statements match the approach of several interviewees in the morning. For example, Richard (Expert-Boiler) says he sees the purpose of heating in the morning as "to take the chill off" as he tends to be quite active at that time and does not feel cold.

5.3.2.3 Individual preferences

Another factor behind changes in temperature setpoint identified from the interviews is the intersection of the routines of different household members. In multi-person households the temperature preferences among individuals often vary. I have already described how Vic (Expert-Boiler) sets the heating to stop when his wife goes to bed, even though he stays up later. A similar point was made by Jim (Expert-Boiler). He explained the end of his evening IN period is set at 22:00, his girlfriend usually goes to bed at 22:30 "it's started to cool down by then" but he often stays up later: "I tweak it manually if I'm too cold, but normally I just try and use a blanket or something". Just as Nick sets heating times for his partner's routine (5.2.2.1) these interviewees described setting temperatures to suit the routine of person who "feels the cold" most in the household. In these cases the routines of one particular individual shape the pattern for the household.

One example where the impact of preferences of different household members could be seen clearly is the data from Ben (Expert-Boiler) and his family's house. The schedule was set to start the heating at 15:30 with a setpoint of 20 degrees. The data showed that nearly every evening at some point between 15:30 and 18:00 the setpoint was increased manually. Ben explained "it's set to start at half three when they get home from school and it's set to 20 but what quite often happens is they get home and then they pop it up to 21 or 22". The time at which his wife and children come home varies as "it depends on whether they do something after school, quite often they might go out, or they might go to grandparents". In this case the pattern of manual alteration of temperature setpoints is linked to the preferences and routines of particular family members.

5.3.2.4 Guests

The addition of extra people - guests - in the home can also alter the goals associated with heating. Matt (Expert-Boiler) and his wife are conscious that most people find their house cold so turn up temperature before the arrival of visitors. Jean (Freedom-Hybrid) said "I belong to a reading group and when they come round I'm very conscious now I don't want it too cold. Yes I definitely worry about it when other people are here." These respondents are conscious that they may be diverging from social norms, and associate the practice of hosting guests with a goal of making sure their guests are warm.

A common theme with childcare is that the interviewees are turning on/ turning up the heating for the sake of other people in the house, in contrast to limiting heating use when they are alone.

This selection of different conditions for guests is not universal. Jill (Freedom-Boiler) said "people come in and say it's cold in here and I'll say 'put a cardi on'". In this case she is prioritising her goal of cost-saving and does not seem concerned that her guests may perceive her as diverging from expected norms.

5.3.2.5 Changing moods

Schatzki (2002)'s discussion of teleoaffectivity includes the emotions and moods of practitioners. This affective dimension of how temperature setpoints are chosen was evident in two interviews in which interviewees described temperature preferences which varied depending on health or mood. Phil (Expert-Boiler) was conscious of variable moods. When I asked "If you're at that point where 'oh it's a bit cold', would you turn up the heating, put on an extra jumper?" he said "it depends quite a bit on my mood ... I might chose a thicker than a thinner one. But other times, if you feel under the weather or whatever, or just fed up, and just want to be warm then I would ramp it [the thermostat setpoint] up".

George (Freedom-Hybrid) explained why he'd turned up the temperature setpoint the earlier in day I interviewed him: "I'd not slept very well and when you're tired you tend to feel the cold more"

I did not ask questions about the impact of poor health on temperature preferences as this seemed to me an unnecessary intrusion on interviewees' privacy. The fact that these two respondents volunteered information about the impact of their state of health suggests that this may be also an issue for other residents.

5.3.2.6 Alternative strategies

A particular strategy for keeping temperature setpoints at a minimum was described by two members of the Expert-Boiler group. Tim (Expert-Boiler) said "my setpoint tends to be set to just below a comfortable level and then I'll often nudge it up". When I asked Phil (Expert-Boiler) about a reduction in setpoint about a month after the controller had been installed he said "I was just finding the lowest value we were comfortable with, and pushed it up when we needed to". Both Tim and Phil linked this strategy to their goal of minimising heating energy use. Their frequent adjustments are not compatible with the requirement for predictable steady temperature requirements to allow DSR.

A heat balance for the building (as described in 2.5) shows that a low setpoint which is "nudged up" when required requires lower overall energy usage compared to a constant setpoint at the highest desired level, so this strategy reduces overall heat consumption for the home and is undoubtedly an efficient strategy for operating a boiler. However, when the heat is supplied by a heat pump, frequent changing of setpoints rather than steady running may lead to less efficient operation and an increase in electricity consumption by the heat pump as described in 2.4.3. The optimum operating pattern to minimise energy consumed depends on the particular circumstances. There is a possibility that encouraging households who are operating, like Tim and Phil, at the minimum tolerable temperature, to instead follow fixed, pre-scheduled temperatures may actually increase their overall heating energy consumption.

5.3.3 Summary: setpoint temperature patterns

Section 5.2.2 described how the times people operate their heating do not always coincide with the times the house is occupied. The evidence on temperature preferences adds another dimension to this, showing that many do not want a consistent temperature across the different periods their heating is running. The quantitative and qualitative evidence presented in this section confirms a point made by Tweed et al. (2015) who write about the "misconception that thermostat settings remain constant" [p.229]. This represents a challenge for the current version of the control algorithm which is designed to provide a very steady temperature throughout heating request periods.

5.4 Patterns of temperature in the home

In this section I move on to discuss the output from heating system: the pattern in time of temperatures in the home which results from the pattern of operation of the heating system. I combine quantitative evidence on temperature patterns from the Freedom-Hybrid and Customer-Boiler cases with qualitative evidence on reactions to the change in output from the Freedom-Hybrid trialists. As discussed in Section 5.1 the Freedom-Hybrid trialists experience a changed output pattern because of the change in heat source and the introduction of a disconnect between the times heating is requested and the times the heat source operates. I investigate whether the new patterns met the residents' goals for their thermal environment. Reactions from residents allowed me to explore their practical understanding of the new system, and whether they were able to achieve their goals.

Case		Description	N (Qual)	N (Quant)
Freedom - Hybrid		Freedom trialists during trial, running hybrid HP with algorithmic control	11	75
Customer - Boiler		Homes with Passiv controller running boiler, preheat algorithm not enabled		771

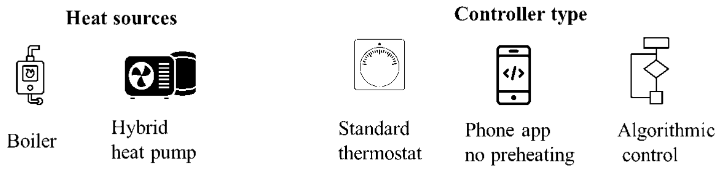


Figure 5.14: Evidence used in this section

5.4.1 Quantitative data

In this section, I describe how setpoint input pattern translate into temperature output patterns in the Customer-Boiler and Freedom-Hybrid quantitative cases.

5.4.1.1 Temperature profiles

Figure 5.15 shows how the profile of mean temperatures across the day for the conventional heating case compares with the profile for homes with hybrid heat pumps. As described in 4.5.7, a mean of the means for individual homes was calculated to ensure equal weighting for each home. Homes where there were less than 20 days of data available were excluded from the analysis. The data for 8 weeks in January and February are plotted. Days on which the heating was not requested at all during the day are excluded.

As discussed in Section 4.5.8 the two groups of homes are not directly comparable, so care should be taken in drawing conclusions from differences between the cases. In particular there may be a different rate of heat loss on average between the two groups of buildings. However, thermodynamic principles determine that there is a changed temperature profile when a lower output heat source (heat pump) runs for a longer length of time, and when the control algorithm shifts the times when

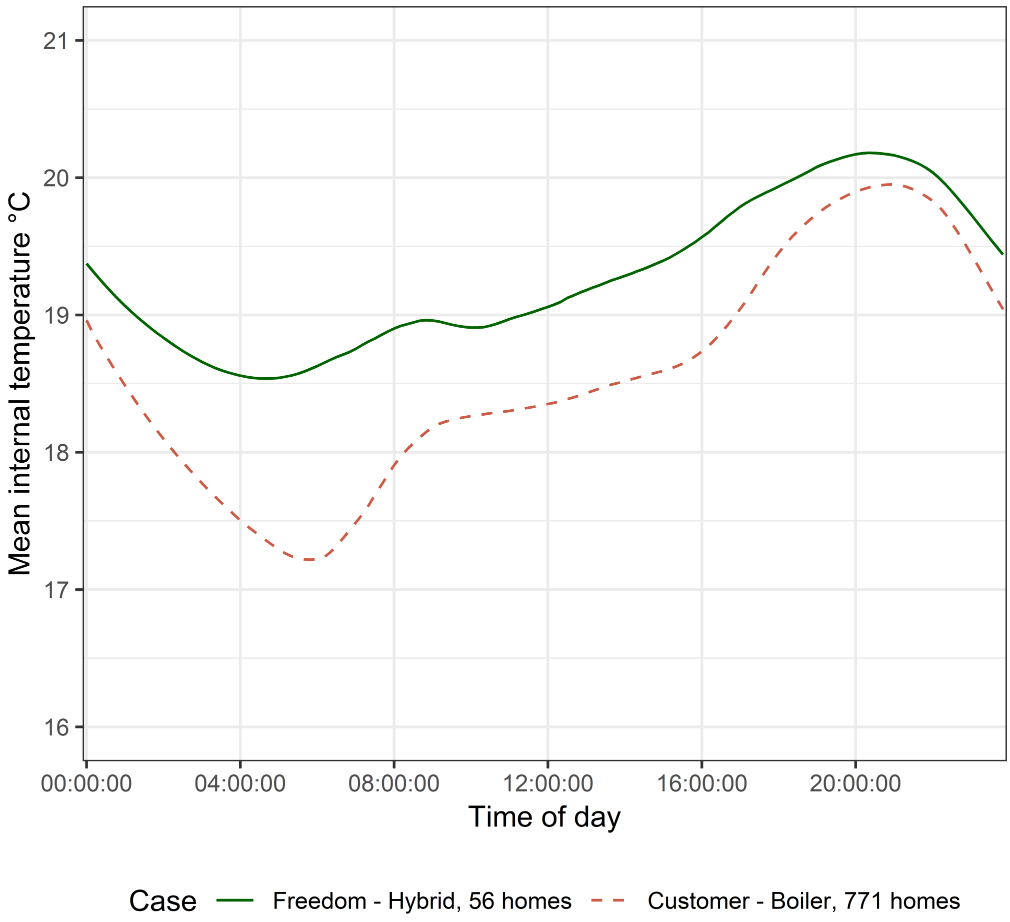


Figure 5.15: How does the typical internal temperature pattern vary between the two cases? Mean temperature at thermostat on winter weekdays, plotted at 10 minute intervals. Weekdays, 8 January 2018 to 2 March 2018.

the heat pump runs. The temperature profiles in Figure 5.15 show, that as would be expected from these basic principles, the profiles for the two cases are different. This suggests that the households in the hybrid heat pump trial were likely to experience a change to a steadier temperature profile following the replacement of their boilers with a hybrid heat pump.

The early morning temperature rise starts earlier for the typical Freedom-Hybrid home. The temperature trace for the case with boilers shows a noticeable variation over the day. The lowest temperature at around 06:00 is followed by a rising temperature reaching a maximum at about 21:00. In contrast, the trace for the hybrid homes shows less overall variation in temperature around a higher mean temperature, but the highest temperature is also at around 21:00. The flatter temperature profile contrasts with the more dynamic situation for the Boiler case. Table 5.4 showed that the median setpoint at 20:00 was slightly higher in the Customer-Boiler than the Freedom-Hybrid case while Figure 5.15 shows that a higher mean temperature is actually reached in the Freedom-Hybrid homes.

5.4.1.2 Different transformations

Since the pattern of switching of setpoints is an important influence on the temperature profile, I investigated days with one period operation and days with two period operation separately. Figure 5.16 compares output for similar input patterns across the two quantitative cases, showing days with a single period of heating separately to days with two periods. The output pattern (mean temperature) for each subgroup is superposed on the input pattern (represented by proportion of homes requesting heating, plotted on a second scale).

The higher temperature in the evening compared to the morning is clear in all the subgroups. The Freedom-Hybrid two period subgroup has a consistently higher mean output temperature than any other subgroup. It also has the lowest daily temperature range (1.6°C). The Customer-Boiler two period subgroup shows the greatest range of temperature over the day, at 3.0°C. It the beginning of the morning heating period for the two period groups is examined, it is clear that the temperature for the Freedom-Hybrid case has dropped much less overnight (to about 19°C compared to around 17°C for the Boiler cases) and starts to rise earlier in the morning.

The night time temperature minimum for the Freedom-Hybrid one period subgroup is lower that the night minimum for the Freedom-Hybrid two period subgroup. This may be linked to the significant proportion (36%) of days in the Freedom-Hybrid one period group when this single period started after noon, i.e. there was no request for heating in the morning at all. The algorithm typically starts to operate the heating to increase the temperature a few hours ahead of the start of the heating request period, and when this period starts late in the day, it is unlikely to run the heating during the night.

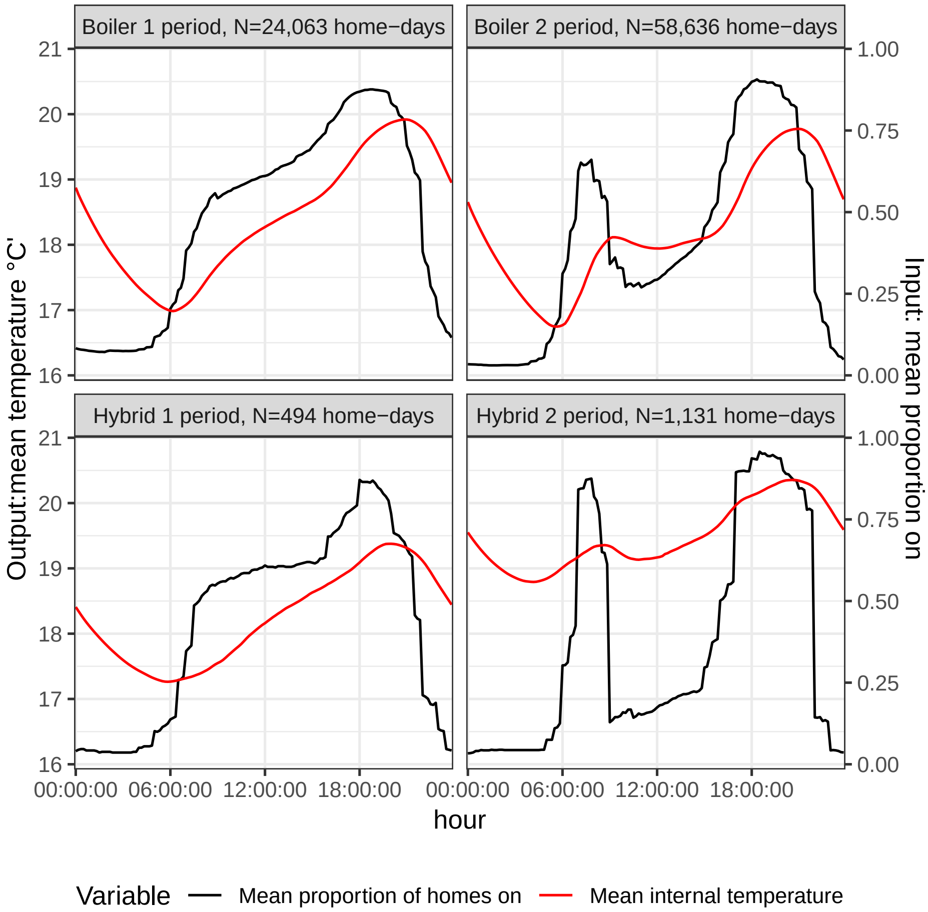


Figure 5.16: How does the output temperature profile differ when similar input patterns are considered?

It is interesting to note the similarities between two of the clusters of temperature profiles identified by Huebner et al. (2015). The Boiler one period profile is similar in shape to that of Huebner et al.'s Cluster 4 (13.8% of their sample, showing a decline until about 07:00, then an increase over the day until around 20:00) and the Boiler two periods is similar to Cluster 3 (40.0%, showing a peaks in the morning and a higher peak in the evening). Huebner et al.'s derivation of setpoints (which they did not monitor) based on inferences from temperature profiles match well with those actually measured in my two quantitative cases.

5.4.1.3 The influence of external temperature

Since heat flow from the building is driven by the temperature difference between inside and outside, the influence of external temperature should be taken into account in any comparison of internal temperatures. Figures 5.17 and 5.18 compare features of the output profile of the Freedom-Hybrid and Boiler groups on days with the same mean external temperature. This allows a check to see that any differences are not simply a result of different external temperatures for the two groups.

The amount of change in temperature over the day was represented by the temperature range (the difference between maximum and minimum internal temperature) for each home on each day. The range was plotted against mean external temperature for that home-day. The points were gathered into "bins" by rounding the external temperatures to the nearest 1°C so that, for example, the mean range was calculated for all home-days when the temperature was greater than 0.5°C and less than 1.5°C. Figure 5.17 shows the mean daily range for the Freedom-Hybrid group is consistently lower than that for the Customer Boiler case for all external temperatures. Figure 5.18 shows the mean night-time temperature (calculated over the six hours from midnight to 06:00), plotted against the mean external temperature for the day. This shows that the mean night time temperatures in the homes with hybrid heat pumps are consistently higher than in the conventionally heated homes.

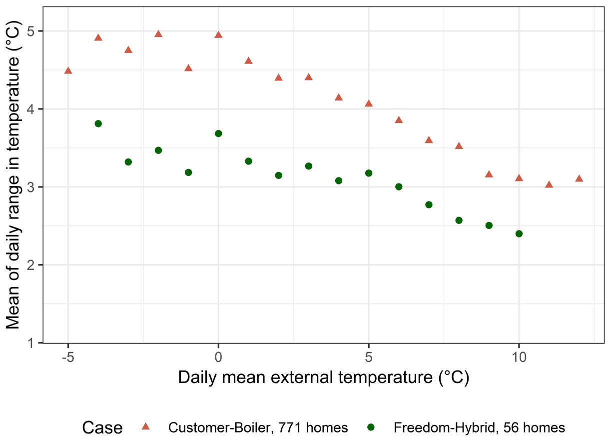


Figure 5.17: Is difference in daily temperature range consistent across all external temperatures? Daily range of internal temperature plotted against external temperature Weekdays, 8 January 2018 to 2 March 2018

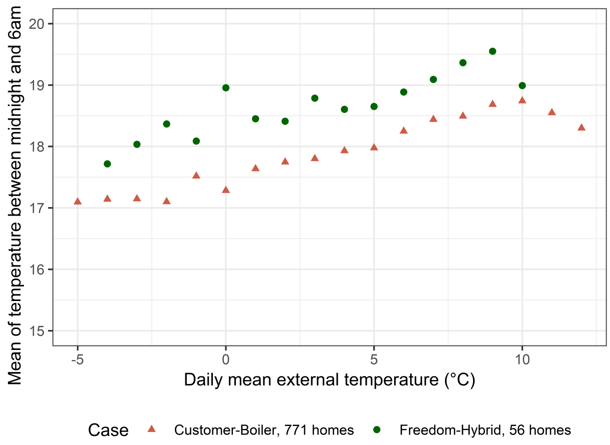


Figure 5.18: Is difference in mean night time temperature consistent across all external temperatures? Daily mean of night time (00:00 to 06:00) temperature plotted against external temperature. Weekdays, 8 January 2018 to 2 March 2018.

5.4.1.4 Evening experience

The mean profile of days with two period operation in Figure 5.16 is the result of the superposition of many individual profiles for different homes on different days, starting at different times and running for different durations. I investigated the temperature rise in the second heating period in more detail in order to compare the variation in output room temperature experienced by those with two heating periods.

As previously discussed, any comparisons between the two cases must be made very cautiously as they represent different people in a different set of buildings. However, if the analysis focuses on homes with exactly the same input patterns, this removes any differences caused by the interactions of residents with heating controllers. The differences in the temperature rise when heating has been requested for exactly the same length of time are affected by a combination of the characteristics of the heating systems - a known difference between the cases - and the difference in the building fabric characteristics, which is not known. (Differences in ventilation patterns may also have an effect.)

Figure 7.3 plots relative temperature rise against time elapsed from the start of the period to enable a more consistent comparison. It includes only those homes with a second heating request period which is five hours long (the most common second period duration). This temperature rise for the two quantitative cases is shown in Figure 5.16. The Freedom-Hybrid data are further divided into those home-days where there was a manual tweak to the temperature setpoint during the second heating period, and those where there was no change. This allows comparison of the experience of the significant proportion of the Freedom-Hybrid case who alter their setpoint at some point during the second heating period.

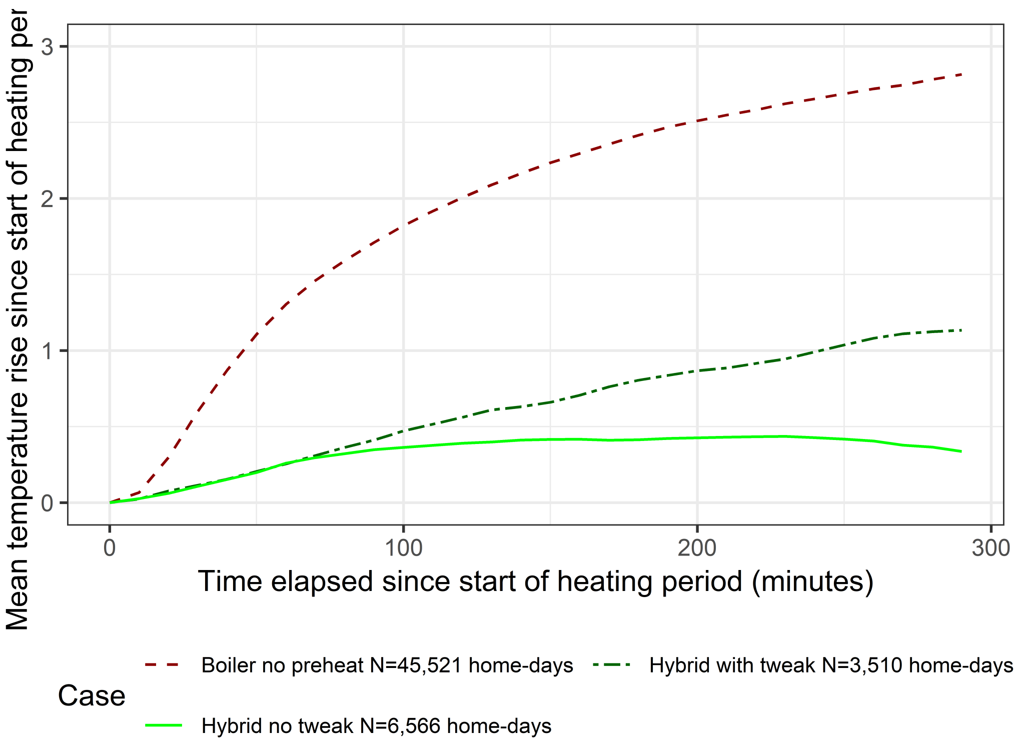


Figure 5.19: How does evening temperature experience differ for the two cases?

The contrast between the nearly three degree rise in mean temperature for the Customer-Boiler group and the 0.6°C temperature rise for the Freedom-Hybrid with no tweak is clear, and reinforces the point that those operating a conventional system without preheat have a different experience of a temperature which rises over the evening compared to the Freedom-Hybrid group with an almost constant temperature.

The varying temperature profile in Figure 5.15, which is similar to those found by Huebner et al. (2015) suggests that many UK households are accustomed to a rising temperature over the evening. The Freedom-Hybrid trialists have a much flatter profile and their pattern of tweaking the setpoint higher in the evening described in Section 5.2.1.4 suggests that they may be aiming to replicate the temperature pattern they were accustomed to with a boiler. This is not the only possible explanation. The difference may also be influenced by technical difficulties experienced during the trial, or increased salience of the new controller because of the disruption associated with the installation of new equipment.

5.4.2 Qualitative data

This section discusses what the hybrid trialists said about their temperature preferences at different times of day, and how they reacted to the new output patterns that result from the changed heating system characteristics. The change in heating system gave me an opportunity to investigate expectations and preferences (both conscious and unspoken) for thermal conditions during the day. Residents may only realise what it is they like about the conditions to which they are accustomed when they identify changes to less satisfactory or unfamiliar conditions.

5.4.2.1 Night-time temperature

I asked all my interviewees before and during the hybrid heat pump trial about their night time temperature preferences. None of the interviewees requested heating when they were asleep, and all were accustomed to heating being off in this period. Most interviewees stated very clear preferences for a cool bedroom when they were sleeping. Ken and Debbie (Freedom-Boiler) are an example of a couple who were clear about their night time preferences:

> Ken: What I find is when you've got the heating coming on when you're in bed, it might be cold outside but suddenly you're boiling hot then in bed and that's not comfortable.
>
> Clare: Do you like to keep the bedroom cool?
>
> Ken: Debbie likes the window open, even in winter, you'll like the window open won't you?
>
> Debbie: Yes

Ed (Freedom-Hybrid) also articulated a clear preference " through the night the temperature needs to drop down. None of us can sleep when it's warm." He went on to explain that his young daughter could not sleep in a warm bedroom. "My little girl, she's three, if she has icicles hanging off the curtain pole she sleeps far better than if it's warm. If she's warm she will toss, turn, grizzle, through the night, but if it's cold... she'll be fast asleep the whole night".

It seems an important goal for many is to ensure a cool bedroom when they are asleep. The preference for cool bedrooms has implications for what Schatzki refers to as material arrangements (Schatzki, 2002). Several interviewees mentioned using warm duvets, for example Tim (Expert-Boiler) explained both he and his wife like a cool bedroom: "I love it cold ... we have an electric blanket at night and a 13 tog duvet"

Before the Freedom trial, none of the households I interviewed had run their heating during the time they were asleep at night. The preheating introduced by the new control algorithm introduced a change, with the heat pump or boiler running ahead of the scheduled morning IN period, frequently for several hours during the ASLEEP period.

Of the Freedom-Hybrid group of eleven trial participants interviewed after the trial began, four said they were unhappy with high temperatures at night. For example, Tracey (Freedom-Hybrid) said "in the middle of the night, I'm waking up in piles of sweat" and "my daughter told me, when she come down the stairs at 3 o'clock this morning, she was boiling and sweating because the heating was on". Ed (Freedom-Hybrid) complained "the house is constantly so hot .... in the middle of the night we wake up with migraines". Frank said: "So the house is over 20 degrees, I think it was 21 or 22 degrees one night, which is unbearable for us, it's too warm".

Two further interviewees said they had noticed higher night time temperatures but did not perceive this as a problem.

The negative reactions to higher night time temperatures are perhaps unsurprising given the widely expressed preference for low temperatures when sleeping expressed by participants before the trial began. This tallies with the dislike of high night time temperatures noted by Caird et al. (2012) and Fell (2016) in studies of British homes with heat pumps.

5.4.2.2 Day-time temperatures

Two households mentioned that they had noticed a change in the steadiness of day time temperatures and both remarked on it favourably. Susan (Freedom-Hybrid) said "it wasn't too hot and I wasn't cold". Rachel (Freedom-Hybrid), who reported often being cold with the previous heating system was very happy with the new installation "it's just constantly warm" and her husband John said "if it keeps on like this I'll be more than pleased".

The only negative comment I heard about daytime temperatures was from Tracey (Freedom-Hybrid), who complained: "It's annoying, you know, because it's like when the house is, the house is either too hot or it's freezing, I've got no happy medium with it." In Tracey's case her negative reactions were linked to a general sense of unhappiness about the cost of the new heating system. She said "it's heating the house too much, it's just heating away on my gas and my electric". For Tracey controlling the cost of the heating was an important goal which, in her view, she was unable to achieve with the new system.

5.4.2.3 Failed workarounds

Section 5.2.2 described the workarounds used by households and how practice theory can be used to link them to their practical understanding of conventional heating control. They start and stop the heating allowing for time lags, to ensure the conditions are cool or warm when they want them to be. In a number of cases I found that interviewees who were dissatisfied with the temperature patterns from the hybrid heating system and had tried to use familiar workarounds, only to find that these did not give the required results.

In particular the four respondents who were unhappy with high night time temperatures had tried to deal with this by turning down the setpoint on the thermostat. With conventional heating control, the boiler stops if the setpoint is reduced below the current temperature. The logic of the algorithm running in the PassivSystems controller is that the controller will run the heat pump or boiler during an ASLEEP period (typical temperature setpoint of 12°C) for a preheat period ahead of ahead of the beginning of an IN period (typical temperature setting of 20°C). Any manual changes made by the residents to the ASLEEP setpoint during this preheating period will not stop the heat source running.

The residents found their accustomed workaround to obtain coolness (turning the thermostat setpoint down) did not work. They did not understand how to stop the heating when they woke up feeling too hot and were aware the heating was running. This led to frustration and negative reactions to the hybrid heating system. Tracey (Freedom-Hybrid) described increasingly desperate attempts to stop the heating: "I'm switching it off by the app on the phone, setting it to that I'm out, then I've got to do it at the thermostat, then in the end I've ended up switching it off by the boiler, at the switch on the wall". These residents' practical understanding of how to achieve their goal of coolness no longer worked and they did not know to specify when they wanted to be cool.

The lack of a workaround for the new system is only an issue for those who objected to the temperature at night. Those who were not unhappy with night time temperatures, and so were not trying to stop the heating at night, had more favourable responses to the new heating system in general.

5.5 Summary of findings

In this chapter I have investigated what pattern of temperatures residents aim to achieve in their homes (RQ1) and how they interact with their heating controller to achieve these patterns (RQ2). Reactions to changes in temperature patterns following the installation of a hybrid heat pump (RQ3) allowed me to explore whether residents are able to achieve their temperature goals with the new system.

I have described patterns in time of heating requests, looking at when the heating request period started and ended. While there was considerable variation in the number and length of the heating request periods in a day, similar typical patterns with a shorter heating request period in the morning and a longer one in the later afternoon/evening were observed for both the Customer-Boiler and Freedom-Hybrid groups. Most households had a mix of scheduled and manual setpoint changes, with frequent manual intervention (in addition to scheduled start and stop times) particularly noticeable in the Freedom-Hybrid case. When I interviewed participants in the Freedom trial, they gave accounts of a mix of manual and scheduled operation to fit daily routines, with the timing of heating requests linked to who is in the home, what they are doing and how long they expect to be at home.

The times heating is required may differ from the times home is occupied. I found several cases where the heating was not operated when the house was occupied in the middle of the day. The residents explained their views on "right" and "wrong" times to run the heating, influenced by social norms.

Particular practices were associated with requirements for warmer temperatures in some households. Often this was associated with practices with low activity levels, such as watching television, but other activities such as childcare were linked to preferences for higher temperatures but not associated with low activity levels.

Several interviewees mentioned that they are satisfied with lower temperatures in a shorter morning heating request period, when they are active and know they will soon leave the house.

The quantitative data for patterns of temperatures requested showed a trend of manual increases in setpoint in the late afternoon or early evening. This trend for a higher temperature setpoint in later in the day has implications for demand in peak periods, since an unanticipated request for a higher setpoint triggers the controller to start the heat source immediately.

The Freedom hybrid heat pump trialists typically experienced a more constant temperature, with less fluctuation over 24 hours and warmer night time mean temperature, than the Customer-Boiler case with conventional boilers.

The pattern of actively increasing the temperature at some point in the late afternoon or evening is more prevalent in the Freedom-Hybrid group than the homes in the Customer-Boiler case. This may indicate that some residents with hybrid heat pumps are actively trying to replicate the fluctuating conditions to which they were accustomed when they were operating a boiler.

Qualitative interview data showed that some Freedom trial participants were unhappy about high night time temperatures and frustrated when they could not stop the hybrid heat pump running during the night. Planning for a heating transition should consider how to mitigate negative reactions to the high night temperatures which are associated with efficient running of heat pumps. This issue has the potential to make the technology unpopular and to lead to inefficient manual operation of heat pumps, which may not realise carbon savings.

Residents have a practical understanding of boiler systems based on many years of experience. They know how to obtain their preferred temperature pattern (including coolness at night) by operating the boiler in a pattern that allows the home to heat up and cool down. Some households struggled to achieve the temperature profile they wanted from a hybrid heating system. In particular they found it challenging to obtain low night-time temperatures. Familiar workarounds no longer provided the conditions they preferred.

This chapter has identified some tensions between the assumptions and language of the heating controller and the ways residents are actually using the equipment. This theme is developed in the next two chapters and leads to the recommendations for control design outlined in Chapter 9.

I have applied the concepts of goals and practical understanding to residents' requirement for particular daily temperature profiles in their homes. In the next chapter I examine other goals which residents aim to achieve with their heating systems.

Chapter 6

Heating as an adaptive system

6.1 Introduction

Chapter 5 investigated daily temperature profiles and the temperature goals of residents. In this chapter the focus shifts to other goals residents have when they operate their heating systems, for example to avoid noise from the heat source or ensure the radiators are hot at a particular time. These goals are associated not with air temperatures, but with the running pattern of the heat source: when it starts and how long it operates. I investigate residents' reactions to the changed operating pattern that results from a hybrid heat pump with algorithmic control.

The chapter focuses on the "non-temperature" responses desired by residents as they relate to my research questions:

RQ1 What output do households want from their heating systems?

- Which aspects of heating system response apart from room temperature are important to residents?

RQ2 How do residents interact with their heating system to get their desired operating patterns?

- How do residents control conventional boiler heating systems to get the patterns of operation they require?
- Are residents able to achieve the (non-temperature) responses they would like with a new heating system (hybrid heat pump with algorithmic control)?

RQ3 How do households react to a change in heating system characteristics?

- How do households accustomed to a conventional gas boiler system react to the changed operating pattern from a hybrid heat pump with algorithmic control?

My discussion of different responses from the heating system is inspired by the adaptive thermal comfort approach outlined in 2.3, which considers occupants in a heated building as an adaptive system with multiple feedback loops. I investigate different types of feedback from central heating mentioned by residents, as I investigate the responses and running patterns they are aiming to achieve.

I draw on the concepts from Social Practice Theory introduced in Chapter 3, discussing how goals and practical understanding relate to non-temperature responses from the heating system.

As I discuss how residents adapt to a new heating system, I refer to Pickering's concept of the "mangle of practice" in which people and things are in a constant state of mutual adaptation by a process of "resistance and accommodation" (Pickering, 1995).

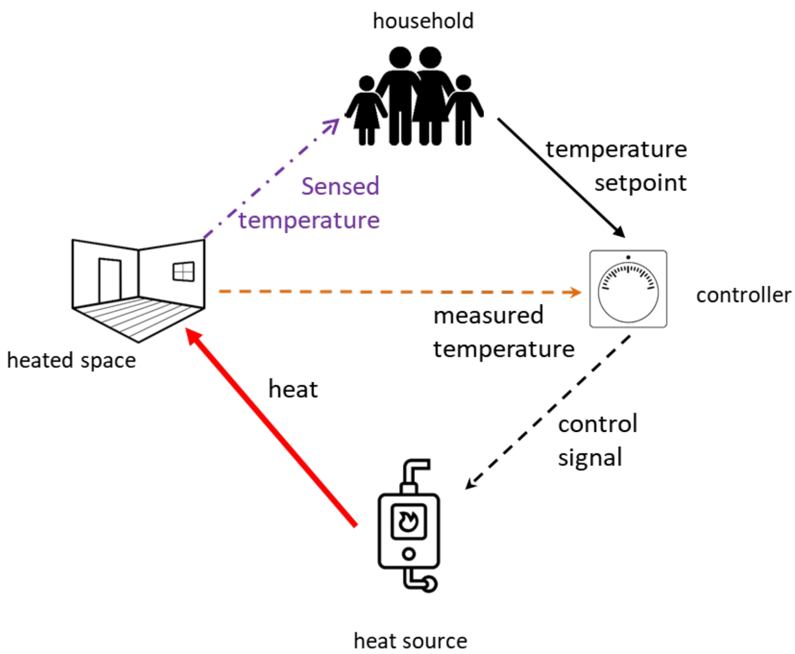


Figure 6.1: Temperature feedback

Section 2.3 introduced the importance of feedback in adaptive systems and described the feedback loops in the ASHRAE RP884 conceptual model of thermal comfort (de Dear et al., 1997). The findings of Chapter 5 about residents' preferred temperatures - and the actions they take to achieve these - can be interpreted as a description of a feedback loop between residents, their heating system and the room temperature they sense. Figure 6.1 shows the feedback from output room temperature back to residents who, if they want to change the conditions, make adjustments to the input by adjusting the settings of the heating controller. This diagram is modified later in the chapter as I identify additional adaptive options and extra feedback loops.

6.1.1 Chapter overview

This chapter starts by building a picture of the key elements of the adaptive system being investigated, discussing the different options residents have to change their thermal conditions.

I then investigate which aspects of output from the heating are seen as important by residents, considering non-temperature responses such as noise. I explore both welcome and unwelcome responses and how these relate to the goals and practical understanding of the residents. I also explore residents' practical understanding of the new control equipment installed in the Freedom hybrid heat pump trial. Drawing on interviews with the Expert-Boiler group I describe how knowledgeable residents gradually alter and adapt to a new heating control strategy.

The main evidence presented in this chapter is from qualitative data but quantitative data are also used to explore some of the changes in behaviour identified through the interviews. Figure 6.2 summarises the qualitative and quantitative cases discussed.

My interviews provided two opportunities to investigate reactions to changes in the heating system. When talking to the Freedom-Hybrid trialists, I asked them about their reactions to all the changes encountered in moving from a boiler with a conventional control system to a hybrid heat pump with algorithmic control.

I was able to ask the Expert-Boiler group about their reactions to changes in the control system for their boilers which they experienced when they changed from a conventional control mode to algorithmic "ontime comfort" control with preheating.

Case		Description	N (Qual)	N (Quant)
Freedom - Boiler		Freedom trialists before start of trial, running boiler with standard thermostat control	7	
Freedom - Hybrid		Freedom trialists during trial, running hybrid HP with algorithmic control	11	75
Expert – Boiler		PassivSystems employees running boiler with algorithmic control	11	
Customer - Boiler		Homes with Passiv controller running boiler, preheat algorithm not enabled		771

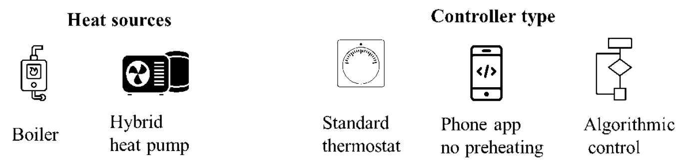


Figure 6.2: Evidence drawn on in this chapter

6.2 Options to keep warm

Section 2.3 describes how adaptive thermal comfort research has conceptualised the many ways occupants adapt (or adapt to) the thermal conditions in a building. Changes to heating controls should not be considered in isolation, but as part of a range of possible behaviour. In my interviews I explored the other options available to residents and the reasons they gave for choosing particular options. This "why" element is rarely considered in adaptive thermal comfort research.

This section sets the wider context in which adjustments to heating controls take place, outlining my findings about how these were combined with other actions to achieve thermal comfort. I use residents' accounts of their interaction with different aspects of their environment to develop a picture of the key elements of the adaptive system being considered, showing how this system incorporates not only residents and their central heating system but also other components including building fabric, clothing and supplementary heating. In practice theory terms, I am identifying the material arrangements associated with different practices of keeping warm at home carried out in these households.

When I asked interviewees whether they sometimes adjusted the clothing they wore if they were cold, most described using “extra layers”. June (Freedom-Hybrid) said “I’ve got a shawl which is usually at the ready”. Tracey (Freedom-Hybrid) and her family wear dressing gowns as an extra layer. In some cases a two step adaptation to achieve goals was described, for example Debbie (Freedom-Boiler) said “I’d put a jumper on, and then if it’s so cold I’d put the heating on”.

In several homes before the trial supplementary heating (such as a gas fire) was used occasionally. Jill (Freedom-Boiler) said “we used to put the gas fire on for about 20 minutes to take the chill off the room.” Her husband Frank (Freedom-Boiler) explained the use of a gas fire in the living room to supplement the central heating: “it’s this room that takes longer [to heat up], that’s why the fire goes on.” Supplementary heating was sometimes part of a strategy of balancing the needs of different household members, for example when Nick (Freedom-Hybrid) was talking about use of the gas fire in the lounge before the trial started, he said “during the winter it could be used every day. Jen might turn the gas fire on whilst our son is having his breakfast to make sure he’s warm in the morning’.’

A further option for adapting the environment is opening and closing doors and windows. Many of the Freedom-Boiler group mentioned keeping a bedroom window open at night to keep the temperature low.

A frequent theme in multi-person households was that different levels of clothing allowed two people with different temperature preferences to be comfortable in the same environment. For example Bill (Freedom-Boiler) said “my wife’ll sit there and put the fleece back on and I’ll sit there feeling warm”. Within the adaptive system, each individual finds the level of clothing where they are most comfortable.

This theme of satisfying the goals of multiple individuals can also be seen when answers from interviewees about choices made about heating controller settings. Section 5.2.2.4 mentioned times when the heating settings were changed because of the goals associated with entertaining guests. In some cases interviewees mentioned the known wishes of visitors. In these cases the guests can be seen as additional elements in the adaptive system, which is adjusted to take their requirements into account. For instance Bill (Freedom-Boiler) said “we put the heating on when the in-laws come up because they’re OAPs [retired]”. Section 5.2.2.5 described how the practice of hosting guests was associated with norms about an appropriate level of heating.

In some home it is not just the requirements of humans which influence the system, but those of pets as well. Vic (Expert-Boiler) described how, when he and his wife were out for the evening, they sometimes left the heating on for their dogs. The influence of pets on heating use was also identified by Morton (2016) and by Strengers et al. (2014).

In my interview with Ed (Freedom-Hybrid) he explained his difficulty in managing temperatures in the bedrooms. Ed has a good technical understanding of heating systems and had done his best to adjust the TRVs on the radiators in the bedroom and elsewhere in the house.

> “We’ve got 2 cats in our house . . . what we do to stop them getting on the beds during the day, we shut the bedroom doors . . . so subsequently we’ve got the heating set to what is a comfortable level with the doors open but . . . if we close the doors, we go into the bedrooms when we come home from work and the bedrooms are really, really warm . . . if we leave those doors open the heat would radiate through the house, but we have animals, we don’t want them on the children.”

This example shows the potential complexity of real life situations in which building fabric (doors and windows), pets, humans and elements of the central heating system are all interacting. The multiple interactions and sets of requirements involved suggest that the relationship between any two parameters in the system is always likely to be influenced by other system characteristics.

In this section I have used interview responses to identify how residents are managing the thermal conditions in their homes and built up a picture of an adaptive system which includes clothing, supplementary heat sources, pets and windows as well as the central heating system. Figure 6.3 updates Figure 6.1. It shows the adaptive system as described by the interviewees, adding the multiple adaptive options they describe.

The different interactions, with heating controller, building fabric, clothing etc can also be considered as practices which fall within Kuijer's "practices for staying warm" discussed in 3.1.4.

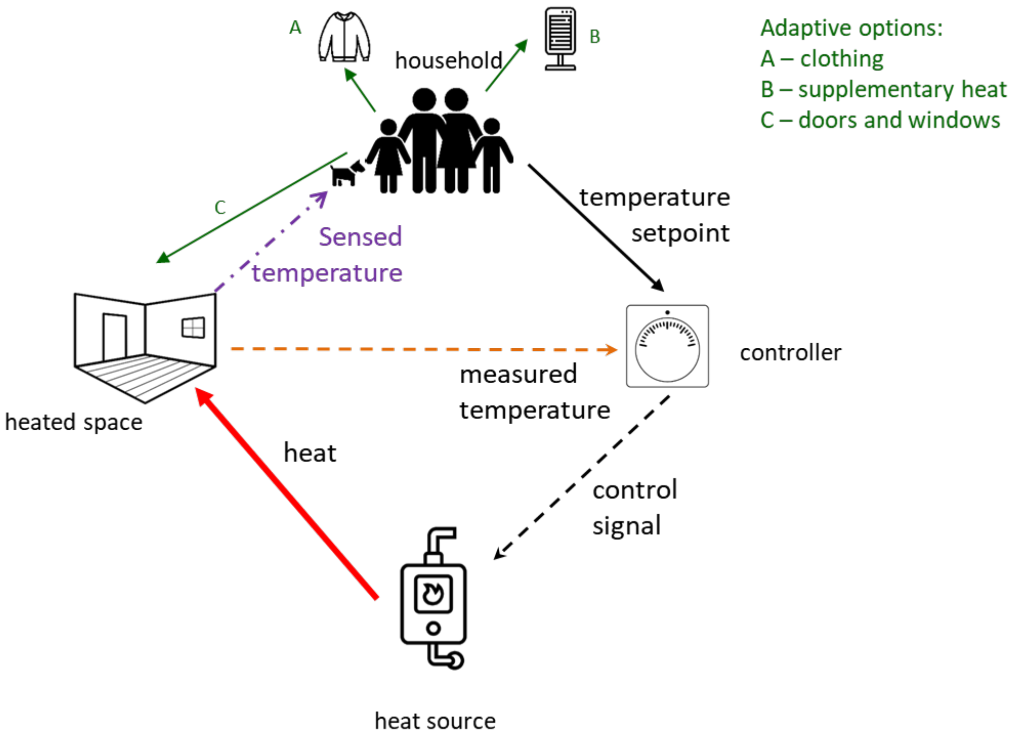


Figure 6.3: Heating system showing adaptive options

6.3 Feedback loops

Figure 6.3 shows the feedback loop by which residents adjust the settings of their heating controller based on the room temperature they experience. My interviews provided examples of other factors apart from air temperature that influenced controller settings. In this section I explore the different responses households want from their heating systems. Often these came up when residents described unwelcome aspects of new operating patterns. I start by describing cases when residents are sensing feedback from the heating that is not aligned with their goals. I then move on to discuss how not achieving the feedback they want leads residents to feel out of control of their heating.

6.3.1 Unwelcome system feedback

Three forms of unwelcome feedback from the heating system to occupants came up in the when I asked about reactions to changes in the operating pattern: noise from the heat source, noise from the hot water circulation pipework and a sense of radiant heat from radiators.

Noise

Frank (Freedom-Hybrid) told me "we've been woken up quite a few times now, say 2 o'clock in the morning, the pump is whirring away and we're boiling in the room". The heat pump external unit was located outside Frank and Jill's bedroom window and the noise from the fan often woke them in the night. The heat pump had been installed some distance from the bedroom in all the other Freedom homes I visited and the residents did not report being woken by noise.

Noise is not only an issue with heat pumps. When Caroline (Expert-Boiler) and her husband changed the settings in their controller to enable the algorithmic preheating option, they reported being woken by the boiler starting while they were asleep.

It is interesting to contrast these reactions to a changed system with Ron (Expert-Boiler) talking about his old, familiar boiler. When I asked if he had problems with noise in the night, he said: "I'm used to it, it's not the quietest system but 'my house, my noises"'. It seems that it is a change in the expected feedback that can cause problems for the residents.

Some residents mentioned noises from the hot water in their heating pipework. Jean (Freedom-Hybrid) said "the heating had woken me up at about half past three in the morning because the radiator was gurgling". On the other hand, Susan (Freedom-Hybrid) said there was no noise at all from her new system: "the old boiler, it would wake me up when it started working, I could hear the water coming through the radiators, but there's none of that, it's completely silent." The level of noise in the system is influenced by installation and maintenance, in Susan's case it is likely that the hybrid heat pump installers bled the air from the system and reduced noise.

Radiant heat from radiators

Two members of the Expert-Boiler case who had recently changed to algorithmic control both mentioned the temperature of bedroom radiators as a factor that was important to them. Phil said: "we did have initially issues of you know, waking up, the bed's quite close to the radiator, so I'd wake up hot early in the morning if I had a high setpoint set. Jim said "on my side of the bed is the radiator. If the radiator comes on, and it's on full whack, I just get way too hot and I've had a couple of times waking up a bit earlier because it's on and I'm too hot, preheating". These interviewees seem to be reacting not to a high air temperature, but to the radiant heat from a nearby radiator. As described in 2.2.1, radiant heat is one the parameters in Fanger's PMV equation. It can be viewed as part of the feedback between people and a heated environment.

These unwelcome responses from the heating system show that residents are not simply concerned about air temperature, but also sense other forms of feedback from the heating system. Figure 6.4 shows the heating system from Figure 6.3 with these additional feedback paths, from the heating equipment direct to the residents (in contrast to the feedback from the temperature of the air heated by the heating system). The pattern of operation of the heat source matters to residents as well as the pattern of temperatures they experience.

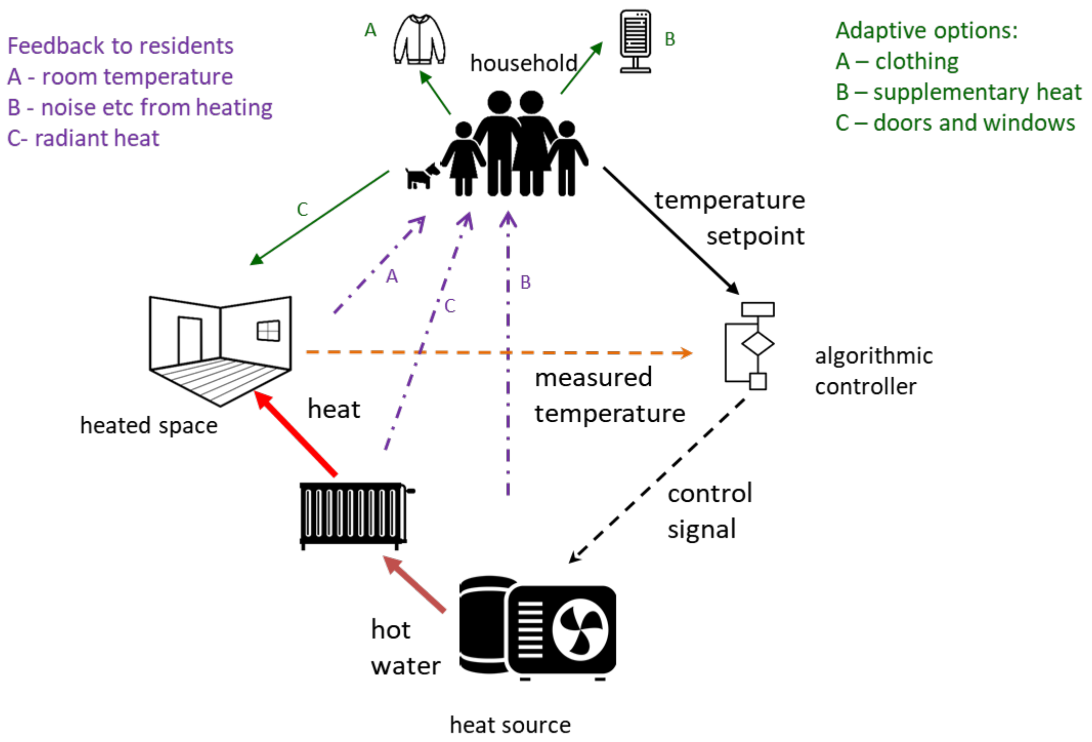


Figure 6.4: System with new control and heat source components, showing extra feedback loop between the status of the heating equipment and user actions

6.3.2 Lack of control

When residents spoke about unwelcome feedback, in particular noise or warm temperatures that disturbed them at night time, they frequently described their frustration about not being able to control the running pattern of the heating. Five of the Freedom-Hybrid interviewees told me that they tried to stop the heating at some point because the unexpected running time was unwelcome. Frequently these interviewees expressed a sense of lack of agency. Nick (Freedom-Hybrid) said "I've set it not to come on and then it's coming on, it just doesn't seem right"

Tracey's (Freedom-Hybrid) increasingly desperate attempts to switch off her heating during the night were described in 5.4.2.3. She said "at the moment it comes on when it wants to come on and it doesn't come on when I want it on." and complained "it's just got a life of its own." Jean (Freedom-Hybrid) expressed a more general lack of control "I don't feel that we have any control over the heating whatsoever".

Ed (Freedom-Hybrid) also explained his frustration that the heating system did not seem to respond to his requests: "The other day we had nice weather, we opened the windows up to get a bit of fresh air through the house, the heating comes on. Turn the [thermo]stat down to like 8 degrees and the heating is still on, there's no way of getting away from that heat."

For Ed this sense of lack of agency was compounded by the fact that he felt he should be in control in his own home: "I sort of feel a little bit trapped with regards to the heat in the house, I haven't had control like you'd expect, considering this is my house, in as much as when the heating's been on, and you don't want it on".

In practice theory terms it seems that the goals of the practices of keeping warm at home include being able to start and stop the heat source whenever the practitioner wishes. When residents sense hot radiators or hear the heat source running at times when they think the heating should not be operating, they resent the fact they cannot achieve their preferred running pattern.

Nick's (Freedom-Hybrid) negative response to the hybrid system shows how lack of a sense of agency leads to sense that someone or something else is in control.

He said “I can’t really give you a good evaluation of it [the new heating system] because they’re messing about with it, you know what I mean, so I’m evaluating something which somebody else is controlling.” In this case Nick’s rather hazy understanding of the experiments being run as part of the Freedom trial has resulted in a sense that his heating system is not being run to meet his own objectives, but to meet the conflicting goals of an outside agency.

The sense of not being in control was limited to those interviewees who were unhappy with the responses from their heating. In the context of considering heating as a system, it is residents who receive unwelcome or unexpected feedback from the system, for instance by noticing that the heat pump is running at times they did not expect, who express a lack of control. For the six Freedom-Hybrid interviewees who did not have a problem with the running pattern, this issue of lack of agency did not arise. They were happy with the feedback and not trying to achieve a different response.

6.3.3 Achieving the desired response

I have described cases where residents noticed unwelcome feedback from the heating system, but my interviews also uncovered cases when residents successfully took action to obtain a response not directly related to room temperature. Several of the interviewees described occasions when they aimed to make sure that the heat source was running, and the radiators were hot.

Phil (Expert-Boiler) and his girlfriend hang clothes to dry on their radiators and he told me when they had a batch of wet washing to dry he would turn the setpoint to 25°C (a temperature he knew would not be reached in practice) so that he could be sure the boiler was on and the radiators stayed hot. This is an example of heating goals being affected by another practice - drying laundry - but, unlike the examples in 5.2.2.4, in this case the aim is to achieve hot radiators, not a particular air temperature.

Linda (Freedom-Hybrid) was also looking for a direct indication that the heat source was running. She was very concerned about controlling the running costs of her heating, and before the trial her usual practice was to run the heating for short periods. Talking about how she operated her boiler before the trial she said “if the heating goes on it would go on between 6 and 7[pm] and it would go on literally like an hour”. She achieved her goal of managing heating costs by manually starting and stopping the heating.

Jim (Expert-Boiler) explained that he occasionally sets a high setpoint to ensure the boiler runs saying “a high setpoint doesn’t necessarily mean people want it really hot, often for me it’s just meant I want it on and I want to know it’s on.” In Jim’s case this was not linked directly with another practice, or a concern on costs, it was simply that his goal was to feel in control.

These cases of increasing the setpoint to make the heat source start show how practical understanding developed with a conventional boiler system: “if I increase the setpoint the boiler will run” can sometimes also be successfully applied to a hybrid heat pump system, since the algorithm will respond to an “in the moment” increase in setpoint by starting the boiler element of the hybrid heat pump.

It seems that there are various reasons why residents may manually increase the setpoint to ensure that the heat source runs. This is a divergence from the ideal DSR customer behaviour outlined in Section 1.2.4 A manual increase in setpoint to ensure the heating starts is not taken into account in the calculation model used by the algorithm (the algorithm decides on operating patterns to satisfy future *scheduled* temperature setpoint changes).

I investigated the frequency of manual operation to increase the setpoint in the two quantitative cases, to see how prevalent this “non-ideal” behaviour was in the Freedom-Hybrid group, and to compare it with the homes with boilers in the Customer-Boiler group.

In the quantitative data I identified the maximum setpoint in each house on each day. I then assessed whether this maximum setpoint was manual or scheduled, using the method described in 4.5.6. This allowed me to find the frequency of manual changes to a high setpoint in each group of homes. Figure 6.5 plots the distribution of the maximum setpoint in the day for the Freedom-Hybrid case. Scheduled setpoints are distinguished from days when the maximum setpoint is set manually. It can be seen that there is a high proportion of manual changes. These include both the "tweaks" upwards in temperature identified in 5.3.1.2 (when there is an adjustments to a higher temperature during a scheduled heating request period) and the occasions when a heating request period is started manually.

A striking feature of the distribution is that there is a high number of manual changes to a setpoint of 30°C. 79% of these changes to 30°C are in just five of the 56 homes in the group, so it would appear that this behaviour is not equally distributed across the homes. Based on the qualitative interview findings, I suggest that many of the manual changes to a high setpoint are cases of the residents in these homes increasing the setpoint to ensure that the heating is running.

Kempton (1986) provides a possible alternative explanation that should be considered. He described residents who had a "valve theory" of how their heating worked. These householders thought that if they turned the setpoint to a higher temperature the building would heat faster. Kempton was describing interactions in US households with furnace and hot air systems which differ from UK boiler and hot water systems. In my interviews I did not find any evidence of people turning up the setpoint because they thought the house would warm up faster. The instances I describe provide an alternative explanation for manual changes to a high setpoint. These residents are choosing high setpoints not to heat up the house faster but because they want the heat source to start.

Figure 6.5 shows the distribution for the Customer-Boiler group. The amount of manual changes is significant, though not as high in as for the Freedom-Boiler group. There are fewer days when the setpoint is 25°C or more.

Both cases show a divergence from the mode of sticking to regular scheduled setpoints which the PassivSystems control interface is designed to encourage. The highest incidence of divergence from this ideal behaviour is in the households in the Freedom trial, which was designed to encourage and test participation in cooperation with network DSR requirements.

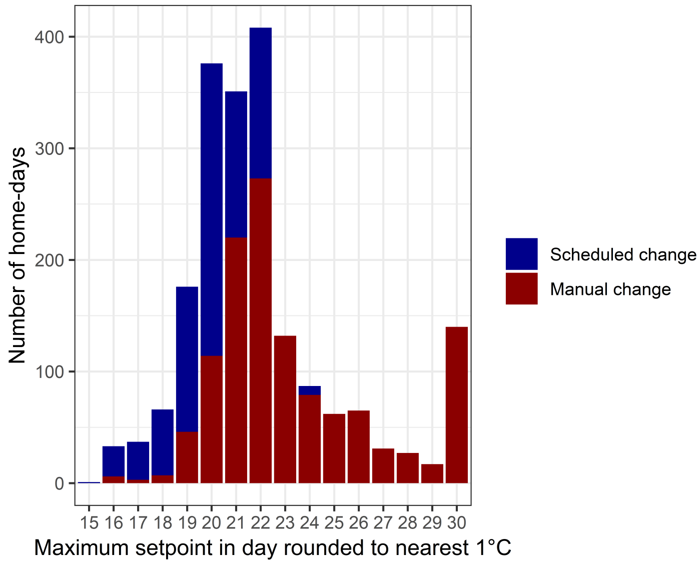


Figure 6.5: Distribution of maximum setpoint in day.
Freedom-Hybrid, Weekdays, 8 January 2018 to 2 March 2018, N=2,009 home-days.

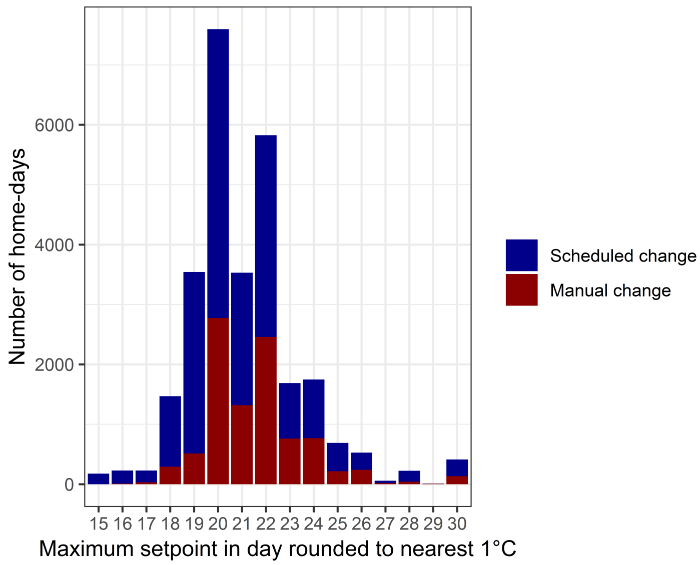


Figure 6.6: Distribution of maximum setpoint in day.
Customer-Boiler, 8 January 2018 to 2 March 2018, N=27,954 home-days.

6.3.4 Hybrid workarounds

In Section 5.2.2.3 I described how residents used their practical understanding of conventional heating systems to devise workarounds to achieve the temperature outputs they required. Section 5.4.2.3 recounts cases when a familiar workaround (reducing the thermostat setpoint to achieve coolness) no longer worked for Freedom-Hybrid interviewees who wished to reduce high night time temperatures. In this section I describe two instances where Freedom-Hybrid trialists found ways to achieve the operating patterns they wanted, but which they could not communicate directly to the controller.

Linda's (Freedom-Hybrid) concern to feel in control of heating costs was mentioned in the previous section. Before the installation of her hybrid system she had usually operated her gas boiler only for an hour or two in the evening, providing short "bursts" of heating. She was able to replicate this behaviour with the new system by setting the schedule to AWAY with a constant low setpoint and then manually changing this setpoint when she wanted to run the heating.

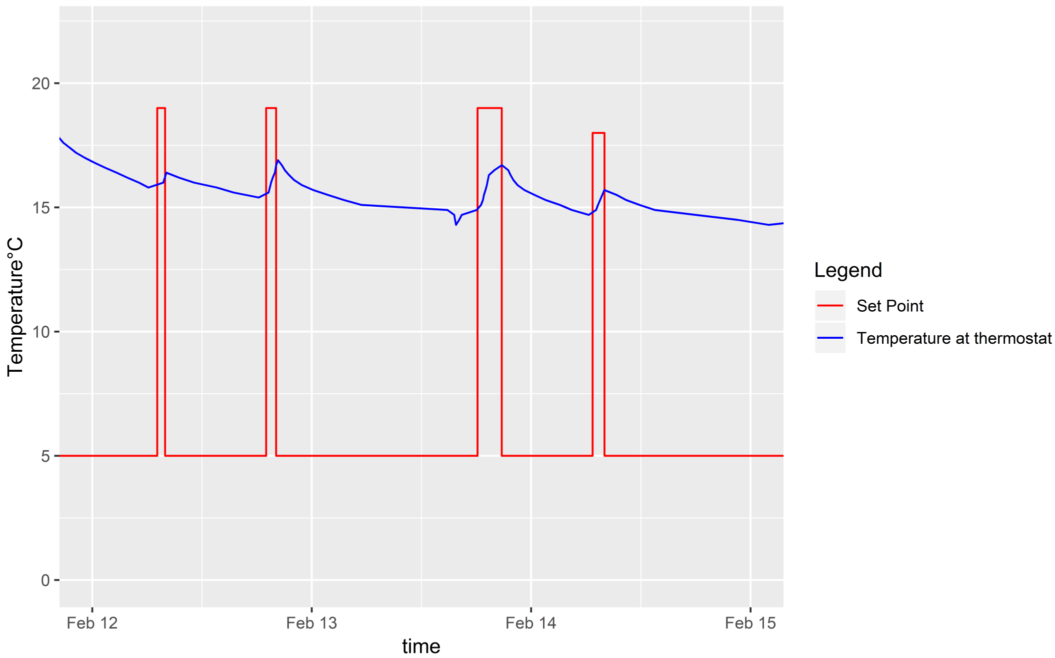


Figure 6.7: Pattern of irregular burst heating over three days in Linda's home

Figure 6.7 shows how she operates her heating for irregular, short durations or bursts. The setpoint temperature was not reached in these short periods, but this did not seem to concern Linda. She was satisfied with the feedback that the boiler was running and the radiators getting hot because that made her feel in control of her heating costs. Relying entirely on manual operation meant that Linda was inadvertently making sure that the heat pump never ran. The consequences for carbon saving and for demand management of this kind of "burst operation" behaviour is discussed in Chapter 7.

Since the PassivSystems controller requires users to set up a schedule, it takes some effort and ingenuity to "opt out" of a regular schedule in this way. Linda's workaround was based on the advice of a housing association employee. Until he helped her, it had not been obvious to her how to get the response she wanted from her heating.

Frank, whose issues with noise from the heat pump during the night are described in 6.3.1, came up with a workaround to get the heating to start later. He used a shorter IN period at a point later than he got up at 07:00 : "the only way I can figure out how to adjust it is I've got it to come on for something like 5 minutes in the morning at 8 o'clock". By taking this action, he hoped that the algorithm would start preheating later, but still be warming the house when he got up. This meant the actual temperature at 07:00 would vary depending on external conditions, but it was more important to Frank not to be woken by the heating than to have a consistent temperature at 07:00.

Frank found that this strategy was not successful in stopping the heating running in the early hours of the morning while he and his wife were trying to sleep, so his second workaround was to change to manual operation. He explained "we're going down the road of saying we're away every night to stop the heat pump from coming on during the night" - in other words they set the schedule to AWAY to be sure the heat pump did not run during the night and manually switched to IN when they got up in the morning.

By saying they are AWAY when they are at home, both Linda and Frank (using his second workaround) are not following the "script" of the controller, but they are achieving their goals of ensuring the heating does not operate at times they do not wish. They have developed a new practical understanding of how to achieve their preferred operating pattern.

6.4 Interacting with new control equipment

As well as a new control strategy, the new control system for the hybrid heat pump trials also involved physical changes to how the residents interacted with their heating system. In this section I discuss residents' reactions to aspects of the new type of control equipment.

6.4.1 Change in control interface

As described in 4.5, households with PassivSystems controllers can use a phone app to set up and change schedules, and they can adjust the setpoint "in the moment" either on the phone app, or a wall-mounted digital thermostat.

Phil from the Boiler-Expert group provided an interesting example of how a change in interface can shift practice. Reflecting on how the way the heating periods are described in the schedule (as IN, OUT etc.) a few months after his controller had been installed, he said "I suppose one thing that has changed significantly is that … we didn't have the weekend, the ability to set it to a different schedule at the weekend … if we were in at the weekend we'd just turn up for a period of time and so that was slightly annoying, because you had to think about it, we'd sort of end up regarding it as a bit of a luxury to have heating at the weekend whereas now it's just programmed to do that so we are warmer at the weekend and the kind of, so it's almost like when we feel like it's OK to have it on all day." Phil mentioned the role of the language of the control interface - the app asked him to declare what times he was IN and OUT. "if you answer those questions [when setting up the schedule] in a straightforward, kind of honest way, then the conclusion is you want it to be 19°C or 20°C all day at the weekend, and so …. I've gone along with that." He was aware that, by taking the terminology at face value, he had shifted to a pattern of heating with higher energy consumption.

This was an isolated example in my interviews, but it does highlight the possibility for changes in technology to change the goals of the residents. In Schatzki's terminology, changes in material arrangements lead to changes in teleoaffective structures.

Three Freedom-Hybrid interviewees mentioned that they had noticed an "overshoot" when the temperature displayed in the app was higher than the setpoint. It was hard to reconcile this with the data from their controllers. For example Rhys said "the operating range of the thermostat seems to be out. If you put a specific setpoint into it, it will certainly go 2 degrees above that setpoint before it shuts the system down, and then it shuts down until it's something like 2 degrees below the setpoint before it comes back on again". When I examined the data from this house I could only see occasional swings of up to a maximum of one degree. Even though Rhys's perception of the size of swings in temperature is that they are higher than the actual recorded values, his impression remains important. It is perception, rather than the physical reality, that is influencing his negative reaction to the controller. Galvin (2015) points out in his discussion of data from interviews about energy topics that "the notions people construct in their conversations have concrete effects in the real world".

What seemed to be happening in these cases was that a resident who was unhappy with the temperature was watching the temperature reading changing frequently on the phone app. The app screen displays a temperature value to one decimal place. This drew their attention to the mismatch between the actual and desired temperature. My own experience of a PassivSystems controller is that watching the temperature rise by 0.1°C increments can give a sense that it is swinging dramatically when in practice the overall change is barely noticeable. In these cases a change in the control interface changes the resident's practical understanding of how the heating is operating.

6.4.2 Shifting relationships

Section 6.2 describes the interactions between different household members, the heating system and other ways to keep warm. In this section I discuss how the new control equipment can change the balance of relationships within the household by changing the access to the heating settings.

The heating schedule in the PassivSystems controller can only be changed by those with the app on their phone, but anyone in the house can adjust the setpoint on the digital thermostat. I asked the Freedom-Hybrid trialists about who in the household had the app, and who it was who usually adjusted the schedule. This led to some interesting insights into family interactions around the heating controller. For example, when I asked Ed whether his wife would ask him to change things on the controller or do it herself, he replied: "if it's cold she'll go to the thermostat and turn it up, but it's the actual programming of times and temperatures things come on at, typically I would do that". In several homes the interviewee reported that their partner played an equal part in setting up the schedule, but for one older lady this was a cause for concern. Jean (Freedom-Hybrid) said "I'm not particularly technical but I don't think I'm stupid, but if I was here on my own and Rhys wasn't here, I wouldn't know what on earth to do with the system" and later in the interview "I wouldn't be able to handle it, if Rhys wasn't here, I just wouldn't want to". She was not confident that she had the relevant practical understanding to set the schedule for the heating controller herself.

In two other Freedom households it was also clear that the male member of a couple took charge of setting the heating schedule. However, in two homes I visited with it was the female bill-payer who was the one in charge, as the following dialogues show.

Tracey lives with her partner and two children

> Clare: Within the family, is it mainly you who's operating the controls?
>
> Tracey: Yeah, I'm the only one because no one else knows how to.
>
> Clare: Then with the old thermostat was that the same, or were other people...?
>
> Tracey: No, everybody used to do it. So me and my partner and the eldest child you know, it would click on and then once the house was heated, it used to take about an hour, and then it'd click off

Susan shares her flat with her adult son.

> Susan: If I turned the old thermostat up, [my son] would complain that it was going to be too hot, but I can do it on here [her phone] and he doesn't know.
>
> Clare: Does your son not have the app on his phone?
>
> Susan: No
>
> Clare: So he can't even...
>
> Susan: [with emphasis] Oh no, no
>
> Clare: You're in control
>
> Susan: Yes

In these two examples the new equipment has changed the access to heating control for some household members, and, particularly in the case of Susan and her son, seems to have led to a shift in power relationships in the family, with Susan's goals prevailing over those of her son.

Strengers (2013) introduces the concept of "Resource Man", deliberately highlighting what she sees as the "gendered, technologically minded, information-oriented" consumer that proponents of the smart grid imagine taking part in the "Smart Utopia". The cases of Susan and Tracey above show that this it was not always the man who took control in the Freedom trial households. For these two female social housing tenants, responsibility for setting the controllers seemed to be linked with being the "head of the household" who holds the tenancy and pays the energy bills.

These examples show how a shift in the access to the heating controls and different levels of practical understanding can lead to a particular member of the family taking charge of the settings. This finding aligns with Nyborg's (2015) description of how, following the introduction of new control equipment to encourage flexible electricity demand, one individual sometimes takes over the operation of the new equipment, leading to a loss of control for other members of the family.

6.5 Change over time

Section 3.1.8 introduces Pickering's account of the work of scientists and how their goals change over time in a process of both making adjustments to equipment and changing expectations. If Pickering's concept of the "mangle of practice" is applied to the interaction of people with their heating controls, it would be expected that there would be resistance to new operating modes as residents experienced unwelcome responses, followed by accommodation as they adjust the system to a more satisfactory state, at the same time as "learning to live with" a new pattern of operation. In this section I examine how far Pickering's description of a gradual process of resistance and accommodation is a helpful way to characterise how residents and their heating systems adapt to one another.

I was able to discuss the process of adapting to the preheating algorithm with members of the Expert-Boiler Group. Their experience was different from that of the Freedom group as there was no change in heat source, simply a change to algorithmic control with preheating. The Expert-Boiler Group understood the reasons for the preheating. They had been told that they could influence the amount of preheating in the ASLEEP period by altering the following IN setpoint temperature.

Several of Expert-Boiler group described a period of "tuning" the IN setpoint, adjusting it several times until they were happy with the temperature pattern, just as Pickering describes scientists altering equipment configurations until they achieved their desired results. Rita said she had adjusted her morning IN setpoint temperature downwards, as initially when the preheating was enabled she woke up in the early hours of the morning. Her bed is next to the radiator and she thought the heat from the radiator was waking her. The adjustment meant that the temperature in the morning heating request period was lower than previously. She was happy to adjust to this, saying "it's only for two hours" and she that she can manually increase the setpoint a bit if she feels cold.

Two members of the Expert-Boiler group, Phil and Jim, had had an algorithmic controller installed to operate their existing boiler shortly before I spoke to them. This meant I was able to ask them for their initial reactions to the new pattern of operation arising from algorithmic control. The way Jim and Phil noticed feedback from radiant heat of radiators at night has already been mentioned in 6.3.1. Jim saw adjusting the morning IN setpoint as part of an on-going process of tuning. He said: "I've been finding, if I set the setpoint too high in the morning it will come on really early, and we'll be heating from 3 o'clock or whatever, because it's so cold outside and our house doesn't retain heat very well. So I've been manually trying to tweak the setpoints quite a lot recently to try and get it right". Phil described a similar process of iterative adjustment.

The process of gradual adjustment that was evident from my interviews with several of the Boiler-Expert group shows that it is possible for those who are knowledgeable and motivated to adapt to new equipment over time. Residents were adapting their goals at the same time as adapting the settings of their heating controllers just as the scientists described by Pickering followed a process of adapting both their equipment and their objectives.

There were limited opportunities to investigate whether a similar process of adaptation over time took place in the Freedom case. Under the terms of the Customer Engagement Plan for the project, I was not allowed to contact the interviewees again in the second winter of operation, but I did have access to quantitative data from 33 homes who retained their hybrid heat pump over the 2018-19 heating system.

I looked for any change in manual interaction, reasoning that, if a similar process of tuning was followed, the Freedom trialists might reach a point where they made less manual adjustments to setpoints owing to a combination of becoming accustomed to a new pattern of heating and of having adjusted the scheduled settings to achieve a satisfactory output.

Table 6.1 shows the same parameters as those in Table 5.3, but this time compares manual operation between two winters for the 33 Freedom-Hybrid homes for which data is available over both winters. The median number of manual interventions decreases slightly from one winter to the next. If the manual operation can be classified as "resistance" to relying on scheduled operation, then there is some sign of "accommodation" by reducing the amount of this resistance in the second winter.

The number of manual changes in each winter period may also have been affected by the weather conditions. The mean external temperature for the 8 week period in 2018 was 4.5°C and in 2019 it was 6.5°C. The warmer conditions in 2019 may have influenced the number of manual interactions.

Year	N (homes)	Median of mean tweaks in day	Median of mean manual on or off in day
2018	33	0.82	0.69
2019	33	0.68	0.49

Table 6.1: Number of manual and setpoint changes in day.
Weekdays, 8 January 2018 to 2 March 2018 and weekdays, 7 January 2019 to 1 March 2019.

6.6 Summary of findings

In this chapter I have investigated the responses residents want from their heating system apart from room temperature (RQ1) and how they interact with their heating controls to obtain the operating patterns they want (RQ2).

The chapter started by describing the interactive system comprising residents and their indoor environment, identifying the various ways residents get feedback from their heating system. Individual residents adjust the heating, the building fabric and their clothing, taking into account the needs of others in the home (including pets).

Residents' reactions to the changed operating patterns following the installation of a hybrid heat pump (RQ3) illustrate the extra insights provided by investigating all the goals residents have for their heating rather than focusing only on temperature. Many residents are not only aiming to experience their preferred temperature but also to achieve a particular operating pattern for the central heating. In several instances residents wished to avoid unwelcome responses from the heating, in particular to avoid noise or hot radiators which wake them during the night. It was also important to some households to feel in control of when the heat source operates and they expressed annoyance when their heating ran at times they did not expect for reasons that they did not understand.

The residents who were not aware of any unwelcome responses from the heating system were satisfied with their new heating system. This chapter has focused on those residents who experienced unwelcome running patterns. The concerns that they raised highlight factors which may prevent hybrid heat pumps with algorithmic control being perceived as an attractive low carbon alternative to gas boilers. Addressing these concerns is likely to increase the potential for flexible demand among households with heat pumps. Chapter 9 outlines suggestions for control design, and for policymakers, to mitigate these issues.

Interviewees described why they operated the heating manually to start and stop the heat source at particular times. Reasons included avoiding noise at night, controlling costs and making sure radiators were hot for drying laundry. Quantitative evidence shows that manual changes to setpoints are a frequent occurrence in the homes in the Freedom hybrid heat pump trial. This is a significant divergence from the "ideal" operating strategy for DSR which relies on residents sticking to scheduled heating patterns.

In some households the residents found ways to adapt their control settings to avoid unwelcome running patterns. The Boiler-Expert group provided multiple examples of knowledgeable residents who adapted to a new control logic, "tuning" their control settings until they reached a point when they were satisfied. I also encountered instances in the Freedom-Hybrid case when residents developed new practical understandings of their hybrid heating system, finding workarounds to achieve their preferred operating pattern. Others expressed frustration as they were unable to stop the heat source during the preheating period.

Pickering's image of a constant process of resistance and accommodation as people both adjust new technology and adapt their goals can be used to explain how households in the Boiler-Expert case gradually adapted both their controller settings and their expectations until they reached a satisfactory outcome. A limited amount of evidence was found to suggest that this process was also under way among the less knowledgeable households participating in the Freedom trial. Chapter 7 explores the different social worlds inhabited by these two groups, with their different levels of understanding and motivation.

Chapter 7

Connecting social worlds

7.1 Introduction

The role of flexible demand in the energy supply system was outlined in Section 2.4.5. This chapter considers the new relationships between households and energy network implied by flexible heating demand. In particular it discusses the role of algorithmic heating controllers in enabling DSR.

As in previous chapters, I draw on social practice theory but I also apply concepts of social worlds and boundary objects to examine flexibility from the perspectives of households and energy network organisations. From the energy network perspective it is important that as many homes as possible are available for demand side response. When DSR is used to balance supply and demand, the important question is whether the households form a reliable demand node on the network: will they collectively respond to provide demand response so that excessive peak demands on the network can be avoided?

7.1.1 Overlapping practices

Two sets of practices with their different goals and practical understandings intersect at the heating controller.

Chapter 5 and Chapter 6 investigated practices of staying warm at home, and in particular how heating systems are operated, discussing the goals and practical understanding of the households carrying out this practice.

Section 2.4.5 introduced the different organisations involved in energy supply.

and described how electrification of heating leads to the requirement to manage patterns of energy demand from households to avoid additional investment.

In the case of algorithmic heating controllers enabling demand management, the heating controller itself is taking part both in home heating practices and in the set of practices around matching supply and demand to ensure a continuous supply of electricity and gas to the households.

In this chapter I consider the different goals and practical understandings of the two sets of practices, and I also discuss the other two practice "linkages" within Schatzki's practice framework introduced in 3.1.7:

- *General understanding*. I discuss general understandings of the purpose and importance of flexible demand among network organisations and households.
- *Rules*. I consider the role of control designers in setting the rules about how residents should use the heating controller.

7.1.2 Social worlds and boundary objects

Section 3.2.1 introduced the concept of social worlds and the definition I am using: a social world is a group with a shared commitment to certain activities.

The two sets of social worlds I am considering are households operating their heating with algorithmic heating controllers, and the set of organisations involved in the energy supply to these homes.

The households have a collective purpose of staying warm at home. This group of homes operating their heating create an aggregate pattern of energy demand.

The social world of the energy network is made up of the organisations responsible for generation, supply, transmission and distribution of electricity and gas described in 2.4.6. The collective activities of this social world focus on maintaining supply to energy customers.

In this chapter I consider the heating controller as a boundary object, following Star and Griesemer (1989)'s definition that this is a scientific object which inhabits several intersecting social worlds. A key concept from the work of Star on boundary objects is that they allow "cooperation without consensus". The network organisations require cooperation from households if they are to rely on them for demand response. As outlined in 1.2.4, homes which do not set a regular schedule and rely on manual operation of the heating are not available to provide flexible demand.

This chapter also introduces the perspective of the organisation designing the heating controllers. The designers are aiming to develop a controller that allows cooperation between households and energy networks, satisfying the requirements of both social worlds. Design of the control equipment to allow the households to provide DSR is a crucial element in achieving this objective. This leads me to consider the organisation designing the controllers as part of the network social world, aligned with the activity of energy supply. They share a general understanding of the benefits of flexible demand with the energy supply companies and have an important role in setting the rules about how household requirements for warmth can be reconciled with energy network requirements for load shifting.

7.1.3 Questions for this chapter

I use the boundary object concept to ask whether the algorithmic controller is acting successfully as a boundary object in my case studies, in particular assessing it against the characteristics identified in 3.2.2, asking:

- Does the controller allow cooperation without consensus?
- Can each social world mould the controller to its own purpose?
- Does it satisfy the information requirements of both the intersecting social worlds?
- Are residents able to interpret the controller flexibly?

Drawing on this framing, I am investigating the following aspects of my research questions in this chapter:

RQ1 What output do households want from their heating systems?

- How well do the assumptions about what households want from their heating used to design the heating controller match the actual goals of residents?

- What is the role of the heating controller in aligning network goals with household goals?

RQ2 How do residents interact with their heating system to get their desired outputs?

- How well do design assumptions about how residents will interact with the controller match with actual operation?

- When does residents' practical understanding of how to operate the controller conflict with network goals for flexible demand?

RQ3 How do households react to a change in heating system characteristics?

- How do households perceive network influence on the operation of their heating?

- Are they prepared to cooperate by setting their heating controllers in a way that is compatible with demand flexibility?

7.1.4 Interacting social worlds

Figure 7.1: Conventional gas supply to boilers

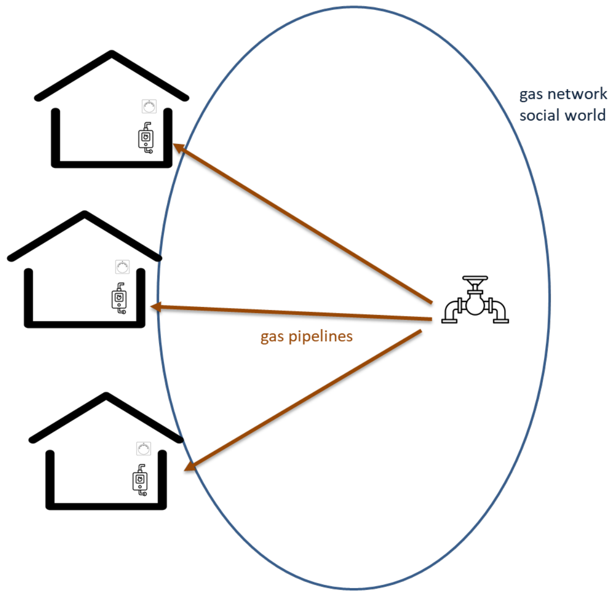


Figure 7.2: Connections to homes with hybrid heat pumps and algorithmic control

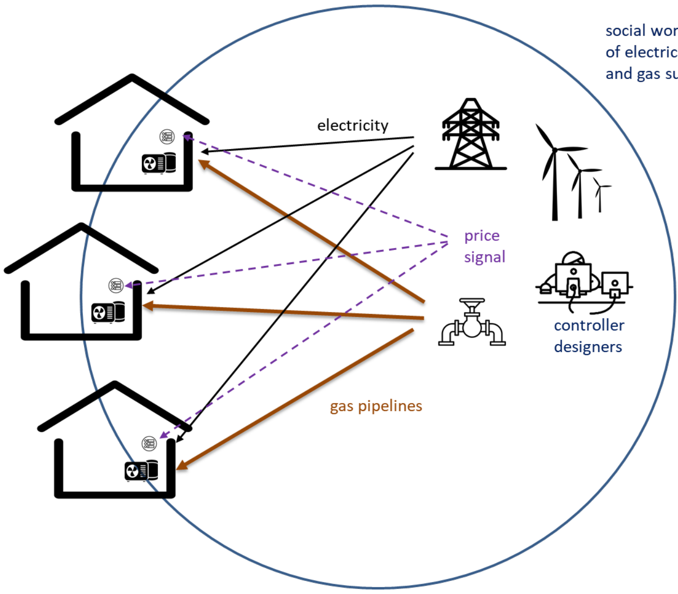


Figure 7.1 shows the conventional relationship between UK homes with gas boilers and the gas network. The social world of the energy supply system stops at the meter, having no influence over when the boiler runs. The information visible to the energy network is the collective gas demand profile for the homes.

Figure 7.2 shows the connections for hybrid heat pumps with algorithmic control. Homes with hybrid heat pumps sit in a new relationship to the energy networks as they link home heating to two different infrastructures, drawing on both gas and electricity for the central heating.

In this new situation there is an extra data connection - a price signal from the energy network to the controller - which, as described in Section 2.4.6, is the means to communicate information about the times when electricity and gas networks wish to encourage or discourage energy demand. In this configuration, the social world of the energy network is influencing the operation of home heating equipment, impinging on households "beyond the meter" in a way it has not in the past. I have included the designers of the control equipment in the social world of the energy network as their activities support network objectives (see Section 7.3).

In order to achieve their objectives for managing the companies involved, the network need the heating equipment in the households to respond to varying price signals. Those households who "opt out" by operating the heating manually rather than setting a schedule are not cooperating with these goals.

7.1.5 Chapter overview

I start by outlining the physical constraints which may affect controller operation. Section 7.3 explores role of control design in creating a boundary object between network and household social worlds. 7.4 explores the household perspective and asks whether the controller is acting successfully as a boundary object. Section 7.5 assesses the level of cooperation with the network in Freedom trial homes. In 7.6 a contrast is drawn between the Expert-Boiler group and the Freedom-Hybrid case, discussing the different reactions of households where the two social worlds intersect.

7.2 The physical interferes

In his influential account of social worlds, Strauss (1978) described how that technology (inherited or innovative modes of carrying out the social world's activities) is always involved in the activities that define social worlds. Certainly technology is central to the interaction between the household and network social worlds described in this chapter. Both social worlds are ultimately interested in using the controller to communicate with the heating equipment in the home. For the controller to fulfil its boundary object role, the equipment (as well as the people) must cooperate. The controller must be able to send a signal to the heat source, and this must respond and operate as expected.

My interviews with Freedom-Hybrid trialists identified a few inter-equipment communication problems which had to be fixed by the installer. Ken explained "my thermostat was installed in the main bedroom as it had kept losing connection with the boiler when positioned downstairs. We needed to move it upstairs to keep a constant connection." Frank had a similar story "the signal on the thermostat wouldn't get through to our living room, the furthest it would go was the kitchen, which is the warmest room in our house and it wasn't really suitable so they had to put in like booster things, so we've got 2 boosters just to get it through to our living room now".

Frank and Jill were unfortunate in experiencing a number of issues with physical equipment in their home. There was a delay in commissioning the heat pump because a key connecting cable burnt out. 6.3.1 has already recounted how they were woken by the noise of the heat pump running outside their bedroom window, a problem that might never have come up if the heat pump had been located elsewhere.

These examples highlight how poor physical configuration of the heating system may make it difficult, or impossible, for the control algorithm to translate residents' input into an output they find acceptable. The controller will not be successful in providing the requirements of households or networks if the heat source itself, or communications with the controller, are not functioning.

7.3 Design perspective

This section discusses the perspective of those designing heating controls and how they aim to provide heating controllers which act as successful boundary objects between households and networks.

Companies developing algorithmic smart controllers share a general understanding of the benefits of flexible demand to support low carbon energy supply. Their activities support network objectives for DSR. I therefore include the control designers in the energy network social world.

The activities carried out by PassivSystems employees include equipment, interface and software design, customer support and project management. These all happen in the context of a commercial organisation which aims to develop a market for its products. An algorithmic controller with its sophisticated control logic and additional communications is inevitably more expensive than a standard heating controller and will only find a market if customers (homeowners and landlords) perceive additional benefits (in terms of comfort, cost, convenience and carbon emissions savings).

Section 3.2.2 describes Clarke and Star (2008)'s account of how successful boundary objects become standardised, in a process that often transforms them into permanent infrastructure elements. The designers of the controllers used in the hybrid heat pump trial aimed to develop control equipment that ran the hybrid heat pump in the lowest carbon operating pattern and provided fuel switching and Demand Side Response (DSR) capacity for the gas and electricity networks. They also aimed to ensure that households with the controller could gain cost savings from participation in fuel switching and DSR.

The activities of designers have the objective of satisfying both the goals of the energy network for flexible demand and of households to be warm, in other words they aim to design the controller to be a successful boundary object allowing "cooperation without consensus" between the two social worlds.

From the point of view of the designers of algorithmic controllers, designing a successful boundary object would open up the possibility of their product becoming part of the standard energy infrastructure, installed in many homes. This would provide a large market for the company. The designers are motivated to understand residents' goals for their heating systems and aim to provide equipment which satisfies both these goals and those of the network.

The employees I spoke to were also highly motivated to support CO_2 emissions reductions. They had an in-depth understanding of efficient heat pump operation and of the role of flexible demand in energy network management. PassivSystems employees frequently expressed disappointment when they discussed customers who were not taking advantage of the energy saving features of their controller and they thought carefully about the reasons why these customers did not understand (or did not wish to use) these features. In practice theory terms their practices of design were influenced by their general understanding of the benefits of decarbonising heating and enabling flexible demand which they share with other organisations in the energy network social world.

Part of the process of design is to imagine the "use cases" or different scenarios for the residents, envisaging what they wish to achieve and how they will interact with the controller to achieve this. This PhD research is part of this process. PassivSystems have provided support and information because they wish to improve their understanding of how the controllers are used in practice.

7.3.1 Reconciling goals

Akrich (1992) describes how designers are “inscribing” a vision of the world in the technical content of the innovative objects they design. The designer of an algorithmic heating controller sets the terms for communication between network, inhabitants and heating system: in Akrich’s terminology, they “write the script” for interactions between residents and controller.

In practice theory terms, the designers are setting the rules about how the households can request particular patterns of heating. The decisions made about the control interface and the language used - for example the designation of IN, OUT, ASLEEP and AWAY occupancy states - shape and constrain what the residents can ask for. The “in-app” messages displayed to indicate the status of the heating script the information provided to the residents. The designers decide which decisions should be taken by the algorithm and which they should delegate to the household.

Akrich (1992) argues that “when technologists define the characteristics of their objects, they necessarily make hypotheses about the entities that make up the world into which the object is to be inserted”[p.207]. In the case of a heating controller, the world into which it is to be inserted is the social world of households and the hypotheses made by the designers are the assumptions they make about how residents will interact with the controller and what they will want to achieve by using it.

As identified in 1.2.4, the control logic incorporates both implicit and explicit assumptions about what people want and how they will set the controller to achieve this. The basic principle of the algorithms used in the Freedom project controllers was delivering the “lowest cost operating strategy to meet specified comfort levels” (Carter, unpublished report, July 2018). The evidence in previous chapters indicates that the goals in many homes were complex. Chapter 5 described cases where it was not correct to assume that “specified comfort levels” equate to a constant temperature during the IN period. Chapter 6 recounted occasions when lowest cost operation was not as important as other household goals. Both chapters give examples when the important factor for residents was not "comfort" translated as a particular temperature level, but another feature of heating operation.

The PassivSystems employees with whom I was interacting were aware of many assumptions involved in the "design model". The statement "we can't use the system to its full potential unless we understand what people really want and get them to communicate it to us effectively" (Carter, personal communication, January 2017) sums up this recognition (and PassivSystem's motivation for supporting my research). In practice theory terms, "what people really want" can be translated into the goals of heating operation and communicating this effectively relates to the residents' practical understanding of the controller.

7.4 Household perspective

In this section I move from discussing how control design involves imagining the goals of the residents to investigate the actual goals of the residents I interviewed in the Freedom-Hybrid case study. I ask whether the heating controller acts as a successful boundary object from the point of view of these households.

7.4.1 Is the controller satisfying household informational requirements?

Chapter 6 described cases when residents did not understand why the heating was running at an unexpected time. An example from my conversation with Jean illustrates this: " the heating had woken me up at about half past three in the morning because the radiator was gurgling and I thought that's strange. Well I got up about 5ish and the heating was set on 8 but the temperature was showing on the thermostat as 22". In this case she had not understood that the heating had started in the early hours in order to preheat the house. She was confused by the difference between the setpoint of 8°C and the measured temperature of 22°C. With conventional thermostatic control, the heat source would not run in this situation.

My conversation with Jean's husband Rhys suggested that he did understand the general principles of the preheating, but he did not understand a running pattern he had noticed in warm weather in April: “we’ve had the heat pump running over the weekend while we’ve been out in the garden and the outside temperature has been up 22, 23 degrees and the HP is continuing to run. I can’t see that a pre-planned warm up time would cause the HP to run 4 or 5 hours before it needs to get to that temperature”. A check on the data from their home showed that the daytime running was a result of the algorithm choosing to run the heat pump over the day in order to meet the evening setpoint of 22°C. This was a correct optimisation based on the lowest cost logic, since the heat pump was operating at a very high coefficient of performance on a relatively warm day, but it seemed counter-intuitive to Jean and Rhys.

These residents did not have sufficient information from the controller (or from the instructions they had received) to understand why the heat pump was operating in a particular pattern. The criterion for a successful boundary object that it should provide sufficient information for the users to achieve their purposes can be linked to the practice theory “practical understanding” required by the residents to operate the heating to meet their goals.

Section 4.5 outlines how the PassivSystems algorithm decides on the lowest cost fuel source based on an input signal of gas to electricity price ratio. This ratio was not based on the actual tariffs for each individual home, but was calculated using mean energy costs in the area. This aspect of the control logic was not mentioned by most interviewees, but two respondents asked questions which showed they had reflected on what they had been told about prices by the project team, and were confused. When I explained that there is a set ratio of gas price to electricity price in the controller, Ed said “my supplier gives me a fixed tariff” and Susan pointed out “but prices vary from supplier to supplier”. They had both realised that the gas to electricity price ratio used in the trial did not necessarily reflect the ratio for their home’s energy charges. The designers had made assumptions on their behalf and they were not able to communicate their actual situation to the algorithm. The price ratio used in the algorithm was likely to be a good approximation of their costs, but there was a sense these householders felt they should have been asked for their input.

The only other interviewee who mentioned cost optimisation was Nick, who had received a rather confused impression: “I was told it would use gas or electric, whichever one is most cheapest at that time, which I’ve since found out is a total load of rubbish, they told me that it doesn’t, because it uses it on demand of the network not on the prices for the consumer”. Nick did not explain exactly what he had been told, but it seems that he had picked up that the trial involved simulation of different tariffs which did not reflect the actual price he was paying. In this case Nick’s rather hazy understanding of the experiments being run as part of the Freedom trial has resulted in a sense that his heating system is not being run to meet his own objectives, but to meet the conflicting goals of an outside agency.

Nick’s reaction was probably coloured by his dissatisfaction with the operation of his new heating system (described in 6.3), but it also highlights the challenges of communicating complex messages about how varying energy prices affect the running pattern of the heating in a particular home. Strengers (2013) writes of the role of price as a “conveyor and distributor of meaning” in a smart energy system, but this case shows that it can be difficult to understand the role of energy prices and there is potential for the meanings conveyed by price to become garbled.

7.4.2 Can the heating controller be “moulded to local purposes”?

Chapter 5 described how residents achieved their temperature goals by using a combination of scheduled and manual temperature setpoints. It also identified how a number of households could not achieve their goal of a cool bedroom at night time.

In several cases residents described times they had tried to stop the heat source running when they were too hot during the night by decreasing the current ASLEEP period setpoint using the thermostat. The logic of the PassivSystems controller is that, if the setpoint is reduced during a preheating period when the algorithm is signalling to the heat source to run ahead of the IN period, the change in setpoint will not affect the heating operation. There is a clash between the assumption built into the algorithm - that the most important requirement of the residents is to achieve the specified IN period temperature setpoint - and the actual goal of the residents who wish to stop the heat source immediately.

The PassivSystems recommendation to those trying to stop preheating during ASLEEP periods is to reduce the setpoint for the IN period which will follow the current ASLEEP period, as this will reduce the time required for preheating. PassivSystems staff described this solution to Rhys, when he complained to them about the heat pump running during the night, but he did not feel confident in adjusting the temperature settings in the schedule. He was not willing to "tune" the controller to match his requirements, unlike the Expert users described in Section 6.5.

When I interviewed Tracey during the hybrid trial, she was very unhappy with the performance of her new heating system. I attempted to explain how she might mitigate high night time temperatures by changing the IN setpoint but she did not show any willingness to try to understand the logic of the operation or learn how to make adjustments. She simply replied "it's costing me a fortune".

Residents may not be able to communicate their requirements in a way that the controller can interpret. Chapter 6 described instances when residents were unable to obtain the responses they wanted from the heating system. These cases can be seen as the household failing to mould the controller to their purposes for particular patterns of operation, for example to avoid noise at night time.

The controller was not operating successfully as a boundary object for those residents who said they did not feel in control of their heating. Their controllers were not delivering the output they wanted and were also failing to satisfy these residents' "informational requirements" and this perception led to negative assessments of the heating system.

7.4.3 Is the controller providing interpretive flexibility?

I have recounted several examples of residents successfully interpreting the language of the controller in flexible ways to get the response they wanted from the heating system. In 4.5 I described the requirement to set IN, OUT and ASLEEP times in the schedule. These terms represent a change to the typical way of thinking about a conventional heating system as on or off, with timer schedules of when the boiler is started and stopped. Households have to "learn a new language" and sometimes use this creatively. The example given in 5.2.2.5 of residents who set the schedule to OUT when they are actually in the house highlights the "built in" assumption in the language of the interface that heating is required all the times the house is occupied and residents are not asleep (or ASLEEP).

Section 6.3.3 described occasions when a resident wanted an immediate response from the heating, so they manually turned the setpoint temperature up very high to make sure the heat source operated. In these cases they used a setpoint of, for instance, 30°C to signal to the controller that they want the heat source to run. They did not actually expect, or wish for, such a high temperature to be achieved but the setting had the desired effect of starting the heat source to provide warmth.

Section 6.3.4 recounted the workarounds used by Frank and Linda to get the operating pattern they required. In these cases they were interpreting the controller instructions flexibly, taking actions not envisaged by the control designers.

Frank's first workaround, to alter the scheduled IN time to a later point in time, satisfied the requirement for scheduled operation to provide DSR for the network. However, this workaround did not succeed in allowing Frank and his wife to sleep undisturbed. The second workaround used by Frank, to tell the controller they were AWAY during the night and then manually switch to IN, did succeed in meeting his objectives, but did not meet the network requirement for visibility of the schedule for DSR. Frank did not find a flexible interpretation that both satisfied his goals and provided cooperation with the network.

Linda's workaround, switching manually from AWAY to IN for short periods was similar to Frank's second solution. To achieve her objective Linda had effectively opted out of demand management, as the algorithm was unable to predict when she wanted heating.

She had also (inadvertently) opted out of using the heat pump since the algorithm always selected the boiler to run in response to a manual increase in setpoint. The boiler responds more quickly than the heat pump so is the option chosen by the algorithm in response to a manual increase in the temperature setpoint.

There is a clear conflict between Linda's requirement for short "bursts" of heating at variable temperatures and the efficient operation of a hybrid system, and in Linda's case the heat pump never operated after she had set up her workaround.

The actions of residents like Linda, who only want to heat for short periods, are challenging for control design, since she was not interested in the steady, efficient running of the heat pump that the algorithm aims to provide. Linda's general understanding of the purpose of her heating did not align with the purposes envisaged by the designers. Her goal does not match the goal of the optimisation model in the algorithm, which aims to achieve the specified temperature for the whole of the heating request period.

7.4.4 Potential for exclusion

Linda was getting no benefit from the heat pump element of her hybrid unit. In this case the unit had been installed free of charge as part of the trial. In cases where landlords or homeowners pay the additional cost of a hybrid heat pump (which is more expensive than a stand-alone boiler), this type of burst operation would not provide any benefits from the extra investment. Running costs and carbon emissions would be the same as with a standard gas boiler but the capital cost would be higher.

In the future, requirements for burst heating are likely to be seen as problematic for the network, particularly in homes with only an electric heat pump and no boiler to provide rapid response. Tariffs may be set up to discourage this kind of behaviour, making an unscheduled demand for a rapid increase in temperature more expensive.

It should be noted that Linda was very concerned about energy costs and minimising the overall energy used by her heating a system and yet the pattern of operation she chose was not saving any money for her as it precluded high-efficiency running of the heat pump. This is a single case, but it does raise questions about the consequences of a tariff system that discourages "burst heating". This could have the effect of penalising those who cannot afford to heat their houses to a constant temperature all the time they are at home.

7.4.5 When is the controller succeeding as a boundary object?

Five of the eleven homes I contacted after the trial began did not have complaints about the temperatures or pattern of heating operation. For example Ken said that the new system "heats the house OK" and that he had not been conscious of either heat pump or boiler running at unexpected times. Leslie was very happy with the general performance of the hybrid system and appreciated the safety benefits of low temperature radiators with children in the home. Both Leslie and George liked the ability to set the heating controls when away from home which was provided by the phone app.

In these and other cases where the residents were not conscious of any conflict between network goals and their own objectives, the controller is operating successfully as a boundary object. The residents succeed in their own purposes by following the instructions in the controller and do not need to consider the goals of the energy network.

In some cases residents interpreted the language of the schedule flexibly, for example by setting the schedule to OUT at times when they were in the house, and succeeded in achieving their goals for patterns of operation. As they did not diverge from scheduled operation this also satisfied network goals. In these cases the controller can be seen as a successful boundary object, which residents mould to their own purposes by interpreting the controller flexibly.

7.5 Cooperation with the network

7.5.1 The need for cooperation

I have described how algorithmic heating controllers can only provide flexible demand if households cooperate by setting (and sticking to) a schedule of times for their heating requirements. From the energy network perspective it is important that as many homes as possible are available for demand side response. To manage the network, some certainty is needed about the level of response that can be expected from households.

Star and Griesemer's (1989) paper introducing the boundary object concept described how the zoological museum director Joseph Grinnell created maps and forms to align the work of amateurs, farmers and animal trappers with his scientific objectives. These boundary objects can be seen as introducing an additional level of standardisation to the haphazard collection process. In the case of the PassivSystems controller used in the hybrid heat pump trials, the heating controller is designed to facilitate the residents' cooperation with network DSR objectives by asking them to enter a schedule. In practice theory terms, the options the phone app gives for residents setting up a heating schedule form the "rules" for the practice. Linda's "opt out" required her to bend the rules and find a workaround.

The evidence outlined in 5.2 showed most homes were prepared to cooperate by setting and following a schedule. Most of the hybrid heat pump trialists I spoke to did not have any issues with setting up a regular schedule and were happy to do this.

7.5.2 Quantifying cooperation

Quantitative data from all the homes in the Freedom trial can be used to investigate how many homes are cooperating by setting (and sticking to) a schedule, and how many are operating their heating manually.

My analysis focused on the first request for heating in the day, which as shown in Figure 5.6 is often at or close to 07:00. Section 2.4.5 mentioned how heat pumps operating like those analysed in Love et al. (2017) start to create a morning peak in demand. The significant figure from the network perspective is the proportion of first changes in the day that are manual changes to a higher value as this indicates the homes that would not be available for DSR of the morning peak. I investigated the data for the Freedom-Hybrid case to see in how many households the first operation in the day was manual rather than scheduled. I identified the first change in setpoint after 5am each morning. This was classified as scheduled or manual using the method described in 4.5.6. Manual setpoint changes to a higher value were designated "manual first start". These manual changes will have the effect of starting the boiler element of the hybrid heat pump instantly, unlike scheduled starts which provide the opportunity for preheating using the heat pump element.

I calculated the proportion of days with a "manual first start" for each of the 33 homes with hybrid heat pumps for which data was available over two heating seasons. The mean for all homes for an eight week period in January and February was calculated for both 2018 and 2019 to allow a comparison of the second heating season with the first. The mean proportion of manual starts is lower in the second heating season, declining from 18.3% in the January/ February 2018 heating season to 12.4% in January/ February 2019. Just as Table 6.1 shows a reduction in overall manual operation in the second winter, there is also a reduction in this key statistic for manual operation which has an impact on the network. This suggests that adaptation to the new mode has taken place in some of the Freedom trial homes.

In both 2018 and 2019 three of the 33 homes had more than 80% of days when the first change in the day was manual. It seems that a small proportion of homes are responsible for most of this behaviour and, like Linda, have effectively opted out of providing demand response. Figure 7.3 shows the distribution of homes with manual first start for the two years.

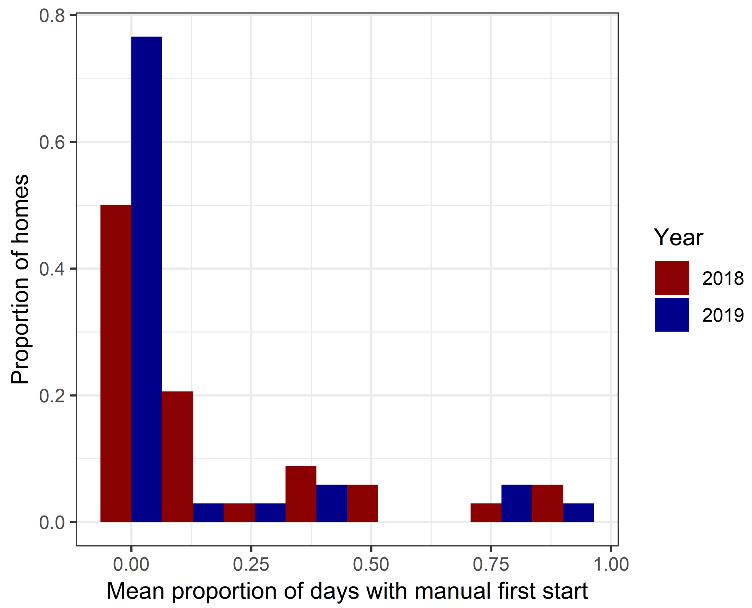


Figure 7.3: How does the distribution of the proportion of manual first starts for each house change over two winters? Weekdays, 8 January 2018 to 2 March 2018 and weekdays, 7 January 2019 to 1 March 2019. N=33 homes.

7.6 Expert perspectives

This section considers the second qualitative case study of the Expert-Boiler group's reactions to a change in their heating control when the "optimum start" preheating algorithm was enabled in their controllers.

Since all the interviewees in the Expert-Boiler group were current or former PassivSystems employees, this group had very different "general understandings" of the reasons for a change in control logic and of the low carbon aims represented by algorithmic control, compared to the households in the Freedom-Hybrid case. While they had different roles within the company, their positive attitude to their company's product and the work of their design colleagues was evident.

They (and through them their families) had access to information about the design intentions and the benefits of preheating which was not available to the Freedom trial participants. The social world of these households overlaps with that of the energy network organisations because of this common general understandings and motivation.

Another difference between the Freedom-Hybrid and Expert-Boiler cases to be borne in mind is that the heat source was a boiler, so preheating periods were shorter, with a more rapid temperature rise, than those for hybrid homes in which a heat pump supplied some or all of the preheating. There was also no energy network connection to the heating controllers. Cost optimisation was simply a matter of minimising gas (or oil) use for the boiler. However, all the households had experienced a change from conventional heating control to algorithmic preheating, and this was perceived as a significant change by all the interviewees. Their specialist knowledge meant that they were very articulate about the impact of the preheating and the adjustments they made to their controllers.

The Expert-Boiler group's commitment to the benefits of algorithmic preheating is exemplified by Ben (Expert-Boiler) (whose job includes explaining the control algorithm to customers). Ben has a very different attitude compared to the hybrid trialists who complained about the heating running at night. He said: "what I've noticed is that depending on the outside temperature the heating comes on a little bit earlier or a little bit later to heat up to the same temperature.... It's quite good to see the heating's coming on while I'm still asleep." His understanding of the algorithm, and commitment to the preheating logic, translated into a very positive attitude to the effects of preheating.

7.6.1 Achieving household goals

My interviews with the Expert-Boiler group identified a number of examples when the respondent used their understanding of the controller to obtain the pattern of heating that they wanted.

Chapter 6 described how Rita, Phil and Jim in the Expert-Boiler group adapted to preheating by re-setting their morning IN point to get the conditions they wanted (balancing a limited amount of night time heating with an acceptable temperature when they got up in the morning). All of them expressed satisfaction with the point where they had ended up. This type of trial-and-error "tuning" was evident in many of the Expert group interviews.

Matt had put a lot of thought into how to match morning heat delivery with his family's requirements and how to specify their goals in a way that the controller could interpret. He explained:

> "my wife was having a shower at about 7 o'clock and she was complaining that the radiator wasn't hot any more because it got up to set point [at IN start time of 06:00] and it just turned the boiler off .... So the radiator wasn't hot and therefore the towel wasn't nice and warm and stuff like that. And also by just getting it to run for 6 o'clock, during the winter it was turning the heating on at about half one in the morning and then we were waking up at about 4am because of the radiant heat, we were too warm at that point, so what we ended up doing... gaming the system, having a very short morning IN period, but set to start at the time my wife goes in the shower so that the radiators are still at their absolute hottest, the optimum start preheating kicks in earlier."

Matt set up a schedule to match his wife's routine, but he was working with his knowledge that preheating will be happening at the point he himself gets up. His remark about "gaming the system" shows that he is conscious that he is not actually truthfully answering the question asked by the controller- what time do you get up in the morning? - but instead telling it a time which he knows will lead to a satisfactory heating pattern. I use the term "shadow schedule" for this type of schedule, which does not reflect actual occupancy patterns, but is set to provide the desired heating output pattern for one family member.

Matt found a similar solution in the evening. His wife arrives home about 16:00 but he has the evening IN period set to start at 18:00 because she said she did not want a high temperature when she first gets home. Matt and his wife are making conscious use of the preheating period in both the morning and the evening.

Other Boiler-Expert group members also interpreted the controller language of IN and OUT flexibly. Like the hybrid interviewees mentioned in Chapter 5, Ben was sometimes in the house when the controller was set to OUT: "I set the system set in the morning to go OUT from 8 o'clock. In fact [his daughter] and I don't leave for school until half eight but it's sufficient enough that it's been on"

In one case a member of the Expert group demonstrated a creative way of "helping" the controller by providing extra input about situations not directly accessible to the algorithm: the operation of a wood burner used as supplementary heating and not monitored by the controller. Tim said: "generally, because we're using the log burner in the evening, the log burner's in the same room as the thermostat, the heating, within half an hour, the heating is turned off automatically. But occasionally I'll nudge it down, as I light the log burner I'll go and turn the heating down".

In this example, rather than expecting interpretive flexibility from the controller, Tim was providing it with extra inputs, motivated by his practical understanding of how the heating system worked.

7.6.2 More than a boundary object

The Expert group are successfully moulding the heating controller to their household purposes and were frequently flexible in their interpretation of how it should be used. Much of the successful operation (in which the residents were obtaining the conditions they wanted) was a result of knowledge that this group had gained through their work. There was already a consensus about goals so the controller can hardly be said to be operating as a boundary object between distinct social worlds with different objectives. In fact it seems that the overlap between the social world of the Experts' workplace and their households meant that there was no need for a boundary object to mediate between them.

Comparing the two cases provides insights about the occasions when controllers were not acting successfully as boundary objects in the Freedom-Hybrid group. The Expert group had access to extra information about algorithmic control, so they were not relying on information conveyed via the controller alone. Their professional knowledge (or conversations with colleagues) led to a good general understanding of the purpose and operation of the controller. They had been told about ways to adjust the heating controller input until a satisfactory running pattern was obtained.

This suggests that more information about the operation of the controllers and better understanding of the complex issues around efficient heat pump running and DSR might have helped those Freedom-Hybrid trialists who were failing to achieve their preferred heating patterns (in terms of patterns of both temperature and operation).

7.7 Summary of findings

This chapter has focused on the role of the algorithmic heating controller in enabling flexible heating demand. Control designers must make assumptions about the outputs residents want from their heating system (RQ1), and envisage how they will use the controller to achieve these outputs (RQ2). I have described how they aim to design the controller to be a successful boundary object allowing "cooperation without consensus", reconciling household goals for their heating and network objectives for flexible demand.

For those households which did not experience any problems in obtaining the conditions they wanted, the heating controller can be said to be acting successfully as a boundary object. These residents are happy to operate their heating controls in a way that is compatible with demand flexibility. It seems likely that as long as householders feel they can achieve their preferred output conditions, they will not be concerned about network influence on the running pattern of their heating. Some households were interpreting the "rules" set by the controller interface in a flexible way to achieve their required running patterns.

The heating controller was not successful as a boundary object in some of the homes in the Freedom hybrid heat pump trials. On some occasions the goals of residents are not the same as those envisaged by the designers, in particular when residents encounter unexpected or unwelcome operating patterns. I have described instances when residents did not have sufficient information or understanding about the operation of the algorithmic controller to be able to adjust the control settings to achieve satisfactory results.

In some cases the residents achieved their goals using manual operation, in effect opting out of cooperation with network requirements for DSR. In one household, a resident (who was very concerned about heating costs) chose a manual operating pattern that precluded operation of the heat pump. This example raises questions about the potential for exclusion of some low income households from the benefits of a transition to heat pumps.

Manual operation, and in particular manual operation to start the heating in the morning, decreased in the second winter for the Freedom trial homes that continued to operate hybrid heat pumps, suggesting that some households are adapting over time.

The Boiler-Expert group of PassivSystems employees illustrates how a motivated and well informed group of households adapt comfortably to a preheating algorithm. This positive experience, based on the extra knowledge and understanding available to this group, suggests that relying on information available via the heating controller alone may not be sufficient to ensure cooperation from all households, and other information channels should be considered to increase general understanding.

Chapter 8

Discussion

8.1 Introduction

In this chapter I draw together the findings in Chapters 5 to 7 and critically reflect on the theoretical framework used for the analysis. I conclude the chapter by outlining the novel features and original contribution of this investigation.

8.2 Overview of findings

What output do households want from their heating systems?

A clear finding from both quantitative and qualitative data is that residents want different temperatures at different times of day. Interviews revealed how the thermal conditions that residents consider appropriate vary at different times, depending on who is present in the home and what they are doing. Frequently a preference for warmer temperatures is associated with practices with low activity levels, such as watching television, but other practices such as childcare and entertaining guests come with high temperature expectations not linked to low activity levels.

Achieving cool conditions at night when they are sleeping is important to many households. Several interviewees said that they were happy with lower temperatures in the morning than the evening, because in the morning they were in the home for a limited time before leaving and they were active rather than sitting still.

In some cases, especially in the middle of the day, residents do not request heating all the time they are at home: when questioned they said there was no need for heating or that it did not seem right to have the heating on all the time.

For one of the eleven Freedom trial households visited, controlling energy costs was more important than reaching setpoint temperatures, and several other interviewees mentioned that they balanced goals of cost and comfort.

The desired output from the heating is not just about the room temperature. Household goals included particular patterns of heating operation. Residents may wish to avoid particular outputs – for example noise at night time – or to ensure others e.g. hot radiators to dry laundry. Some residents placed more importance on achieving particular running patterns than on obtaining a constant temperature. Some households were setting high temperatures simply to ensure that the heating ran when they wanted and were well aware that their home was not reaching the setpoint temperature. The PassivSystems control algorithm is designed to ensure residents' requests for temperatures during the scheduled IN period are met. The divergence of goals led to problems for this group of residents as they tried to find ways to communicate preferences that had not been expected by the designers.

Some residents expressed a sense of frustration that they did not feel in control of their heating system after they had an algorithmic heating controller installed. It was important to them not only to avoid unwelcome running patterns, but also to get the immediate response they wanted. These perceptions align with the findings about smart homes described by Randall in Harper (2003) [p.233-234] who writes that "control systems were resented if they did not allow users to engage in and complete the activities they wished to undertake" and goes on to say "paradoxically, it seems, the elaboration of control can result in a sense of lack of control".

The variety of goals for heating uncovered in the interviews highlight the need to design flexibility in controllers, so residents are able to obtain the responses they want, even when this is not a constant temperature during the heating request period. Specific recommendations for design are outlined in Section 9.2.1.

How do residents interact with their heating system to get their required outputs?

A mix of manual and scheduled changes to setpoints were found in the case studies for this investigation. Many households manually increased the setpoint temperature part way through the evening heating period. On an average day a quarter of the homes in the Freedom hybrid heat pump trial manually "tweaked" their setpoint upwards at some point in the afternoon or evening.

Residents operate their heating based on their understanding of how long the home takes to warm up and cool down. They may be controlling to ensure coolness at particular times as well as warmth at other times. In some cases setpoint changes were motivated not by a wish for a particular temperature, but to ensure the heat source operated at the times the residents wanted. The transition from a fast responding gas boiler to an algorithmically controlled hybrid heat pump may disrupt this "practical understanding". Some households struggled to achieve the temperature profile and pattern of operation they wanted from the new system. In particular they found it challenging to obtain the cool, quiet conditions they want at night time. This highlights the importance of providing information for residents about how to operate the controller to obtain their preferred conditions. This could be from a combination of guidance within a phone app and information provided by the installer.

How do households react to a change in heating system characteristics?

Interviews with residents during a hybrid heat pump trial allowed investigation of their reaction to the change from a gas boiler with conventional controls to a hybrid heat pump with algorithmic control.

Only one of the eleven Freedom hybrid trial households I visited did not wish to set a schedule for the heating, but preferred to operate the heating manually in order to control costs and match an irregular routine. All the other households I interviewed were happy to set a schedule even if they had been operating entirely manually before the trial.

The most common issue raised in interviews with the Freedom trialists was that they experienced unwelcome high night time temperatures following the installation of the hybrid heat pump.

These residents were frustrated when their heating was not operating in the pattern they thought appropriate. This led to a sense that they were not in control of the heating because they were not deciding when the heat source ran. Some residents were frustrated when they found that they were unable to set the new controller to achieve coolness at night, or that they could not obtain an instant response to requests to stop the heating during a preheating period. This highlights a potential clash between residents' preferences and an optimised control strategy for flexible, low carbon heating (steady running of heat pumps ahead of peak demand periods).

A few homes frequently started their heating manually, rather than relying on scheduled settings, effectively "opting out" of providing flexible demand for the network, since the algorithm was unable to predict when they required warmth. Across 33 homes in the Freedom trial, the first operation in the day was a manual increase in setpoint in an average of 18% of homes on weekdays in January and February 2018. These homes did not provide the predictable start time which allows shifting of the electricity demand away from the morning peak demand period. Data from interviews suggests that dislike of high night temperatures, irregular routines and lack of understanding of the value of setting a schedule are likely to be contributing factors to this behaviour.

Five of the eleven Freedom trial households I visited were satisfied with their new heating system. It is only when residents are unable to achieve their preferences for patterns of temperature and heating operation that limits to flexibility become apparent.

Most households were happy to accept energy network influence over the running of their heating (via time-varying tariffs). A few interviewees expressed confusion about how the price optimisation algorithm ensured minimum running costs.

These findings highlight the need for careful communication both to explain the operation of the controller and to show residents how they benefit from the cost optimisation features of algorithmic control.

8.3 Limitations of research

All the homes considered in this investigation had a particular type of smart controller supplied by PassivSystems Ltd. Specific details of the configuration of the PassivSystems controller and instructions given to users may have encouraged or constrained particular patterns of operation. If a different controller design had been used, the findings might have differed, indeed there are theoretical reasons to suggest that a change in "material arrangements" of the control or heating equipment is likely to alter the reactions of residents.

Some interviewees were experiencing technical "teething problems" with their heating system (as would be expected in early stages of trial of new technology). These may have affected their responses to the new system, which might have been different if they had not encountered any problems.

The two quantitative samples are not representative of all UK households. Conclusions based on the data cannot be generalised to other groups of homes which may have different demographics or building fabric characteristics.

The interviews for the Freedom-Hybrid group were with subset of trial participants who volunteered to speak to a researcher. The circumstances of the request for interview varies between the social housing tenants and homeowners as described in 4.3.3.1. Recruitment bias could mean that those who took part in interviews differed systematically from those who did not, for instance in the level of their interest in new technology. A single interview during the trial only provided a snapshot of the household's reactions to the new technology, which might have changed as they became more accustomed to the equipment.

Although seven interviews in the Freedom-Hybrid group involved both adults (or the only adult) in the household, in four cases I spoke to only one person and relied on them to pass on the views of other household members. This was also the case for all of the eleven Expert group interviews, with PassivSystems employees who reported the views of other family members.

8.4 Applying Schatzkian practice theory

This section evaluates the theoretical approach followed in this investigation. The discussion is framed around the linkages between sayings and doings identified by Schatkzi and introduced in Section 3.1.7.2. As I discuss my results I reflect on the insights provided by this approach and also on some of the limitations of the framework that became apparent as I analysed the results.

8.4.1 Heating goals

Schatzki's concept of teleoaffectivity incorporates the purposes and emotions associated with a practice: he points out that people take actions for the sake of a future result. I have used the shorthand "goals" for teleoaffectivity as I applied it to my investigation of residents' reasons for operating their heating systems. I found a variety of goals in the households I interviewed, which went beyond simply obtaining comfortable thermal conditions. A practice theory approach allows the linking of heating operation to other activities going on in the home such as drying laundry, looking after children or hosting guests.

My finding that residents do not request heating all the time they are at home can be interpreted in the light of the normative dimension of teleoaffectivity identified by Schatzki. Residents are influenced by norms about what they "ought" to be doing at particular points in time.

Practice theory has less to say about how the influence of social norms varies between individuals. Approaches from social psychology, for example Ajzen's theory of planned behaviour (Ajzen, 1991), are likely to provide additional insights about variation in the effect of norms on different households. In general social psychology gives more consideration to differences between individuals and to "individuals' power of action" (Whitmarsh et al., 2011). This would be relevant for investigating, for example, why some residents do not run the heating when they are at home in the middle of the day and others do.

Practice theory can be used to associate a sense of control with the goals of heating operation but other approaches can add extra insights. Hargreaves and Wilson (2017) identify three distinct approaches to the term “control”.

- “Control of technology” assumes that automation is in the interests of users. This study has identified occasions when the assumptions behind the heating controllers do not match the actual goals of residents.

- For “control by users” the objective should be to “give users a perception of control over devices”. My findings suggest that residents experience a sense of lack of control only when the controller does not deliver the running pattern that seems appropriate to them.

- The third approach is “control of lives and relationships”, looking at how smart home technologies affect domestic life and relations. I found instances where the level of access to the new heating controls varied between household members, leaving one person with overall control of the new system.

Galvin and Sunikka-Blank (2016) criticise the lack of engagement of Schatzkian practice theory with the socioeconomic dimension of social theory. They suggest Schatzki’s approach lacks concepts to examine differences in energy consumption affected by fuel poverty or ethnicity. A contrast was evident in the socioeconomic circumstances of the households in the Freedom trial. There was a difference in motivation for participation between the social housing tenants, who responded to their landlord’s suggestion of a new heating system, and the homeowners who pro-actively decided to participate in the hybrid heat pump trial. The different goals of the two groups can be discussed within Schatzki’s framework, but a consideration of how to achieve an equitable heating transition for all socioeconomic groups would require additional theoretical perspectives.

8.4.2 Practical and general understanding

I have found Schatzki’s concept of practical understanding, with its emphasis on bodily experience rather than intellectual analysis, very helpful in investigating how residents interact with their heating systems. People make changes to heating settings based on their understanding of how to achieve the conditions they wish for.

Pickering's concept of the "mangle of practice" adds an extra dimension to this analysis by highlighting how understanding (and goals) change over time. It can be used to explain how households in the Boiler-Expert group gradually adjusted their controller settings until they reached a satisfactory outcome. This concept suggests that helping residents to adapt to a new heating system should be a two-way process, both allowing them to indicate their preferred running pattern and encouraging them to adapt to new patterns which reduce the running costs.

Chapter 7 described the contrast in attitudes between the subset of Freedom trialists, who were unhappy with changes in operating patterns, and the Boiler-Expert group, whose more positive attitude was linked to their appreciation of the benefits of preheating. Schatzki's concept of general understanding is a helpful way to analyse the contrasting attitudes of the two groups, considering the differences in their understanding of the purpose and value of algorithmic heating control. This suggests that it is not sufficient to assume that automated controllers can make optimum decisions on behalf of residents, but it is also important that the residents have a general appreciation of the reasons for, and benefits of, a new pattern of heating operation.

8.4.3 Designing rules

In Chapter 7 I applied Schatzki's concept of the rules which link multiple performances of a practice to the design of a heating controller interface, in particular the design of the user interface in which the residents are asked to set up their daily schedules. The designers can be said to be setting the rules for the interaction between residents and their heating. Sometimes residents succeeded in meeting their goals by interpreting these rules flexibly, for example telling the controller they were OUT at times they were in the house but did not want the heating to operate.

A Schatzkian practice framing presents the challenge for designers in terms of understanding residents' motivations and encouraging their practical understanding. A more detailed treatment of similar themes is provided by Suchman's analysis of the challenges faced by designers of machine interfaces. In her discussion of user reactions to the instructions provided by a photocopier, she points out that "making sense of a new artifact is an inherently problematic activity" (Suchman, 1987, p.9) and highlights the many opportunities for misunderstandings of the "plans and situated actions" of the users.

8.4.4 Heating controller as boundary object

As my investigation progressed I became conscious that many conversations focused on the heating controller rather than the hybrid heat pump or flexible demand patterns. Residents adjusting to a new heating system frequently expressed problems in terms of unexpected results of control settings. Chapter 7 introduced the concept of boundary objects as a framework to consider the intersection of two sets of practices, and two social worlds, at the heating controller. Star and Griesemer's concept of "cooperation without consensus" can be applied to the aspiration of control designers to provide a device which satisfies household goals for thermal comfort and network goals for flexible demand. The framing allows an exploration of the reasons why the controller sometimes fails to satisfy household goals and investigate situations when households "opt out" of providing demand response by operating their heating manually. By examining cases when the heating controller is not acting successfully as a boundary object, I could provide suggestions for design improvements (outlined in Chapter 9).

A further insight provided by the boundary object framing is that the ultimate objective of control design is to provide a device that becomes a standardised part of the energy infrastructure. In order to achieve this, a careful balance has to be found between flexible interpretation by households and incorporating rules for operation which enable Demand Side Response.

8.5 Contribution

For this investigation I developed a novel theoretical framework and a new approach to quantitative analysis which led to recommendations for policymakers and heating control designers.

Few other researchers have had access to data which allowed identification of manual setpoint changes. Morton (2016) and Bruce-Konuah et al. (2019) distinguished between manual and scheduled setpoint changes in data from 12 and 10 homes respectively. As far as I am aware, this investigation is the first to investigate patterns of manual operation over the day in relatively larger groups of UK homes. It is also the first to focus on residents' reactions to algorithmic preheating which leads to a disconnect between the times the heating operates and the times the residents say they want to be warm.

A novel feature of the analysis is the focus on the heating controller as the central point for interactions between residents, their heating equipment and the energy network. I have identified the assumptions "built into" a particular algorithmic controller and drawn together quantitative and qualitative evidence about occasions when these assumptions do not match the preferences of residents.

Theoretical approach

The combination of practice theory and adaptive thermal comfort frameworks used in this investigation opened up novel lines of enquiry. It enabled consideration of a range of reasons for running the heating rather than simply considering a "heating service" providing a steady temperature. Schatzki's concept of "practical understanding" provided insight into operation of heating systems. This has allowed me to analyse the tensions between assumptions about goals and practical understanding built into heating controllers and the actual objectives and operating strategies of residents in the case studies.

The concept of goals for heating helped me to draw together patterns of actions visible in quantitative data and reasons given for actions in qualitative interview data, in particular linking patterns of manual actions in quantitative data with possible reasons underlying these patterns suggested by responses from interviewees.

In Chapter 7 I applied the boundary object concept to the new relationship in which energy network requirements influence patterns of operation of heating in the home and developed a method to quantify the level of cooperation and how it changes over time.

Quantifying heating practices

Social practice theory has inspired quantitative analysis of patterns of time use and the energy associated with particular domestic activities, for example in Torriti (2017) and Satre-Meloy et al. (2019).

My quantitative analysis of patterns of heating use over the day takes a slightly different approach. The focus has not been on energy use data but on patterns of temperature setpoint requests and internal temperatures achieved.

The time lag between when the heat source starts and when the desired temperature is reached complicates the relationship between actions and results. Analysing patterns of temperature achieved over the day has allowed me to link actions with their results which unfold over time and to highlight the changed conditions households experience as a result of algorithmic preheating.

Availability of setpoint data opens up possibilities which are not available to those who are only working with measured temperature data, in particular granular analysis of changes to setpoints and whether these are manual or scheduled. The identification of manual and scheduled setpoint changes have allowed analysis of the way residents are interacting with their heating controllers.

The methods developed for the quantitative analysis have provided insights about residents' goals when operating their heating. The practice theory framework has led me to interpret temperature setpoints as indicating the goals of the residents. Analysis of how often (and when) setpoints are changed has allowed me to track goals which change over time and to compare different cases. Quantitative analysis also highlighted the variability of patterns in individual homes, for instance showing that the assumption that households consistently operate the heating for either one or two periods each weekday (Kane et al., 2015; BRE, 2013) does not hold in all homes. The techniques developed for this investigation could be applied to other datasets incorporating temperature setpoints.

Chapter 9

Conclusions and recommendations

9.1 Summary of findings

Electrification of home heating is an important element of scenarios to reduce UK carbon dioxide emissions. Flexible heating demand is required to minimise the additional investments required in electricity supply and distribution. This investigation has explored household reactions to flexible patterns of heating demand.

Findings from a trial of hybrid heat pumps providing Demand Side Response highlight aspects of new patterns of heating operation which are unfamiliar to residents. The households in the trial experienced a disconnect between the times they requested warmth and the times when the heat sources operated. This represented a major change for residents accustomed to a gas boiler which only ran during times they selected.

Those households who were satisfied with new patterns of operation and had not noticed any adverse effects were happy with the new system. Many appreciated new features such as the ability to control remotely, and the steadier heat delivery from a hybrid heat pump.

The issues raised by those who encountered unexpected or unwelcome features of their new system highlight requirements which might limit acceptance of a demand response algorithm which controls when the heating runs.

Table 9.1 summarises the findings in the light of characteristics of "ideal" households providing flexible demand for the energy networks identified in Section 1.2.4.

Characteristic of “ideal” household	**Findings**
Sets schedule (and updates it promptly if there is a change in routine)	Setting a schedule is likely to be acceptable to a high proportion of homes but a few households in the trial were regularly using manual setpoint changes to start their heating instead of relying on a pre-set schedule. These homes did not provide the predictable start time which allows shifting of the electricity demand away from the morning peak demand period.
Rarely or predictably makes manual adjustments to temperature setpoints	A mix of manual and scheduled changes to setpoints were found in the case studies for this investigation. Manual changes were triggered either because residents wanted a change in temperature, or because they wanted to be sure their heating was operating (for example to dry laundry) A quarter of the homes in the Freedom hybrid heat pump trial manually “tweaked” their setpoint upwards at some point in the afternoon or evening.
Not concerned by a change in the pattern of temperature over the day	High night temperatures were a concern in four of the eleven homes visited during the Freedom hybrid heat-pump trial.
Not concerned by “disconnect” between times heating requested and times heat source runs	Some households in the Freedom trial noticed unwelcome night-time running patterns either because they were unhappy with higher temperatures at night or because they were woken by noise from the heating system. Concerns about lack of control only arise when the residents are not happy with the results of the decisions the control algorithm is making on their behalf.
Prepared to accept network influence on when heat source runs	Most households in the Freedom trial were happy to accept energy network influence over the running of their heating (via time-varying tariffs). A few homes frequently started their heating manually, rather than relying on scheduled settings, effectively “opting out” of providing flexible demand for the network. Two interviewees expressed confusion about how the price optimisation algorithm ensured minimum running costs.

Table 9.1: Divergences from “ideal” DSR behaviour

A widespread dislike of high night time temperatures is an issue which limits the acceptance of preheating at night time. Residents are not only concerned about temperatures, but also about operating patterns. There were negative responses to the heating running at what some residents perceived as the "wrong" time, particularly if it disturbed them at night. Some residents wished for a rapid response from the heating system and expressed frustration if radiators were not hot, or the boiler did not stop, at times when they wanted this to happen.

High levels of manual operation of the heating system were seen in many homes. Residents may change settings manually to satisfy varying temperature requirements at different points during the day, or to be sure that the heating is running (or not running) at a particular time. There is a tension between this behaviour and the need for predictable, scheduled demand to allow demand management for the network.

A small proportion of homes started their heating manually on most days. These households are effectively opting out of providing demand response for the network as it is not possible to predict and therefore shift the demand to a point earlier in time.

Challenges of understanding of new heating systems were also identified. Residents may not understand how to adjust controls to get a running pattern and temperature profile which is acceptable. They also may not appreciate that running a heat pump steadily is more efficient than operating it in short "bursts".

Different perspectives on flexibility

This investigation has shown how electricity network requirements for shifting demand in time interact with household routines in various, sometimes unexpected ways. Demand flexibility is normally framed as a benefit to networks which is practically invisible to households (Strengers, 2013). Smart heating controllers with demand management algorithms aim to deliver the thermal comfort required by residents while shifting demand as the electricity network requires. But when the control logic does not deliver the heating output residents wish for, the operation of the algorithm becomes both visible and unwelcome.

To provide flexibility for the network, household co-operation is needed in declaring schedules in advance, minimising manual operation and accepting new operating patterns. If they are not satisfied with the initial running pattern, residents need to be flexible about adjusting control settings until a satisfactory temperature pattern is reached.

Designers of algorithmic controllers also need to be flexible, providing a device that accommodates a variety of household goals. Instead of assuming residents want fixed temperatures for scheduled time periods, flexible options should be allowed.

Those residents who feel that they are not in control of their heating because they are conscious of unwelcome operating patterns experience a system as inflexible to their needs.

Flexible heating demand requires both flexibility from households in adapting to new control strategies, and control design which allows flexibility for residents to achieve a range of requirements.

9.2 Recommendations for control design

Algorithmic heating control plays an important role in Demand Side Response, aligning objectives between energy consumers and supply organisations. Controllers should be designed to encourage flexibility and make it easy for households to take part in DSR. In this section I identify important themes for consideration in design, and outline some specific suggestions for improvements based on the current controller implementation.

Many of the concerns I encountered among households arose either because the residents were not able to specify a particular requirement, or because the controller did not interpret their setpoint inputs in the way they expected.

My investigation of the aspects of heating control which are important to households highlights three topics which are significant for the design of algorithmic controllers:

- Night time running of a heat pump is an unfamiliar situation for most households and unwelcome to those whose sleep is disturbed by high temperatures or noise.

- For some residents, a sense that they are in control of exactly when their heating operates is important.

- The control algorithm deals with complex calculations about how to optimise the operation of a hybrid heat pump on behalf of the household. It is difficult to explain how the algorithm selects the optimum running pattern for a hybrid heat pump. Some residents were unclear about the benefits of this optimised running for their household and for the energy network.

9.2.1 Suggestions for modifications to the case study controller

It is clear many household would like to achieve cool temperatures at particular points in the day, especially during the night. If residents were able to specify the maximum temperature they are prepared to tolerate at a specified point during the period they are asleep, this would allow them to indicate the times when it is important to them to be cool. It is likely that these requirements would conflict with the most cost effective pattern of running the heat pump for long periods overnight. One way to deal with this would be to show messages in the phone app associated with the controller, to inform the residents of the increased running costs that result from their request for a lower temperature overnight.

I have described the frustration of those residents who were unable to stop the hybrid heat pump operating during preheating periods. An option to override the preheating and tell the controller to stop the heating immediately could deal with this situation. However, this would then leave a dilemma for control design about interpreting what the resident does want to achieve and when it will be acceptable to restart the heat source. Context-specific messages about common problems, and ways to adjust the control setting to overcome these, should be provided.

The widespread occurrence of "tweaking" the setpoint upwards in the afternoon or evening suggests that residents would like the opportunity to schedule different temperature setpoints at different points in the day during the heating request periods. The PassivSystems controller already allows a different IN period setpoint to be scheduled before and after noon but it seems that many households are adjusting settings at a point part way through their afternoon heating period. Allowing the residents to choose two IN setpoint levels and also the time of day when the second level should apply might satisfy this requirement.

An alternative approach would be to include an additional algorithm that learns the patterns in time of manual setpoint changes followed by a particular household. If these requests have a regular pattern, this can then be used as the target temperature profile in the optimisation model.

Control designers are very conscious of the importance of easy to use interfaces with clear guidance on settings. The additional options I have described would add complexity to the controller. Decisions about options to satisfy a minority of users would have to be balanced with providing a simple interface for the majority of users who do not require these extra choices.

The "on-boarding" process of setting up a heating schedule is a crucial step for households using an algorithmic controller. The language used for the schedule should be considered carefully. I have described occasions when the residents set the schedule in a PassivSystems controller to OUT or AWAY when in fact they are in the house. Alternative terminology, making it clear that the residents are being asked to schedule the times when they require warmth, should be considered.

PassivSystems use messages in the heating control phone app to provide information about the status of the heating system, for example indicating "warming ahead of IN period". The confusion experienced by some trialists about why the hybrid heat pump operated at times they did not expect shows there is scope for improving information provision.

Installers play a key role in explaining unfamiliar heating systems and should be supported with suitable material designed to explain the key features of the new equipment. This initial information could include suggestions based on strategies used successfully by expert users. For example, hints could be given about setting up the schedule to match the routine of a particular household member who "feels the cold".

9.2.2 The challenge of automation

Control designers face a challenge in deciding how far to automate heating operation and which decisions to delegate to the residents. I have found a high level of manual interaction with heating controllers, even among an expert group who understand the benefit of scheduled operation. This suggests that the focus of design should be to allow residents different options rather than automating a particular mode of operation which may not suit every household.

Pickering's (1995) image of a process of resistance and accommodation as people adapt to a new technology suggests that residents should be encouraged to adjust the setting in their controllers until they are happy with the operating pattern. Providing flexible demand is a shared responsibility between households and control designers and residents should be considered as partners in the process. Control design should be responsive to the requirements of the residents but also influence residents to operate their heating in ways which are compatible with demand flexibility.

9.3 Implications for policy

A widespread transition to low-carbon heating of homes is an important strand in UK policy to achieve emissions targets. A successful transition in UK homes requires households to adapt to unfamiliar forms of heating technology and to cooperate with requirements for flexible demand.

This thesis describes reactions of households involved in a trial of hybrid heat pumps, but many of challenges encountered also apply more generally to all kinds of heat pumps. Two main themes which limit heating demand flexibility have been identified in this investigation.

- **High night temperatures** resulting from preheating. A widespread dislike of high night time temperatures could prove a barrier to uptake of heat pumps. Installation practices and control schemes to minimise night time disturbances should be encouraged.

- **High levels of manual operation** of the heating system were seen in many homes. This limits the potential for demand management based on predictable, scheduled demand. Heat pumps that are operated manually by households who do not understand the efficiency benefits of steady operation will have high operating costs and may not reduce carbon emissions.

Ensuring that households are fully informed about the benefits of efficient running patterns and flexible demand is an important element of any transition. Some households may struggle to adapt to unfamiliar forms of heating. Policymakers should encourage consistent and clear messaging from equipment manufacturers and energy suppliers. Encouraging scheduled operation and discouraging frequent manual changing of temperature setpoints are likely to be important dimensions of plans for a transition involving large numbers of hybrid heat pumps.

The Renewable Heat Incentive and policies which succeed this will have an important influence on encouraging uptake of low carbon replacements for gas boilers. Incentives should support design features that encourage demand flexibility while providing residents with the heating output they want.

This investigation has identified potential barriers to participation in a transition to hybrid (or stand-alone) heat pumps that may be faced by some low-income households. Those who currently operate their boilers in short "bursts" to control their energy costs would have to substantially modify this behaviour if they are to gain any benefit from a heat pump. If this pattern, which was identified in one of the homes in my investigation, is typical of a proportion of low income households, another low carbon solution should be considered for this group.

"Heat as a service" is increasingly mentioned as an approach to providing low carbon heating. BEIS (2018) explains "there are a number of ways this could be achieved, from simply financing the heating appliance, to selling a package of heat for a fixed price to suit different consumer lifestyles (for example, 21°C during waking occupancy hours)". My findings show that simply providing a specified temperature at the times the household indicates will not satisfy the requirements of many households for other features such as cool temperatures at night and a sense of control about when the heating operates. In many homes the desired thermal conditions change over the course of the day depending on who is at home and what they are doing. Guidance on heating control should consider the varying heating requirements found in many households, and how to reconcile these with efficient, low carbon heating operation.

9.4 Implications for energy supply organisations

When considering future network investment, transmission and distribution system operators have to make assumptions about how much flexible demand will be available. Understanding limits of household flexibility is also important for energy suppliers, especially when offering variable tariffs to encourage flexible demand.

This investigation shows that, while most households are happy in principle to participate in DSR, there are limits on the flexibility of heating energy demand. If morning peaks in electricity demand are managed by shifting heat pump operation to an earlier time during the night, this may meet resistance in some households if they experience unwelcome noise or warmth when trying to sleep.

Manual operation of heating controls is widespread and it seems unlikely that many households will be prepared to accept completely automated control of heating. Data from both the quantitative case studies in this investigation show a clear profile of manual requests for increased temperatures at particular points in the day. This information could be included in demand prediction tools.

9.5 Ideas for further research

This section outlines ideas for further research which have arisen from this investigation. A constant theme has been the interaction of people and technology and all of the suggestions have a mix of technical and social research elements. I start with research to address three issues identified in this investigation and then make suggestions about how the methods used in this investigation could be extended to other case studies to provide additional insights.

Managing high night temperatures

This is not the first piece of research to identify high temperatures in bedroom during the night as an issue for some UK households when they encounter the efficient operating patterns for heat pumps. A technical solution to this is efficient "zoning" of the bedroom. This implies controlling hot water flow through the bedroom radiator separately from the radiators in the rest of the home, so that the bedroom can be kept cooler than other rooms.

Most academic work on zoning to date has been based on simulations and modelling. Beizaee et al. (2015) demonstrated energy savings from zoning based on measurements in a matched pair of (unoccupied) houses. Individual programmable temperature control valves for radiators have been trialled by ETI (Batterbee, 2018) and others but more work is required to quantify the benefits of retrofitting this type of control in a variety of types of occupied homes.

Non-technical methods to address high temperatures at night should also be investigated. The temperatures encountered are not particularly high compared to the night temperatures normally encountered in summer in the same homes. Adaptive thermal comfort principles suggest that adjustments to clothing and bedding (for example, using a thinner duvet) might mitigate night-time issues.

How to encourage new practical understanding

I have described the challenges faced by residents trying to understand the relationship between controller setpoints and the operating pattern of their heating with algorithmic control. The optimisation process is complex, and hard to explain even in a PhD thesis. More work is required on how to convey information, either through the controller or some other method, so that residents understand:

- Running a heat pump steadily for a long time can be more efficient than operating it in short "bursts".
- The benefits of setting and sticking to a schedule both for the energy network and for the household (in terms of lower bills).
- The importance of flexible demand for decarbonisation, and how individual

household actions can contribute to meeting national emissions targets.

Low carbon solutions for “burst” heating group

Section 6.3.4 described the burst heating pattern seen in one low-income household. This type of operation is not compatible with operating a hybrid heat pump to reduce emissions and provide flexible demand, but simply results in the heat pump element of the hybrid never running.

As electrification of heating progresses, with favourable tariffs for those with flexible demand, this type of behaviour may be lead to high energy costs. A fundamental question is whether, with sufficient information and support, households like this would be prepared to change their operating pattern, or whether they require a different type of heating system.

Investigating adaptation over time

This investigation only provided a snapshot in time of the reaction of residents who were encountering various unfamiliar aspects of a new heating system.

A longitudinal study of a change from boiler to heat pump or hybrid heat pump, collecting quantitative data before as well as after the change would enable investigation of changes in behaviour over time. This would allow before and after comparisons that were not possible with the boiler and hybrid heat pump case studies described in this thesis. For example the duration of heating requested periods before and after the introduction of preheating could be analysed to see if residents adapt to the preheating by choosing shorter request periods.

Effect of level of insulation of home

In a house built to high standards of insulation and air-tightness the temperature resulting from intermittent patterns of heating operation will be less variable than in a poorly insulated house, where the temperature drops relatively rapidly every time the heat source stops running. It may be those who are accustomed to steady temperatures because their home is well insulated will adjust more easily to the new temperature patterns from a heat pump because they are already experiencing a low level of temperature fluctuation over the day. An investigation comparing the reactions to a new heat pump of a group in residents in older, poorly insulated homes with those in modern, well insulated dwellings would allow testing of this hypothesis.

Appendix A

Freedom interview information sheet

Participant Information Sheet: Project FREEDOM field trial interviews

What is the purpose of the study?

This study forms part of the FREEDOM field trial of hybrid heat pumps. This interview forms part of Clare Hanmer's work for a PhD degree at University College London (UCL). She is investigating the patterns of heating use in British homes, looking at how people control their heating, and how this changes when a new type of heating is installed.

Do I have to take part?

Participation in the interview is voluntary and you can choose not to participate in part or all of the study. If you decide to take part, you will be asked to sign a consent form.

What will happen if I take part?

Clare Hanmer from University College London (UCL) will visit your home for a meeting of up to 1 hour. She will interview you about how you ran your previous heating system and how the new hybrid heat pump system compares with your previous heating. An audio recording will be made of the interview.

Clare would also like, with your permission, to analyse the data from your PassivSystems heating controller (e.g what time the heating switches on in the morning) and link it to the information from the interview. If you do not want your controller data to be identified to Clare, you can indicate this on the consent form.

Clare will be analysing the responses from the interviews to draw out common themes and to compare with data about households with different heating systems.

Expenses and Payments

After the meeting, your household will receive a £20 gift certificate as a small thank-you.

What are the possible benefits of taking part?

You will have a chance to talk about the new heating system and how it compares with your previous heating. This will help us understand more about the experience of using a hybrid heat pump with smart controls, and will help future development of user-friendly systems.

Will my taking part in the study be kept confidential?

Only Clare will have access to the raw data from the interviews. Your consent form and personal information will be stored in a locked filing cabinet and will be shredded at the end of the project.

All data will be anonymized before any reports and publications, so there is no way to link it to your name or address. Only anonymised data will be shared with other partners in the FREEDOM project.

What will happen to the results of the research study?

Results from the interviews will form part of reports about the FREEDOM project as well as publications in academic journals and conferences. If you would like to receive a copy of any research publications from the project, please contact [redacted]

What will happen if I do not want to carry on with the study?

You can withdraw from the interview without an explanation or penalty at any time

Further information and contact details

The UCL researcher, Clare Hanmer, can be contacted on [redacted] / [redacted]

If you have any problems or concerns about this study you can contact the PassivSystems operations team on [redacted]/ [redacted]. Clare Hanmer's PhD is supervised by Professor David Shipworth at UCL who can be contacted on [redacted]/ [redacted]

Appendix B

Freedom consent form

CONSENT FORM

FREEDOM project: Interviews by University College London (UCL) researcher

Please tick the boxes as appropriate.

1. I confirm that I have read and understand the participant information sheet for the above study. I have had the opportunity to ask questions which have been answered fully.	☐
2. I understand that my participation is voluntary and that I am free to interrupt the interview or withdraw from this research at any time, without giving any reason, and without being penalised or disadvantaged in any way.	☐
3. I understand my personal details such as e-mail and address will not be revealed to people outside the project, and that these details will be stored securely.	☐
4. I am willing to have this interview audio recorded.	☐
5. I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party. No identifiable data will be published.	☐
6. I consent to PassivSystems Ltd releasing data from my home heating controller to Clare Hanmer of UCL, for the purposes of academic research.	☐
6. I agree to take part in the interview.	☐

Name of participant **Date** **Signature**

Name of researcher **Date** **Signature**

Appendix C

Expert consent form

Informed consent

This research forms part of my work towards a PhD in Energy Demand Studies at the UCL Energy Institute. If you have any questions about the study, please contact me, or my supervisor, Professor David Shipworth, who can be contacted at [redacted], (telephone [redacted]).

Clare Hanmer
PhD Researcher, Energy Institute, University College London ([redacted])

- I confirm I have been briefed about the study and I have had the opportunity to ask questions which have been answered fully.
- I consent to PassivSystems Ltd releasing data from my home heating controller to Clare Hanmer of UCL, for the purposes of academic research
- I understand my personal details such as e-mail and address will not be revealed to people outside the project, and that these details will be stored securely.
- I understand that my participation is voluntary and that I am free to interrupt the interview or withdraw from this research at any time, without giving any reason, and ask that data I have provided is destroyed.
- I understand that the researchers will maintain my anonymity throughout the project, including in publications

Name **Date** **Signature**

Appendix D

Freedom interview guide

Interview guide – for Freedom trail participants visited during trial

Demographics and house information

How many people in house, ages. Any pets?

House type and age.

How long at this address?

Weekday occupancy patterns – who is in the house when on weekdays, how much this varies.

Previous heating: boiler type? How old was it?

What controls did you have on previous heating system?

Location of current heating controls.

Location of external HP unit

Heating control

Who usually set the controls on old system? Has that changed with the new system?

Who has the app on their phone?

Can you get the conditions you want with the controls, if not what is wrong?

Do you adjust schedule ahead of a change in routine?

How would you adjust "on the fly" – on app or thermostat?

What advice did you get on how to set up controls?

Motivation: probe on relative importance of: comfort / saving money /concern for the environment

Routines

What are heating on/off times? How much do they vary? Have they changed from the times you used with your previous (boiler) system?

Do they coincide with actual bedtime, getting up time etc? If there is a difference, why?

If heating is set to off when people in house, ask about this in more detail – why, how do you keep warm enough?

Do you make changes in the schedule if the external temperature / weather changes?

Temperature preferences

Current temperature settings and reasons for these. Have these changed compared to previous systems?

Any differences of opinions / preferences of household members about temperatures?

Is there someone who particularly feels the cold?
Probe whether they have different temperature requirements at different times.

What are your temperature preferences in bedroom when sleeping? How do you achieve this? Do you try to keep bedroom temperatures different from living room? (e.g. using TRVs, opening windows)?

New system

Anything you are puzzled by?
Problems encountered?
Too hot/cold at any point? Issues at night?
Have you noticed the HP running? If so, how?
Noticed difference in radiator temperatures?
Any concerns on energy bills?
Comments from visitors?

Actions apart from central heating

Supplementary heating, and when used (how often, time of day). Has this changed with new heating compared to last winter?
Do you have TRVs? How have you set them up?
Ventilation strategy – which windows are opened in winter? How often? Why?
What would you do first if feeling too cold: Do nothing; more clothes; turn up/ on heating, supplementary heat, hot drink, other
General household strategy on what to wear in winter.

Non thermal comfort reasons for running heating

Do you run heating to prevent mould/ damp; dry laundry; other reason?

Constraints:

Are there particular hot / cold spots in the house
How quickly does house heat up once the heating has come on? Has this changed?
How quickly does it cool down? Does this vary between rooms?

Appendix E

Coding structure

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