Heating use in UK homes

By

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Abstract

Within the UK, space heating accounts for 66% of the total domestic energy used. New heating controls may offer a means to reduce this figure and help meet the UK's target of reducing its greenhouse gas emissions by 2050. However these technologies will only save energy if occupants are able to use them effectively. Currently, little is known about how occupants interact with their heating systems, in particular how they use the heating within their home and the reasons behind why it is used a specific way. To investigate further, this thesis presents research which used both qualitative and quantitative methods over two separate studies to uncover why and how households heat their homes and how people use their heating system following the installation of new heating controls.

The results identify key drivers which impact how people heat their homes and highlight numerous issues preventing them from using their heating how they wish to. A taxonomy of heating use is presented based on the factors influencing heating use in homes and how those factors impact the use and control of the heating system. Occupants' use of new heating controls over a ten month period is presented. Manual interaction with controls is separated from programmed heating schedules showing increased manual use over winter and a reliance on heating schedules during shoulder months. The analysis of measured heating use showed similar findings to larger scale studies, however the demanded set-point temperatures were varied and occupants regularly changed heating schedules throughout winter, indicating some of this complexity may be lost by studies inferring heating use patterns from internal temperature measurements alone.

The research presented within this thesis is novel, in developing heating characters based on the factors which influence occupants' heating behaviours, by presenting measured heating use, which included measured set-point temperatures, heating schedules and heating use duration. The thesis also presented the complexity of heating use within homes uncovered through use of mixed methods.

Key words: domestic heating, heating patterns, heating user categories, multi-disciplinary methods

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Chapter 1: Introduction

This chapter introduces the research carried out for this thesis. It details the background to the research area and explains the relevance of this research to the wider context. The research aims and objectives are introduced within this chapter and related to the research questions which this doctoral research aims to tackle. Finally the thesis structure is explained.

1.1 Introduction

The UK is committed to a reduction of its greenhouse gas emissions by 80% of a 1990 base level by 2050 due to the Climate Change Act of 2008 (UKGov, 2008). These legally binding targets and a change in people's inherent concerns and priorities following recent economic situations means that it is vital that a shift towards a more sustainable and efficient use of energy is needed. Although this shift is needed in all energy consuming sectors, one of the biggest users is the domestic sector, accounting for 502 TWh of the UK's 1,724 TWh total energy consumption (DECC, 2013a). The domestic sector energy consumption includes the demand for space heating, hot water, lighting and electrical appliances. This demand has risen 16% between 1970 and 2012 (DECC, 2013a). Space heating has been identified as the main component of energy consumption within the domestic sector, accounting for 66% of energy use (DECC, 2013b) and therefore has to be part of any solution put forward as a means of reducing energy and emissions within the domestic sector.

The variation of energy consumption between dwellings is due to three main factors – the building fabric, the system efficiency and ultimately occupant behaviour within the buildings. Projections of the 2050 housing stock show that two thirds of the stock will be currently existing dwellings (ECI, 2005) and with a housing stock replacement rate of 1% per year (TRCCG, 2008) it is essential to focus on retrofitting the current housing sector to not only reduce carbon emissions but cut energy consumption and improve energy efficiency. However one of the largest issues surrounding retrofitting the UK housing stock is the diversity of the current building stock within the UK meaning that it is almost impossible to roll out blanket solutions as different dwelling types and ages will have different issues which need to be addressed. Further to this there is the issue that not all occupants within the same dwelling types will use energy in the same way, which again raises the concern that a blanket solution will not be sufficiently effective and therefore any energy saving technology or scheme must take the occupants into consideration also.

Since space heating has been identified as the largest component of energy consumption within the domestic energy, the potential of reducing energy use and improving energy efficiency with new heating controls is of high importance and interest. Occupant behaviour is already known to be of importance relating to variation in energy consumption, with Socolow identifying back in the 1970s that differences in energy consumption within the same building type being influenced by differences in occupants' temperature preferences, level of knowledge, attitudes and concerns (Socolow, 1978). However, even with occupant behaviour being known to be a significant influencing factor little research has been carried out to investigate occupant behaviour relating to heating use in homes and in particular little is known about how occupants' interact with new heating controls. This doctoral research aims to address this knowledge gap by developing a deeper understanding into current heating use within homes and uncovering the drivers behind heating use. By also investigating the potential influence new heating controls have on heating habits within homes this thesis uncovers how occupants use new, smarter heating controls and reports measured heating use within homes.

1.2 Research context

This doctoral research was carried out as part of the Engineering and Physical Sciences Research Council (EPSRC) funded London-Loughborough Centre for Doctoral Training (LoLo CDT) in Energy Demand. The doctoral research also formed part of the 5-year EPSRC funded Digital Energy Feedback and Control Technology Optimisation (DEFACTO) interdisciplinary research project. DEFACTO was funded under the EPSRC "Transforming Energy Demand in Buildings through Digital Innovation" (BuildTEDDI) call (Ref EP/K00249X/1) with the aim to investigate the energy saving potential of the digital innovation in space heating controls. To investigate the impact of new digital heating control technology on reducing domestic energy demand, the DEFACTO project aimed to monitor energy use in homes with an intervention in a number of homes to replace existing heating controls with new digital heating controls. This intervention, alongside pre and post installation monitoring of energy use and internal temperatures, not only shows the impact of new heating controls being installed in UK homes but gives a rich understanding of how occupants interact with a new technology and adapt their energy use following the intervention.

Several stakeholders worked in collaboration with the project with the aim that stakeholder involvement would support the project. This involvement included development of the monitoring equipment kit to be installed in households and with participant recruitment. The collaboration will continue through to the final stages of the project with regards to data analysis and feedback of better heating control technology design. This thesis reports a contained piece of work within the DEFACTO project, undertaken by the author.

This doctoral research focused on the DEFACTO pilot study households with the author being part of the project team. Participants of the DEFACTO project were recruited to be part of the "Go Digital" study, essentially giving a public facing front to the project. The decision to brand the study under a different name to participants was to ensure that participants could not easily find out all of the study's aims and objectives as this might impact their use of the new controls and any answers given in questionnaires or interviews. The Go Digital branding included a distinctive logo as shown in Figure 1.1, this was used on all participant information, correspondence and email signatures so that the study had a clear image and participants knew that any mail or study materials were from the study.

Figure 1.1 Go Digital logo

The pilot study was carried out as an initial exploration phase for the main DEFACTO study, not only to test the process for equipment installation but also to test the Go Digital branding and uncover any potential issues that may impact the main study. The pilot study sample consisted of twelve households across the Leicestershire area and was recruited through a project stakeholder by a snowballing strategy of staff, families and friends of the company (further details are presented in Chapter 5). The pilot study did not focus on one particular dwelling type, rather recruited based on three main criteria. The main criteria were as follows:

- the occupants owned the property (outright or with a mortgage);
- the property had gas central heating; and,
- the property had a broadband internet connection.

Participants were told from the start that they would get to keep the new heating controls installed as part of the study and were also rewarded with gift vouchers at various stages for taking part in additional activities such as interviews and diary keeping. Full details of the methodology are presented in Chapter 5 and 6.

The involvement of this doctoral research with the Go Digital study formed Phase 2 of this thesis and, as such, the author was involved with the design of the pilot study and with the data collection. The Go Digital study was also focused on researching the way different households use their heating systems to help design better heating controls that could help save money and energy, therefore allowing this phase of the doctoral research to be easily integrated to the project. The Go Digital pilot study was expanded to allow the author to further explore how and why the newly installed heating controls were being used a specific way and what occupants did with the additional functions to their previous controls, so to achieve the overall aim and the specific objectives for this part of the doctoral research. The author assisted with the design of the initial Go Digital household interview questions as well as developing the information pack materials sent to those interested in the study prior to their consenting to being part of the study. Although not a part of the first interviews with the study participants, the author was present at all of the second households' interviews, primarily as a way for participants to get to know the author for future communications and interview visits, but also to cover any areas not addressed in the first interview which were needed for this doctoral research. Phase 1 of the research was carried out independently of the Go Digital study and was undertaken solely by the author for this thesis.

The doctoral research carried out for Phase 1 and Phase 2 of this thesis contributes knowledge on how people currently use heating systems and controls within their home and identifies the factors which influence this. Occupants' heating patterns are also presented, which unlike previous research in this area, includes findings regarding demanded set-point temperatures and interactions by occupants. Therefore the research presented in this thesis not only expands on previous work but allows for a better indication of the appropriateness of energy model assumptions and research methods used to monitor heating and energy use in homes.

1.3 Aims and Objectives

The aim of this doctoral research was to examine household space heating use and to identify the reasons behind heating use in UK homes.

This aim will be achieved through the following objectives:

1. To execute a comprehensive literature review to develop an understanding of heating use in UK homes, covering aspects of heating systems, controls, demand temperatures and energy use in relation to occupant behaviour to place this work within a broader context.

2. Conduct a qualitative focused exploratory study to investigate how people currently use their heating within their home and the reasons behind why they have such heating practices.

3. Develop a taxonomy of heating behaviours relating to preferential heating practices identified through Objective 2 and building on current heating behaviour types identified in literature.

4. Conduct a second phase explorative study using both qualitative and quantitative methods to develop an in-depth understanding of heating use within a small sample of households with new heating controls installed.

5. Analyse the evolution of heating use through seasonal shifts from analysis of quantitative data achieved from the new heating controls installed to see how occupants change their heating practices moving between seasons.

6. Based on the understanding from the Phase 2 explorative study carried out for Objective 4, justify the need for mixed method approaches in relation to heating use within the domestic sector by identifying the true complexity of

heating use within homes through combining both measured monitoring data and in-depth interview data.

7. Draw conclusions based on the research as a whole regarding space heating behaviours, evaluate the outcomes and highlight the consequences of unchanged heating behaviours on meeting energy reduction targets and critique the approach taken.

The aim and objectives of this study address the following research questions which have driven and shaped the body of this research:

1. How do people currently heat their homes – what controls do they have and what do they use?

2. What are the reasons behind occupants' reported heating use?

3. Can heating behaviours be categorised by understanding how occupants use their heating, why occupants heat their homes in a particular way and what occupants use to control their heating?

4. How varied are household heating patterns regarding demand temperatures, heating period durations, household temperatures achieved and the household interaction level with heating controls?

5. How does heating use in UK households evolve during seasonal shifts from autumn into winter and how does this compare with moving from winter into spring?

6. Do many households keep the default settings after installation of new controls?

7. Do new heating controls lead to a reported change in heating use for households?

8. Is how occupants report using their heating different to measured heating use?

9. How does the combination of qualitative and quantitative heating data add to the understanding of heating use?

1.4 Thesis Structure

The doctoral research carried out to produce this thesis is reported over six further chapters. The content and structure of the chapters are summarised below with the link between each chapter being summarised in Figure 1.2.

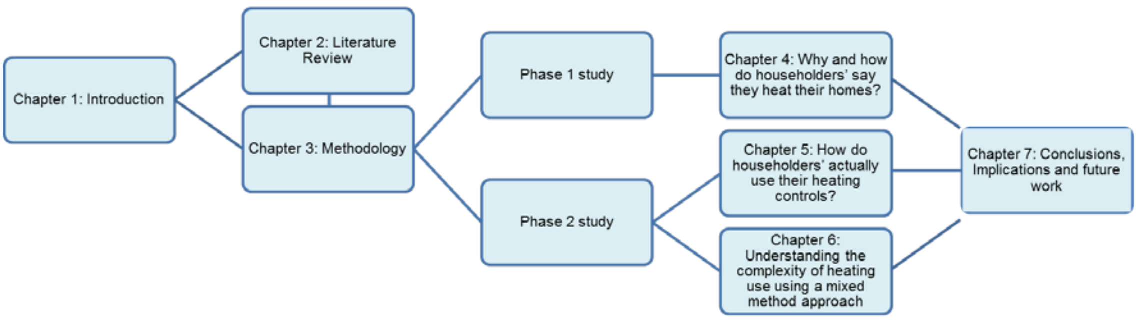


Figure 1.2 Thesis structure and linkage between chapters

Chapter 2 presents an in-depth review of the current literature published in the areas surrounding this doctoral research. The chapter begins with an overview of energy demand within the UK focusing on the domestic sector before providing more detail on heating use, accounting for the systems, building fabric and occupants, and the difficulty in reducing energy use and emissions due to the UK domestic building stock. The chapter outlines UK heating systems before focusing on heating controls and their potential to contribute towards energy savings and the relevance of this to the doctoral research being presented. The review then moves on to detail work that has previously been carried out on heating use within UK homes, presenting current knowledge and assumptions on heating use patterns, temperatures and savings. The review then tackles the occupant research side, presenting an overview of behaviour research theories and issues before discussing behavioural impacts which can influence heating use in homes such as thermal comfort, adaptive behaviour and the level of occupant understanding. The review focuses on the most relevant work relating to this doctoral research in the form of heating behaviour types and motives and discusses the areas in which the research presented in this thesis can contribute to this knowledge and support the limited research which has been done so far in this area. This in-depth review of the current knowledge and subsequent gaps both in domestic heating use and heating use behaviours places this doctoral research into the wider context and supports the reasons behind carrying out the research for this thesis.

Chapter 3 presents this doctoral research strategy and the approach which has been applied to this work. The chapter presents some of the background into the research methods used and then explains the use of such methods for this research. The chapter details both qualitative and quantitative methodological approaches incorporated within this doctoral research and the data analysis techniques applied. Finally the chapter covers the reliability and validity of the research methodology applied and details the ethical considerations of this approach.

Chapter 4 presents the first phase of research carried out for this thesis, an exploratory study aimed at understanding why and how householders heat their home the way they do. This chapter presents the variation in heating behaviours within homes and highlights the array of factors influencing householders' space heating use. The chapter presents the methods used within this study, details the results of the mainly qualitative focused study and discusses the implications of the findings, as well as critiquing the methods used. A taxonomy of heating use is presented within the chapter based upon the factors identified as influencing householders' space heating use.

Chapter 5 and 6 both focus on the Phase 2 research. Chapter 5 presents the findings from the Phase 2 research in relation to how occupants use their heating controls as well as detailing heating use patterns and behaviours from quantitative measurements. The chapter describes the background to the study, the methods used for Phase 2 before presenting the results, including characterisations of heating use within the sample, and then discussing the implications of the findings as well as comparing against previous research/assumptions of heating use patterns.

Chapter 6 expands on the Phase 2 research presented in Chapter 5 by focusing on the mixed method approach within this research. The chapter highlights the benefits of using both methods through examples and also discusses the implications of mixed method research gaining popularity within the energy research field. The chapter also discusses some of the potential issues when combining both qualitative and quantitative methods and critiques the use of mixed methods within this doctoral research.

Chapter 7 provides an overall conclusion of the research undertaken and presents the contributions from this research towards developing a more in-depth understanding regarding heating use within UK homes as well as the factors influencing such heating behaviours. The chapter summarises the findings of this research in relation to the research questions presented within Chapter 1. The chapter then discusses the implications of the outcomes from this research. The research methods used are critiqued along with a discussion around the successes and limitations of these methods with regards to the research. Finally the application of the research outcomes are discussed in terms of a wider context and how the research could be applied or expanded on in future work.

Chapter 2: Literature Review

Chapter 2 summarises an extensive review of all current literature available within the scope of this research. The literature review aims to place this doctoral research within a broader context, highlight its importance and originality and give the reader the relevant background and information regarding domestic heating use and occupant behaviour.

2.1. Introduction

Space heating not only provides a level of comfort and satisfaction to the occupants but it is also the largest energy consuming activity in homes. Controlling heating has advanced significantly since the introduction of central heating systems into homes, ranging from controls on boilers and heaters to standalone heating controls. Heating controls come in a wide range of styles, have a multitude of different functions and have differing levels of usability, yet they form an essential part of a home heating system. They provide a way for occupants to change the temperature within their home, allow them to programme the heating to come on and off when they want, give occupants the opportunity to set different schedules to reflect their daily needs and often give occupants a sense of reassurance in knowing that their controls will ensure their heating system does not freeze whilst they may be away from home. Yet there is little evidence detailing the interaction between the occupants and the heating controls.

This literature review is designed to provide an insight into this area of research and the current state of heating use within UK homes. The review begins with an overview of the UK domestic energy sector in Section 2.2 which introduces the triangle of factors which influence energy use within homes, the building fabric, the heating system and the occupants. Previous research into these three factors is presented and discussed. Section 2.3 presents the current knowledge on heating use within homes and heating controls, touching on the temperatures which have been recorded in previous studies, the model assumptions made regarding heating schedules and the advancements in heating control technology. Section 2.4 then presents what is currently known about heating behaviours and the attempts which have been made to understand more about the occupants' interaction with heating controls, their level of understanding, and the different types of heating user types that occupants may fall into. Finally Section 2.5 concludes the literature review with suggestions of where knowledge gaps are within this research area and how this doctoral research can contribute knowledge to these gaps.

2.2. UK Domestic energy

The UK energy system is changing due to two main factors – the introduction of legally binding targets and a change in people's inherent concerns and priorities following recent economic and environmental situations from economic recessions and the increasing awareness of climate change. The Energy White Paper published in 2003 (DTI, 2003) sets out a UK target to reduce CO_2 emissions by 60% by 2050, whilst maintaining the reliability of the UK energy supply, promoting competition within energy markets and ensuring that homes are heated to an adequate level at an affordable cost. This was later increased by the Climate Change Act of 2008 (UKGov, 2008) setting a target of reducing the UK greenhouse gas emissions by 80% of the 1990 baseline levels by 2050. In recent years the UK has gone through periods of economic recession causing many families to be impacted as well as increased awareness of the damage being caused by climate change due to extreme weather events, with many having a stronger desire to be sustainable and as eco-friendly as possible.

Alongside an increasing population total within the UK comes an increased need for more energy. The total UK energy demand growth increased between 1990 and 2003 by 7.3%, yet the residential sector showed a growth of 17.5% indicating that reducing the UK carbon emissions and energy demand will require treating each sector of demand separately to reach the best solutions (ECI, 2005). In 2014, the domestic sector accounted for 27% of the total final UK energy consumption by consuming 38.2 million tonnes of oil equivalent (Mtoe). Of this total, almost 63% came from the use of natural gas and a further 24% from electricity (DECC, 2015). The domestic sector energy consumption relates to the demand for space heating, hot water, lighting and electrical appliances. Of the domestic energy gas consumption, 63%, the majority is used for heating purposes with only a small percentage being for cooking. DECC estimated that within 2013 space heating alone accounted for 77% of gas and 22% of electricity used within the domestic sector (DECC, 2016). Latest figures suggest that the energy consumption within the domestic sector has increased by around 4% within 2015, however this is likely to be in correlation with the fact 2015 was a colder year compared to 2014, with an observed increase of 10% in the total number of heating degree days (DECC, 2016).

However the UK domestic building stock is extremely diverse in size and shape spanning many decades. This diversification means vastly different energy performances for these buildings making the task of reducing energy consumption and carbon emissions difficult to tailor for the domestic sector. The average dwelling within the UK domestic sector has an Energy Performance Certificate (EPC) grade of E, on a scale of A to G with A being the most energy efficient, therefore it is easy to understand why the domestic sector accounts for 27% of the total carbon emissions for the UK; the average household is responsible for over six tonnes of carbon every year (DECC, 2012). Since projections of the 2050 housing stock show that two thirds of the stock will be currently existing dwellings (ECI, 2005) and with a housing stock replacement rate of 1% per year (TRCCG, 2008), it is essential to focus on retrofitting the current domestic sector to not only reduce carbon emissions but also cut energy consumption and improve energy efficiency.

Energy use in homes can differ dramatically from one household to the next, however even those thought to be very similar dwellings can differ in their use of energy. The energy use of a home is impacted by three factors – the building fabric and its physical performance, relating to the energy efficiency of a building, the system within a home which comprises mainly of the heating system but in some cases this may also include mechanical ventilation, and finally the occupants of a building directly influence the energy use of a home as shown in Figure 2.1 (CIBSE, 2004), after all “buildings don’t use energy, people do” (Janda, 2009).

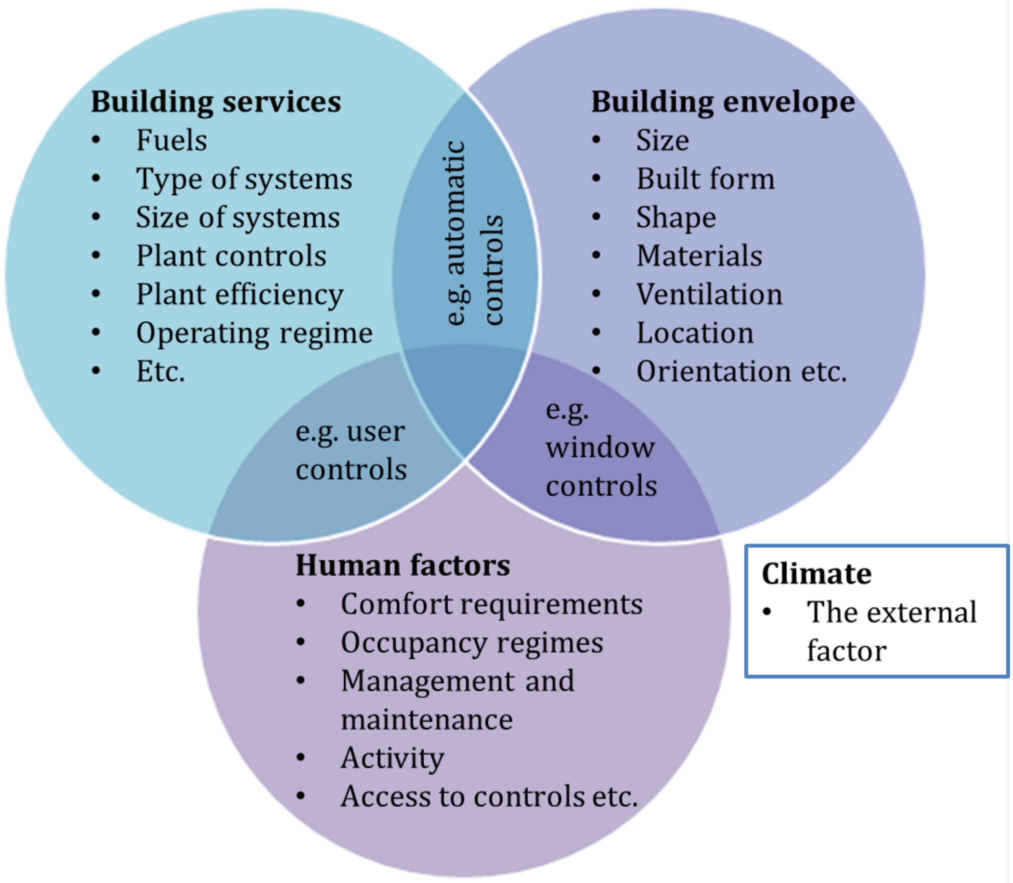


Figure 2.1 Key factors which Influence energy use in building (CIBSE Guide F, 2004)

It is the overlap between human factors and building services where this doctoral research fits, identified in Figure 2.1 as being user controls. However it is vital to understand the impact each of these three areas have on energy consumption within homes, in particular in relation to heating use.

2.2.1 The fabric

It can be assumed that the temperature demanded within a home influences its energy use, however there are many factors (Wei et al, 2014) which can influence the temperature within homes, factors such as the type of building (Kane, 2011), the orientation of the building, levels of thermal insulation and the presence of eaves, as all of these affect the heat transfer of the dwelling (Bekkouche et al, 2011). The fabric of the building itself impacts the energy efficiency of the building and therefore impact the energy used within it. A study by the Energy Saving Trust

(2006) found that insulation caused an increase of 0.57^{o}C in internal temperature. The thermal performance of a building can also be dependent on factors which influence the heating load such as temperature variations between internal and external environments, different floors, adjacent rooms and distinctive heat losses expected for certain materials such as glass, walls, windows and roofs etc. (Raaij et al, 1983a).

To improve the fabric of a building and the physical performance of it, such that the energy efficiency of the building increases, various measures have been implemented over the last decade. Stricter building regulations mean that new homes are built to a much higher specification than was expected 20 or 30 years ago. Improvements in technology and renewable energy sources mean that buildings are becoming more sustainable and reaching new efficiency levels. Government schemes and grants have also been introduced to help persuade householders to take up different improvement measures and to begin retrofitting their homes.

Within the domestic sector, retrofit is used in the context of energy performance improvements, where a domestic property may have its energy performance improved by changing the building fabric or improving it through added insulation etc. It also includes changing the energy system within a property, changing any energy consuming appliances to more energy efficient ones or even changing the level of control over energy systems within the property. However one of the largest issues surrounding retrofitting the UK building stock is the sheer volume; the Department for Communities and Local Government state that roughly 22 million homes need to be improved by 2050 which they calculated to be around 1,600 homes per day (DCLG, 2012). Another issue challenging the completion of this task is the diversity of the current building stock within the UK meaning that it is almost impossible to roll out blanket solutions as different dwelling types and ages have different issues which need to be addressed. On top of these issues comes the fact that the ease of retrofit will be influenced by the tenure. Within the UK, 70% of the residential building stock is owner-occupied with 12% being private rental and the remaining 18% being social housing (Chahal, 2012). The tenure impacts the ease of retrofit as owner-occupied have more say over deciding on retrofitting their property which will be influenced by cost and level of disruption involved. Social housing is seen to be the easiest class of tenure to target for retrofit and various retrofit research studies have focused on them for this reason (Lowe et al, 2012, Chahal, 2012, Bates, 2012).

To help accelerate improving the housing stock through retrofit measures the government has previously introduced various schemes/initiatives to help people afford to improve their properties. The Energy Efficiency Commitment (EEC) required energy companies to reduce their customer's energy consumption and emissions through funding various measures, however this was replaced in 2008 by the Carbon Emissions Reduction Target (CERT) which was a larger scheme aimed at improving the energy efficiency of the housing stock mainly through various insulation measures. Alongside CERT the government also launched the Community Energy Saving Scheme (CESP) aimed at tackling community energy efficiency instead of just individual properties. The Warm Front scheme also helped provide measures such as loft or cavity wall insulation or even new boilers for owner-occupied or privately rented properties on income related benefits to help reduce the fuel poverty issue within the UK. The Decent Homes Standard aimed to do a similar task but for those within social housing or particularly vulnerable owner occupied homes (Boardman, 2010). However it is worth noting that these schemes were designed for self-referrals from qualifying households therefore attracted the households where occupants were not only aware of these schemes but also understood about the disruption possible from installation of these measures and possible upheaval. The government announced a new scheme to help target more properties needing energy efficiency measures installed in the form of the Green Deal which was further supported with the Energy Company Obligation (ECO) scheme. The Green Deal had many barriers to overcome to ensure that it was successful (Dowson, 2012). The financial structure of repayments through energy savings was seen to be weak due to the energy savings being reliant on estimates from modelled assumptions which could be impacted by poorly installed measures and occupants increasing their energy use. The complicated process of gaining grants towards any retrofit measures also did not help and therefore there was not a great uptake after initial assessments were carried out on properties.

The issue of comparing energy use after improvements is slowly becoming an issue that is needed to be studied in more detail within the domestic sector and example has been taken from non-domestic building sector to introduce post-occupancy evaluation. Currently there is no UK policy which requires post-occupancy evaluations to be carried out on domestic properties and in fact little real feedback exists, therefore it is extremely difficult to assess whether an improvement has made an impact on a buildings energy consumption/emissions in reality (Stevenson & Leaman, 2010). Vale (2010) points out that it is not simply enough to ask questions on building performance as part of a post-occupancy evaluation but, to have a real impact, real data are required on that individual household to give a better basis for comparison pre and post improvement. Vale also points out that a roll out of smart meters, such as the UK government has committed itself to, may not be the only action required. Showing occupants' information about their energy use may not be the trigger to encourage people to reduce their consumption. In fact Vale suggests it will be more effective to set real system limits for people to compare against, like how a car speedometer helps us towards reducing speed but only when people take into consideration the speed limit set.

Aside from physical building properties affecting the thermal performance of a building, it is also related to the efficiency of the heating system present within the building with regards to type of boiler and type of fuel required (Yohanis, 2012). This links to the second influence on the energy consumption within a home, the heating system present.

2.2.2 The system

Methods of providing heat and warmth within domestic properties have advanced from the open fires within communal rooms of the early 1900s. The introduction of central heating systems into UK homes from the early 1970s has changed the use of heating in homes significantly over the past half a century. At the time of the last national census, 2011, 97% of the 23 million homes in England and Wales had central heating, 83% being gas fired (ONS, 2011). Central heating systems within homes are typically one of three types, 'wet' systems, warm air systems or systems involving storage heaters.

Storage heat systems typically have both electric storage heating and direct electric heating present within the property. Storage heaters are located in the main rooms of the dwelling and charged at night when electricity is at a relatively low cost (EST, n.d, a). The heaters are programmed to release this heat during the next day at the time set by the occupants. However some only have input and output level controls on the system so occupants are unable to set times for when the heat should be released. Storage heaters are often unable to meet peak evening heat loads and so are supplemented by direct electric heaters. Warm air systems are not as common in the UK as other countries but essentially air is heated by a central boiler and this warm air is then circulated round the home via ducts. These systems typically run on natural gas to warm the air being circulated, however these are seen to be not as efficient or comfortable as wet systems.

Wet heating systems can be described as those which have a boiler which heats and circulates hot water through the home via a circuit of pipes leading to radiators. Boilers commonly run on mains gas, however there are wet systems which can run on oil, liquid petroleum gas (LPG), coal or wood. Boilers can either be conventional boilers or combination boilers (combi) (APHC, 2013). A conventional boiler also heats the water stored in an insulated cylinder (hot water tank), which supplies the hot water taps in the dwelling. A combi-boiler directly heats the hot water supplied to taps when a tap is turned on, so no cylinder is needed as part of the system.

The heating controls, which influence the inter-room temperature variations, are the same for either boiler type. The variety in heating controls available is further described in Section 2.3.3. When the heating controls signal to turn the system on, the gas boiler fires and the circulating pump runs and within a few minutes, hot water is delivered to the radiators (APHC, 2013). The temperature of the supply water can often be controlled by a dial on the boiler; although most homeowners are unlikely to use this facility. The pump runs continually until the thermostat senses that the set-point temperature has been reached. This is the temperature set by the occupants. When the set-point temperature is reached, an interlock will turn the boiler off. The boiler and pump cycles on and off to try and maintain the set-point temperature.

Individual rooms within the dwelling are heated by panel radiators supplied by hot water from the boiler. These are traditionally fitted with manually operated radiator valves, but increasingly these valves have been replaced by thermostatic radiator valves (TRVs). TRVs allow occupants to control the environment in each individual room to suit their needs and preferences.

Since 2002 UK Building Regulations state that the basic central heating system configuration within new homes (or if existing heating systems are being replaced) require that the system must have a timer, central thermostat, boiler interlock and TRVs on all but one radiator (typically where the room where the thermostat is located) (ODPM, 2002, EST, 2001). Since Oct. 1st 2010, the UK Building Regulations (HM Government, 2013) have required that the ground and upper floors of new homes over 150m^2 must be controlled independently, each with their own wall thermostat. Very few homes built before this time have such a system and retrofitting to such a configuration can be difficult and expensive. The Energy Follow-Up Survey (BRE, 2013a) reported that 90% of the homes researched had central heating systems with 98% of those having the primary central heating system controls (therefore at least one form of control from either a boiler on/off switch, boiler thermostat or a central timer to control the heating). Only 49% of the homes met with the Building Regulations of 2002 where a full set of controls were present within the home (TRVs, central timer and room thermostat) (Consumer Focus, 2012). This will be due to many occupants not upgrading their heating controls until the existing boiler needs replaced.

Many homes with central heating also have secondary heat sources (EST, n.d, a), commonly a gas or electric 'fire' which is typically located in the main living room where there would traditionally have been an open fire. Thus living rooms can be heated even when the main central heating system is switched off. This could increase the temperature variation between the living room and other rooms in the home. Often households also have small portable oil filled radiators which can then be moved from room to room depending on where the additional heat is required. Electric fan heaters can also be used where the air is warmed within the appliance and then blown into the room.

2.2.3 The occupant

The Department of Energy and Climate Change (DECC) states the definition of behaviour to be 'the action, reaction, or functioning of an organism or system, under normal or specified circumstances' (DECC, 2011). Energy behaviour is an important element to understand with regards to retrofitting existing dwellings as attitudes towards energy can play a crucial role in energy saving potential. Guerra-Santin (2010) summed up the relationship for energy use in buildings to essentially be two main factors as shown in Figure 2.2 – the building characteristics and occupant behaviour.

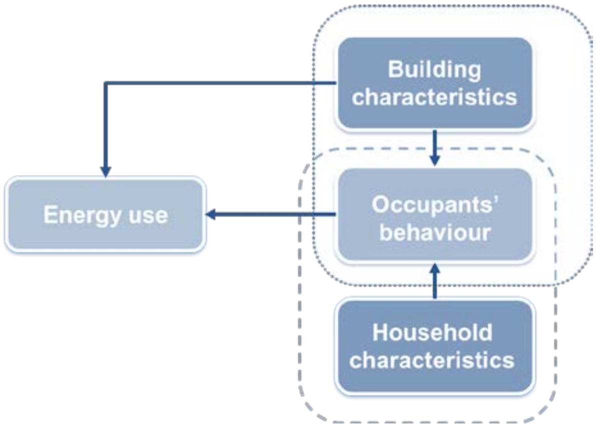


Figure 2.2 Energy use relationships (Guerra-Santin, 2010)

Occupant behaviour can be influenced by various factors not just due to expectations resulting from previous knowledge but also due to financial issues, health reasons, size of family, anticipated standard of living alongside comfort expectations and cultural habits, energy use and attitude towards it, energy consuming appliances within the dwelling and the frequency of use of these, occupants' individual thermal comfort and the occupants level of understanding towards certain elements relating to the thermal performance of their home, for instance how well do they understand their heating system or the stated 'comfortable' temperature range (Hunt 1982, Mullaly 1998, Jaber 2002, Schipper 1982, Westergren 1999, Deering 1993). It is also difficult to 'measure' behaviour as picking a representative sample is very subjective as often behaviour is influenced by awareness and attitudes which can form opposite extremes due to factors such as level of education, political beliefs, income, location of residence and even age (Yohanis, 2012).

When it comes down to rationalising occupant behaviour there are various frameworks which can be used to justify findings – however the chosen framework will depend greatly on the theory behind the framework. There are four main theories which relate to occupant energy behaviour (DECC, 2011) which are summarised in Table 2.1.

Table 2.1 Summary of the four main energy behaviour theories (DECC, 2011)

Theory	Related to energy	Description
Economic theories	"Energy is a commodity and consumers will adapt usage in response to price signals"	Theory suggests that occupants adapt their energy use according to energy price however this is likely to be a short-term response mainly affected by cold weather situations and likely that would not be an individual reason.
Psychological theories	"Energy use can be affected by stimulus-response mechanisms and by engaging attention"	Theory suggests that occupants may adapt their energy behaviour in relation to new information such as that provided from in-home displays or bill information giving advice on reduced energy use.
Sociological theories	"Energy use is largely invisible, energy systems are complex, and daily practices are significant"	Theory relates to the view that people do not directly use energy and it is occupants' practices that lead to the consumption of energy.
Educational theories	"Energy use is a skill that is learned through experience in specific situations"	Theory emphasises the differences between occupants and does not treat occupants as having homogeneous energy consumption. Brings in factors such as level of understanding, skills, motives, world-views etc.

Certain norms and/or expectations may result in an energy behaviour which occupants see as being a way of keeping up appearances and in fact may not indeed be the same behaviour exhibited when there is no 'expectation'. Therefore single 'behaviours' may in reality form part of a complex set of practices. It is also worth considering that certain objects or practices may have symbolic meanings or be resultant from social stigmas (Goffman, 1963), for instance occupants may not want to admit to using a blanket when feeling cold as there is often a stereotype that those who use blankets are often elderly or frail and it is often linked with the image of people not being able to afford to heat their home to an adequate level so need an alternative heat source. Issacs' (2010) work suggested that occupants' behaviour can be driven by some sort of 'pride' factor alongside normative standards. Similarly it is known that window opening behaviours influence the thermal environment of a household, resulting in impacts on energy consumption and internal temperatures (Jian, 2011). However window opening behaviours are not always related to improving indoor environment quality for occupants but are often related to previous images given to occupants that it is expected as a means to ‘air’ a room so becomes an everyday action and often habitual.

Energy behaviour in homes has been widely studied in relation to total energy use and as such Hitchcock (1993) classified energy behaviour into three main categories; usage-related behaviour meaning the day to day patterns of use such as the duration certain appliances are used for etc., the second category being maintenance-related so referring to the behaviour associated with maintaining and repairing energy systems, and finally the last category being purchase-related referring to changing occupant behaviour in relation to purchasing a low energy solution such as low energy light bulbs etc. However purchase-related behaviour could also result in take-back and in particular temperature take-back where the occupant thinks that improving the energy efficiency of their home means that they can achieve higher temperatures or the energy savings made by the purchase mean they can afford turning the thermostat up. A study relating to temperature take-back (Milne, 2000) found that low temperatures in low-income households meant only half of the potential energy savings were made as the remainder was taken as increased temperatures. Take-back effects hinder the true extent of potential energy savings for retrofits and are extremely hard to plan for.

Income influences energy behaviour as it can essentially limit energy use. However it has been shown that the relationship between energy and income is very complex due to the intricate interaction between income in relation to education and environmental issue beliefs (Roberts 2008, Summerfield 2007, Wall 2009). Rose (1989) identified that heating within pensioner flats was influenced by the weekly income (except living rooms which always seemed to have preferential heating priority) and linked together various socioeconomic factors with resultant fuel use as shown in Figure 2.3. Income is also a sensitive issue with regards to heating homes as there is the prominent topic of fuel poverty within the UK. Fuel poverty affected 4.75 million homes in the UK in 2010, which equates to 19% of UK households. The original definition of fuel poverty states that a household is fuel poor when they are spending 10% or more of the household income on fuel to maintain an adequate level of warmth (Boardman, 1991). The adequate level of warmth is stated as being 21°C within living rooms and 18°C in all other occupied rooms (BRE, 2010). Following an independent review and consultation the UK Government announced a new definition to those who should be classed as being 'fuel poor' which according to the new definition includes households where the total income is below the poverty line and where the energy costs are higher than what would be typically expected (Hills, 2012). Key elements influencing a household being fuel poor or not include income, fuel prices and fuel consumption (which are influenced by dwelling physical characteristics and household lifestyles), so it is easy to see why the issue of relating income with energy behaviour is such a complex one.

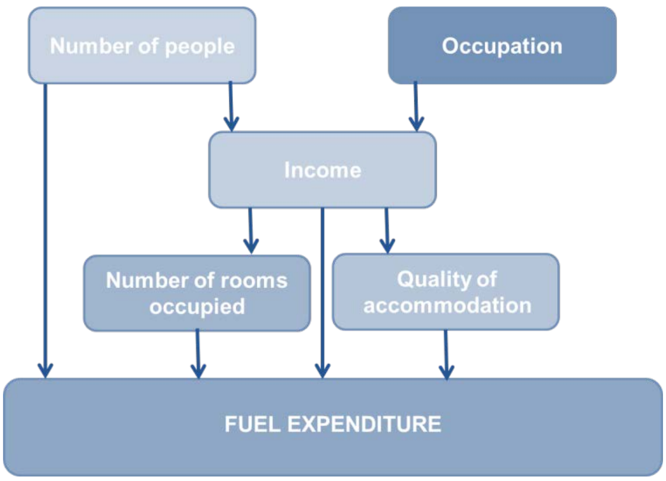


Figure 2.3 Rose (1989) relationship of socioeconomic factors relating to financial expenditure on fuel

Energy behaviour can also be linked with personal values (Mirosa, 2011). However the issue of how prolonged these behaviours last for is hard to state without prolonged monitoring. Van Dam (2010) found that the levels of energy savings originally made notably decreased after only a few months.

Occupant behaviour is a key way of assessing whether the use of digital controls will save energy in the long run as Gill (2010) was able to account behaviour to be responsible for 51% of heating energy variation, 37% of electricity variation and 11% water consumption variation within similar dwelling types so behaviour does play an important part in occupants heating behaviours. However, as Stevenson and Rijal (2010) highlights, how occupant behaviour is measured is something that needs to be evaluated and potentially use of new methods such as video analysis, activity logging and/or analysis of information provided to the occupant needs to be included within future research. Ultimately for this doctoral research a focus on the users' relationship with the control interface will need to be monitored/measured as this could potentially show that occupants exhibit "interactive adaptability" when new controls are installed. Interactive adaptability is seen to be when occupants adapt to new systems within their dwellings through interaction of that system which causes the occupant to adapt their usual practices to those which are required of the new system. For effective occupant adaptability of new systems it requires occupant understanding and there are various barriers to this such as hard to understand controls, rushed hand-overs resulting in occupants getting insufficient information or time to understand the systems before being left alone with them (Lowe et al, 2012). So part of this doctoral research was to assess the level of information and support given to occupants alongside the new controls during the installation within the Phase 2 study of this doctoral research.

2.3. Heating use and controls

Heating use within homes is a vital part in the occupants' comfort level and therefore subjective to occupants' own preferential comfort level. However the heating use within homes can also be impacted by the building demographics and heating system as described in Section 2.2. As heating use within homes accounts for the largest proportion of energy use, it is a key area to reduce consumption and emissions, however this will only be possible with a deeper understanding of how heating use varies within UK homes and how occupants use heating controls within their homes to gain their preferential comfort levels. Within this section, literature covering energy model predictions of heating use, current knowledge from measured heating use in homes, variety of heating controls available and the use of heating controls in homes is presented.

2.3.1 Model predictions of energy use

Energy savings due to energy efficiency improvements, including the installation of new heating controls is extremely hard to see due to the complex nature of energy use in homes, particularly the variations within the three factors previously mentioned: building fabric, heating system and the occupants. This is further complicated by a lack of substantial data on energy use before and after any improvements. Therefore the use of energy model predictions is often used within studies to determine the impact of new energy efficiency improvements or policies aimed at reducing emissions. Many studies rely on modelling heating use within homes as part of investigating energy use as a whole and typically these models use standard assumptions regarding heating use patterns within homes.

To assess the energy efficiency within UK homes often the household characteristics are inputted into a RdSAP calculation, which is where the household characteristics are fed into an energy model using a BREDEM (Building Research Establishment's Domestic Energy Model) adaptation. The BREDEM model has been used in various studies which have developed energy models including BREHOMES, Johnston's, UKDCM, DECard and CDEM (Kavgic et al, 2010). The energy demand calculation in BREDEM is influenced by three main categories: the size of dwelling, the amount of heat energy lost and the amount of fuel required reaching the heat and electricity needs (Weiner, 2009). As the model uses an average dwelling this also means that a set of standard assumptions are used based on the fact that the model does not know the occupant or temperature difference between inside and outside or the heating schedules, therefore this assumption is often called the standard occupancy. In fact the BREDEM model estimates the number of occupants per dwelling based on the floor area, and the number of occupants then determines the energy required for hot water and lighting within the calculation (BRE, 2010).

BREDEM assumes a heating pattern of 9 hours per day, with a different heating demand within bedrooms. Figure 2.4 represents the heating schedule for both zones during the weekdays, where zone 1 has a demand temperature of 21^{o}C for the 9 hours and zone 2 has a demand temperature of 18^{o}C for 7 hours. Figure 2.5 represents the heating schedule in BREDEM used for weekends, which shows that zone 1 increasing its heating period to 16 hours of the day but the demand temperatures remain the same.

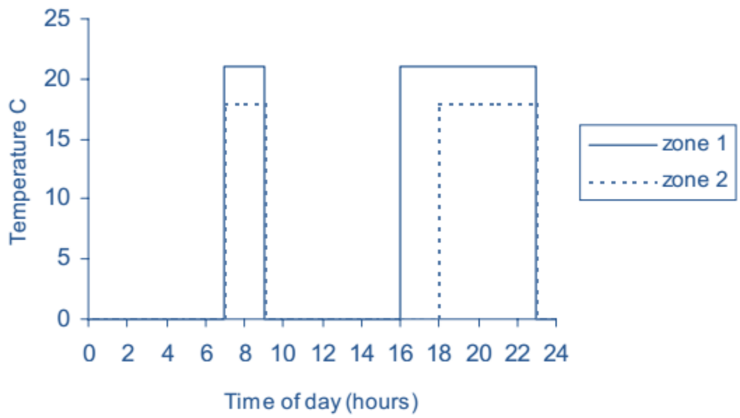


Figure 2.4 BREDEM weekday heating pattern (Anderson, 2002)

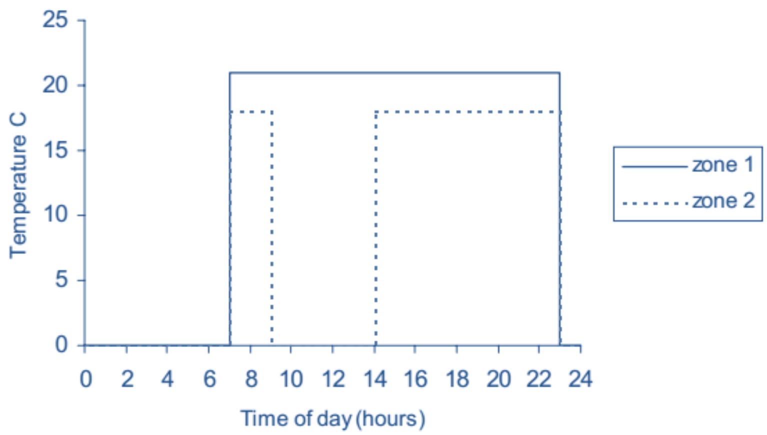


Figure 2.5 BREDEM weekend heating pattern (Anderson, 2002)

BREDEM is fundamentally a two zone model which allows for various inputs of building characteristics to be included. BREDEM-12 allows the user to also insert information about demand temperatures for each zone and length of heating periods but if the information is not inputted then the standard occupancy is used as default. Zone 1 within BREDEM represents the main living area of a property which is taken to be heated to a higher temperature than zone 2, which represents the rest of the dwelling. Zone 2 can be calculated as having full, partial or no heating.

However the assumptions made within energy models are just recommendations for the heating system use and although different set-point temperatures can be inputted with many models they do not take into account variations within heating use across households such as different set-points, different durations of heating use, different heating periods or any manual use. Therefore it is important that studies measure heating use within homes to access just how appropriate the energy model assumptions are for calculating energy savings from new heating control technologies to truly know what impact new controls may have on reducing domestic energy use and emissions. This is shown by Firth et al (2010) identifying that the heating demand temperature within domestic building calculations has a significant influence on the calculated energy use and emissions savings by reporting that every 1% increase in the demanded temperature equates to a 1.55% increase in the average CO_2 emission of that dwelling. The findings from the EFUS study (BRE, 2013b) also suggest some discrepancies between energy model assumptions and measurements with the difference in temperature between zone 1 and zone 2 being larger within the model assumptions to those recorded with an average difference of only 0.6^{o}C found from measured temperatures. The EFUS study also failed to observe the same level of difference in temperatures between weekdays and weekends as assumed by models.

2.3.2 Studies involving measurement

In recent years there have been a number of large scale projects which have focused on energy use within the domestic sector as well as the EFUS study including 4M: Measurement, Modelling, Mapping and Management (EPSRC Grant: EP/F0007604/1), LEEDR: Low Effort Energy Demand Reduction (EPSRC Grant: EP/I000267/1), REFIT: Personalised Retrofit Decision Support Tools for UK Homes using Smart Home Technology (EPSRC Grant: EP/K002457/1), CALEBRE: Consumer-Appealing Low Energy technologies for Building Retrofitting (EPSRC Grant: EP/G000387/1) and CaRB: Carbon Reduction in Buildings (EPSRC Grant: GR/S94377/01). All of these studies will have inherently experienced difficulties due to the uncertainty of measuring energy use within the domestic sector which can often be a highly uncontrollable environment. Buswell (2013) suggests that a pragmatic approach should be taken to evaluate the uncertainties which may come about from different methods of monitoring energy use and the monitoring equipment used within whole household energy studies. Therefore, the area of energy monitoring in real world environments currently benefits from these larger projects identifying issues and uncertainties from energy measurements so that future studies can learn from these issues and develop on methods and measurements.

2.3.2.1 Internal temperatures

Besides from the heating system itself within UK homes, heating can differ between homes due to the temperature which is being demanded within each home differing. There have been a number of studies looking into temperatures within UK homes with the majority focusing on wintertime temperatures, effectively gaining internal temperature averages during a period where it is expected to have extensive space heating demand. However, as mentioned previously, many studies use models to predict wintertime temperatures relating to differences in inputs for household characteristics such as ventilation levels and occupancy profiles, rather than taking measurements. Table 2.2 summarises the main studies which have been carried out using temperature measurements to gain a better picture of UK home internal temperatures during winter months. The studies found within the literature all vary in sample size, duration of measurements and limitations to findings.

Table 2.2 Measured internal temperature studies for UK homes

Author	Year	Focus	No. of homes	Duration	Specifics
Hunt, Gidman	1982	National field survey	901	Feb – March 1978	Spot measurements on single occasions in each room
Oreszczyn et al	2006	Fuel poor homes	1600	2-4 weeks	Half hour measurements – living room and bedroom over two winters
Summerfield et al	2007	Low-energy homes	14	2 years	Two years monitoring
Shipworth et al	2010	CaRB study	427	6 months July 07 – Feb 08	Living room and main bedroom measurements
Yohanis et al	2010	Northern Ireland households	25	1 year Feb 04 – Jan 05	Bedroom, Living room, Kitchen and Hall measurements
Kavgic et al	2012	Belgrade urban dwellings	96	1 year 2009-2010	Living room and bedroom measurements
Kane et al	2015	4M study, Leicester	469	Measured between Dec 2009 and Feb 2010	Living room and bedroom measurements
BRE	2013b	Energy Follow Up Survey 2011– temperature monitoring survey	823	Data collected during Feb 2011 – Jan 2012 (Heating season Oct-April)	Living room, main bedroom and hallway

Research on internal UK temperatures has been reported for many years but Vadodaria et al (2014) highlights that many of the early studies focused on the temperatures in homes of the elderly due to awareness of temperature related health risks. Many of the early studies were therefore indoor temperature surveys within the homes of elderly participants such as that of Collins (1986) which reports finding ranges of 3-14^{o}C in temperature variation between living rooms and bedrooms within substandard dwellings during 1969. Fox et al (1973) reports the first large scale study with a sample of 1020 elderly participants across various UK locations. However this study was focused on measuring the body temperature of participants and the measured indoor temperatures recorded were to put the participant's body temperature in relation to the environmental temperature. Fox et al (1973) reports an average on 16.2^{o}C for the living room temperature across their sample. Hunt and Gidman's study (Hunt and Gidman, 1982) was one of the first extensive studies specifically investigating UK domestic temperatures and covered a range of geographical locations, dwelling types and occupancy patterns. However due to the scale of the study and cost implication of measurements it meant that they only took spot dry-bulb measurements in each room of the dwelling and a wet-bulb measurement in the room where the interview was carried out in as part of the study. This means that the study does not consider the variation of temperatures through time. Yohanis et al study into annual variations of temperatures (Yohanis, 2010) measured temperatures in four rooms within each home during one year as it was a much smaller sample size compared to Hunt. However even though the study measured temperatures at 30 minute intervals over a year the results are presented as banded groups due to their average temperature relating to proposed energy behaviour – for example those households which maintain a certain temperature level throughout the year are summarised as having prudent household energy behaviour.

Kane et al (2015) took a socio-technical approach to investigating internal temperatures within UK homes. They reported findings based on a study of 469 homes with temperature monitoring and an in-depth survey. The temperatures of the living room and main bedroom were measured every hour for a total of 90 days covering a winter period of December to February. The analysis of temperature data was carried out on a total of 249 homes after removing those that were identified to have had either: a missing sensor, been in range of direct sunlight, if moved during monitoring period, both placed in the same location, placed in an unheated space, covered over therefore not recording temperature swings or if there was an error with the timestamp of the sensor. This highlights many of the potential issues with measured studies which rely on monitoring over a substantial time period and which rely on occupants placing and returning sensors. Kane found that the mean air temperatures recorded varied between 9.7-25.7^{o}C within living rooms and between 7.6-24.2^{o}C within the main bedrooms. The average internal temperatures from the study were 18.5^{o}C for living rooms and 17.4^{o}C in the main bedroom. However it was noted that the recorded measurements within this study occurred during a much colder winter than average.

The EFUS study (BRE, 2013b) recorded temperatures in 823 homes in three rooms, living room, main bedroom and hallway over the course of almost a year (Feb 2011 – Jan 2012) in twenty minute intervals. It found mean winter temperatures of 19.3^{o}C in living rooms, 18.8^{o}C in hallways and 18.9^{o}C for the main bedroom. The EFUS study found that there was no significant difference in internal temperatures between weekdays and weekends. Lower average temperatures were also recorded within pre-1919 buildings as well as owner occupied properties having lower mean living room temperatures than local authority properties.

Obviously each of the studies will have limitations to their chosen methodology or what results were published, in particular the lack of published findings regarding shoulder season heating use. However these studies give a very good insight into what temperatures have been recorded already within UK homes and allows for the breadth of ‘averages’ to be observed and question just what average temperatures reflect the UK housing stock currently.

2.3.2.2 Set-Point temperatures

No studies were found of measured demanded set-point temperatures within the literature. Those that did report set-point temperatures were based on occupants' self-reported demanded temperatures and as such could be influenced by the occupants' desire to meet certain expectations. However there have been a couple of studies which have estimated demanded set-point temperatures based on internal temperature measurements. Kane et al (2015) calculated a mean demand temperature of 20.9^{o}C based upon average achieved internal temperatures. Huebner et al (2013) report an average demand temperature of 20.6^{o}C whilst Shipworth et al (2010) report an average thermostat temperature of 21.2^{o}C. The EFUS (BRE, 2013b) report mean achieved temperatures of 20.2^{o}C for living rooms and combined the main bedroom and hallway to achieve a mean achieved temperature of 19.1^{o}C, which would represent zone 2 within the BREDEM energy model. Since often thermostats are located within hallways the zone 2 achieved a mean air temperature lower than the model assumed demand temperature of 21^{o}C.

These studies assumed the set-point temperatures based on measurements of internal temperatures within living rooms and bedrooms, however as previously mentioned, often thermostats tend to be located within hallways. Living rooms commonly have sources of secondary heating also, therefore the average assumed set-point temperature could be influenced by occupants using these additional heat sources. Shipworth et al (2010) report a significant difference between the estimated set-point temperature calculated and the occupant reported set-point temperature. Therefore there is an obvious need for research which reports demanded set-point temperature measurements.

2.3.2.3 Heating periods and durations

Similar to set-point temperature research there is currently no literature on measured heating period durations other than estimates taken from internal temperature measurements. As presented earlier, energy model predictions based on a BREDEM model assume two periods of heating for weekdays and one for weekends. Within the EFUS study (BRE, 2013b) it was found that 77% reported using two periods of heating per day, and about 14% reported one period, with 9% using multiple heating periods. The study also found little difference between reported use on weekdays and weekends. Kane et al (2015) report that 51% of sample households were heated for two periods each day and 33% were heated for only one period per day. The heating periods were recorded through visual inspection of the internal temperature traces, which meant that for some of the sample households it was not possible to identify a pattern within their heating periods due to irregular temperature patterns, leading to the assumption that these households may have regular occupant interaction with the heating system or it is often manually overridden.

Kane used similar methods of identifying the heating duration as was used by Shipworth et al (2010) by calculating the average number of heating hours by identifying increases in internal temperatures. However Kane reported inconsistent heating times via this method therefore relied on a method of identifying the first hour where the heating was observed to be on more than 10% of the time, similarly the end time was taken to be the last hour where more than 10% of the days suggested the heating to still be on at. The analysis found median time periods of 7am-11pm for one heating period patterns and 6-9am/3-10pm for two period heating patterns. This meant an average of 15 hours of heating in single heating period households and 10 hours of heating in those exhibiting a double heating period pattern. The overall heating duration average was 12.6 hours, with a range of 4-22 hours recorded within the sample.

The EFUS study (BRE, 2013a) found mean total heating durations as 8 hours 15 minutes on weekdays and 8 hours 39 minutes on weekends. However these values varied significantly. Households which reported using their heating for one daily heating period averaged 10 hours 24 minutes on weekdays and 10 hours 51 minutes on weekends, with this mainly occurring during 7am to 10pm. Those which reported two heating periods averaged at 6 hours 45 minutes on weekdays and 7 hours 14 minutes on weekends, with peaks appearing between 6am-9am and 4pm-10pm. The study found that although heating durations were very similar between weekdays and weekends, the heating was typically switched on slightly later on weekends.

Shipworth et al (2010) estimated weekday heating durations to total 8.2 hours and 8.4 hours on weekends, however also reported a difference between the calculated heating durations and those reported by the occupants. Huebner et al (2013) report finding much shorter heating durations that those assumed by energy models and found lower internal temperatures to those assumed during heating periods by energy models. Similar to Shipworth et al (2010), Huebner et al (2013) found little variation between the heating period durations on weekdays and weekends, a difference of only 45 minutes. Huebner et al also report differences to energy model assumptions of a two-peaked heating pattern for weekdays with the findings showing the morning heating period to be colder than the evening period. This is in line with Kane et al's findings that the internal temperature increases throughout the day therefore the second heating period is typically warmer than the first heating period. Huebner et al then expands on this work in 2015 by use of cluster analysis to identify four types of temperature profiles within homes (Huebner, 2015), disputing the energy model assumption of one pattern fits all homes. These four clusters included steady rise, flat line, two peak and steep rise. This analysis found that only 40% of the sample households exhibited the BREDEM assumption of a bimodal temperature pattern from two periods of active heating daily.

2.3.2.4 Zones of heating use

There has been little evidence found within literature on zonal heating preferences from measurements. It is generally believed that bedrooms are heated to a lesser extent to the main living areas of dwelling, which is why many studies measure both living room and bedroom temperatures as this is seen to give a better indication to an average temperature estimate for the whole dwelling (EST, 2006). However many studies have shown that these lesser temperatures are due to preferences of cooler temperatures for spaces used for sleeping. It has been shown that to be comfortable in bedrooms they have to exhibit lower temperature ranges of less than 5^{o}C variation as anything above this range can be seen as excessive and cause disturbance to sleep patterns (Evans, 2003). Other areas of households which can often exhibit lower temperatures are spaces such as hallways and staircases which tend to have low occupied periods therefore expectations are often flexible and occupants tend to have a high activity level whilst in these spaces (Evans, 2003).

There does seem to be a move within the domestic sector to move away from whole household heating. The desire to reduce energy by reducing the room temperature of those rooms not being used has been shown with 76% of a surveyed sample saying they attempted to try and keep unused rooms at a cooler temperature (DECC, 2013c). This normally involves turning radiators within rooms used less often to a lower setting or off completely. This however will be impacted by occupants' desire to save energy and by how enthusiastic they are at interacting with their controls to change settings on numerous occasions.

2.3.3 Heating controls

There are six common methods for controlling heating use within homes: built in boiler controls, a timer, a room thermostat, a programmer, thermostatic radiator valves (TRVs) and smart thermostats (Knight, n.d). The type of control and number of control options varies from household to household, dependent on the heating system, building age and the occupants' interest in having up-to-date control strategies within their home.

Built in boiler controls typically include an on/off switch giving occupants the opportunity to switch their heating off at the boiler itself. They may also have a water temperature control allowing occupants to adjust the temperature of the water being pumped to the radiators from the boiler and may have controls to adjust the temperature of the water reaching the taps within the property (Knight, n.d). Some boilers also have a built in timer which typically has a clock interface with individual pins which can be pushed in or pulled out to set the desired times for when the boiler should be active. Separate timer controls turn the boiler on and off at defined times set by the occupants. A timer enables occupants to set a heating pattern with defined on and off times which repeat every day (EST, n.d, b). Occupants often set times to provide heat in the morning and again, for a longer period, in the evening; although modern timers offer more flexibility, enabling, for example different weekday and weekend heating schedules. Thus central heating systems operate automatically such that, without occupant intervention, a continuous regular on/off pattern of heating is established. Most timers enable occupants to override the set-times in order turn on or off the heating at the press of a button (for example when returning home early or leaving early). Similarly, the whole system can be switched on or off relatively easily at the timer, for example at the start and end of the winter heating period or during holidays.

Room thermostats operate the heating system by sensing the air temperature within the room and switching the heating on whenever the sensed air temperature drops below the desired set-point temperature. Similarly it then switches the heating off once the temperature is sensed to have reached the desired set-point temperature (EST, n.d, b). Due to the need to sense the air temperature room thermostats need to be located where they can have a free flow of air reach it and not be influenced by heat sources and located in an appropriate location as the room thermostat determines the heating for the whole household.

Programmable room thermostats include a timer function to allow occupants the opportunity to set their desired times for when the occupants want the heating to be on and off, but unlike a timer, programmable room thermostats allow occupants to also demand a temperature that they prefer. Programmable room thermostats are available in many different designs and have different levels of functionality, with some giving occupants the ability to set different heating schedules and temperatures for weekdays, weekends or individual days to suit the occupants' lifestyle. Some additional functions on programmable room thermostats include boost functions, override functions and holiday settings (Knight, n.d.).

Most heating controls determine the whole household heating use based on one thermostat location however the individual rooms/spaces within a dwelling can be adjusted to the preferred temperature for its use with thermostatic radiator valves (TRVs). TRVs have a rotating head, which occupants can use to set the desired room temperature. TRVs, similar to room thermostats, sense the air around them and from this regulate the hot water flow within the radiator that they are attached to as needed. TRVs allow occupants the opportunity to set individual rooms to different thermal environments depending on preferences and use of the room. Unlike the room thermostat, TRVs do not cause the boiler to switch on or off depending on the air temperature being sensed.

Smart thermostats are typically digital heating controls with additionally functionalities to those of programmable room thermostats (EST, n.d, b). The basic smart thermostat is one which gives occupants remote access of their heating through mobile phone apps or online. This allows occupants to react to changing circumstances which may mean they want to change their heating settings, such as being delayed or going to arrive home earlier than first thought. Other smart thermostats can adapt to external weather conditions automatically and can be described as "learning" from previous heating requirements. Other smart thermostats are those which allow occupants to treat their home as individual spaces instead of the standard single zone heating. These controls allow occupants to set different temperatures and schedules for different rooms, essentially combining the functions of programmable room thermostats and TRVs on one control interface. This is sometimes referred to as zonal control. Some zonal control systems also incorporate programmable TRVs. Programmable TRVs replace existing radiator valve heads with a battery operated TRV head typically with a digital interface which allows occupants to set a desired temperature and on/off times for individual rooms. Therefore allowing occupants to only heat desired spaces at specific times within their home and as such potentially save energy in comparison to heating the whole dwelling.

2.3.3.1 Savings from heating controls

New heating controls may not be the most obvious thought for a household when looking for potential ways to improve energy efficiency in their home. Focus in recent years has been more on insulation measures such as cavity wall or loft insulation, therefore public awareness of such measures is a lot higher. However, the Green Deal, the last large scale energy efficiency improvement program within the UK, listed heating controls as one of the approved measures which could receive funding towards as a means of improving energy efficiency. Shipworth et al (2010) highlighted the saving potential reported by the Energy Saving Trust that correct heating controls such as having a timer, room thermostat and thermostatic radiator valves could save 17% of a typical heating bill, however noted that there was no evidence given for how this saving was calculated. Shipworth et al (2010) also emphasised the lack of evidence from research into the energy and cost saving potential of heating controls prior to their research. SAP 2005 adds the assumption that thermostatic controls being added to a central heating system would reduce the living room temperature by 0.6^{o}C helping to reduce the energy consumption within a home (BRE, 2008). The Energy Saving Trust website (EST, 2013) recommends various thermostat control options and makes a point of stating the benefit of having proper controls regardless of boiler age to help save energy and money. Table 2.3 shows the level of savings they would expect in a typical three-bedroom semi-detached gas central heating home. Similar to that reported by Shipworth et al (2010) no evidence is given with these figures as to how the savings were calculated. However the author uncovered details regarding EST calculations stating that calculations are based on modelled predictions or field trials of products. The heating calculations are based on a SAP model using the assumption that 21°C is used for the living area and 18°C for the remaining areas with a central UK location. The three bed semi-detached house has a floor area of $89m^3$, with $17m^2$ window area, 94% double glazing, a roof U-value of 0.34 W/m^2K and an exposed wall U-value of 1.42 W/m^2K. Although it mentions making regular adjustments for energy prices (EST, 2016), it could be assumed that the modelled dwelling assumptions and temperature assumptions were the same for the saving potentials reported in 2013.

Table 2.3 Potential emissions and money savings from installing new controls in a 3-bed semi-detached home(EST, 2013)

Measure Installed	CO_2 saved/ per year	Money saved £/ per year
Room thermostat (if one not already there)	280 kg	70
Hot water tank thermostat	130 kg	30
Turning room thermostat down by one degree	260 kg	65

Recent research has shown that the use of smart heating control technologies such as those which offer zonal control could save a potential 12% of annual heating energy consumption within an un-furbished home (Beizaee, 2015). Potential energy consumption savings of 25% are possible from new technologies, including new space and hot water controls, however occupants need to be invested in the new technologies and use them effectively for this to be reflected (Cosar-Jorda et al, 2013). Therefore it is important to understand how occupants interact with heating controls to see if they will adapt to new heating control technologies well.

2.3.3.2 Use of heating controls

Upgrading the domestic sector so that homes have both a room thermostat and thermostatic radiator valves has the potential to reduce the domestic sectors emissions by 8% (Consumer Focus, 2012). However potential energy savings and emission reductions are only possible if occupants are able to use them effectively. Shipworth et al (2010) reported that simply adding controls does not lead to a reduction in average maximum recorded temperatures within living rooms, however the potential to save energy is there if new heating control technologies are both appealing to and usable by occupants. Therefore it is important to understand in detail the ways in which occupants interact with controls so that new technologies can meet users' needs in a way which is energy efficient. Table 2.4 shows a summary of thermostat studies found during the literature review and the subsequent findings regarding the level of interaction found.

Shipworth (2011) is the only selected study which analysed UK data however it is worth noting that it was a comparison of reported thermostat settings not measured settings, which, as Vine and Barnes (1989) show, there can be substantial differences between the reported values and measured thermostat settings. It should also be noted that the comparison between the two different surveys in Shipworth's work do not cover the same geographical location and only two of the 2007 sample met the same geographical and energy consumption criteria as shown in the 1984 sample. There is an obvious lack of UK based studies which do not only rely on reported values from occupants. The use of heating controls can reflect occupants' lifestyles, understanding of their heating system and their heating preferences (Consumer Focus, 2012). Rathouse & Young (2004) identified that comfort and cost can influence occupants' use of their controls, highlighting the importance of understanding the drivers behind occupants' use of controls in relation to how occupants use the controls.

Table 2.4 Summary of thermostat studies found within literature

Author	Year	Location	Building types	Measurement methods	Findings
Karjalainen	2009	Finland	Domestic properties and offices	Quantitative interview survey (telephone)	3094 out of 34935 phone calls took part in the study <20% of them used their thermostat weekly in domestic properties ~ 60% said they do not use it at all or use it less than once a month in homes
Brown et al	2013	France	Office building	Randomized controlled experiment	Decreasing the default thermostat setting by more than 2˚C caused the office workers to override the default to an increased temperature (which often exceeded the original default) 93 occupied offices studied
Vine and Barnes	1989	Pacific North-west	Residential	Survey and temperature measurements	The reported thermostat settings were on average 2˚F cooler than the recorded measurements. The properties which were classed as being more energy efficient tended to have smaller observed differences in reported and measured values. Managed to classify some of the differences to be caused by energy behaviour of the occupants in some cases.
Karjalainen	2007a	Finland	Residential, offices and University	Quantitative interview survey and controlled experiments	Males tend to use thermostats in households more frequently than females indicating a gender difference. Females tended to record a more thermal dissatisfaction.
Shipworth	2011	England	Residential	Repeated cross-sectional social survey (INT84 and CARB) and statistical analysis	Data gained in 1984 and 2007. No statistical significance was found between comparing the reported thermostat settings between 1984 and 2007. Reported mean setting in 1984 was 0.3˚C cooler than 2007
Meier et al	2011	US	Residential	On-line survey, interviews and laboratory experiments	~ 90% of those surveyed said they rarely/never adjusted their thermostat settings to separate difference between weekday and weekend schedules. The majority of the sample indicated that they chose to set their thermostats manually than use programmable functions.

Investigating heating control use can often be limited by the research method. Self-reported heating use behaviours could fail to identify when controls are being used in a non-efficient way or differently to that of the designed use (NHBC, 2011) especially if the occupants are unaware of the designed use of the controls. Focus groups (NHBC, 2012 and Shipworth, 2000) and ethnographic methods typically identify when controls are not being used as designed or identify any lack of understanding regarding the use and/or design of the controls, and often these methods uncover more detail than survey use could. Ethnographic approaches can provide rich data on heating control use within homes however these studies can be influenced by occupants' being overly aware of their use of controls being observed (Combe, 2011 and Meier 2010). However, these investigations also typically occur within controlled and unfamiliar environments to the occupants, use controls which occupants are not familiar with, and typically occur during a short monitoring period or even one-off measurements. Therefore there is a lack of knowledge regarding the longitudinal use of controls where occupants may become more familiar with the controls and as such may change their use of them.

The use of heating controls themselves can be hindered by many factors including unsuitable locations, illegible interfaces, being too difficult for occupants to understand and use, lack of support documents/advice for occupants and often a lack of an intuitive display (Consumer Focus, 2012). When these issues occur the occupant cannot use the controls as designed or occupants will use them in an ineffective manner. This could be detrimental to new heating controls saving energy and reducing emissions within the domestic sector. However improved controls can also lead to take back with occupants, so it is important to understand what type of heating control technology best suits each heating user type.

The design of the heating control is a vital part in how occupants use the control and the inclusivity of heating controls can be impacted due to visual aspects of the controls and the dexterity required. This has been shown by studies reporting large variations with the use of controls due to difficulties from buttons, dials or tappets on the controls, ranging from their size, ease to press, located too close to other features (Combe, 2011, Ricability, 2004, Rathouse & Young, 2004, Meier, 2010 and Caird, 2007). Occupants may find difficulties from hard to read markings or display screens which could lead to occupant errors when using the controls.

The location of heating controls impacts their use with research showing that occupants use of their controls can often be made difficult and more challenging when controls are either too high or too low, or if they are installed out of the occupant's reach, for instance, shut away in cupboards which are not easily accessed. Occupants' also report that often they avoid adjusting thermostatic radiator valves due to them being located too low (Rathouse & Young, 2004), this is particularly the case for occupants with mobility issues or those who are elderly. Often however occupants do not have much to say regarding the location of controls as these are often decided by installers. The installers have been identified as being a key factor to occupants understanding of their heating system and controls due to the information they provide occupants regarding the new system or controls (Wade, 2016).

The occupants' understanding of the controls is influenced by the design of the control itself and how intuitive it is to use but also by the information provided to the occupants about the control, such as the user manual or any help guides. Various studies have identified issues surrounding the information provided to occupants as being overly technical and designed more for professionals, too detailed or 'wordy', not visual enough, not procedural, generic and therefore occupants found them not relatable to them and time consuming (Meier, 2010). Often occupants misplace any supporting documentation, making it even harder for occupants to understand how to use their controls or change any settings. However, occupants often report finding it easy to use heating controls when in reality they are using the controls in a way that was not intended or the way the controls were designed to be used (Scottish Government, 2007), this highlights the importance in the intended use of controls being easy for occupants to understand as well as the design of the control themselves.

Occupants' attitude towards new heating controls can also impact the way in which the controls are used. Research has shown that occupants do not necessarily link the environmental benefits of new improved heating controls as a direct impact (DCLG, 2010) and often the increased wellbeing and comfort, money savings, improved energy efficiency and improved control are the driving forces for occupants to decide on installing new heating controls. However, new controls are often only thought about when the heating system requires a new boiler and therefore new controls are installed alongside the installation. Some occupants see installing new heating controls as more of a hassle due to the installation process and often believe that any potential savings are not worth the installation process and cost of buying the new controls (Consumer Focus, 2012).

These findings show that the use of heating controls is influenced by many factors and areas of further research have been identified. However ultimately the occupant using the heating controls has the greatest influence on how the controls are used and this can be influenced by the heating behaviours of that individual.

2.4. Heating behaviours

Influences on occupants which have an impact on energy use within homes have been mentioned previously within section 2.2.3, however most of these studies look at the energy use within homes as a whole and do not focus on heating behaviours specifically. Wei et al (2014) carried out a review of literature available of factors influencing occupant's space heating behaviours and identify a total of 27 influencing factors. These factors were classified into four categories: environmental factors, building and system related factors, occupant related factors and other factors. The occupant factors included many demographic influences such as age, sex and gender; however the key driver for space-heating use can be seen to be impacted by the occupants' own thermal sensation (Wei et al, 2014). The occupants' heating behaviours have also been identified within this literature review as being influenced by the usability of the heating system itself and the occupants' understanding of how the complex system responds to their actions as well as whether occupants use adaptive actions to provide additional comfort on top of use of the heating system. Attempts have been made to identify heating behaviour types within the literature but only one refers to a UK sample (Rubens and Knowles, 2013) discussed further in section 2.4.5. Therefore indicating that understanding more regarding heating behaviours within UK homes is of key interest to the area of research on heating use within the UK.

2.4.1 Thermal comfort

Energy behaviour in homes regarding heating is ultimately influenced significantly by the occupants' personal comfort level as people generally do not want to be uncomfortable within their own home. However the temperatures that occupants class to be comfortable vary as these are influenced by the thermal comfort level of each occupant.

Thermal comfort is essentially a measure of a person's psychological state of mind concerning if they feel hot or cold (BSI, 2006). To define thermal comfort, a number of factors must be considered to achieve a measurement, see Table 2.5 for the various factors.

Table 2.5 Six basic factors required for thermal comfort measurement (HSE, 2016).

Factor	Factor type	Measurement description
Air temperature	Environmental	Temperature of air surrounding body
Radiant temperature	Environmental	Temperature of radiant heat from a warm object e.g. sun, fire, cookers, oven etc.
Air velocity	Environmental	Speed of air moving across a person
Humidity	Environmental	Resultant amount of water in air after evaporation of water once heated
Clothing insulation	Personal	Insulation effect of persons clothing level
Metabolic heat	Personal	Heat produced inside a person's body during a physical activity

However often indoor air temperature alone is often used as a measurement of thermal comfort. Due to this there are various 'standards' which are mentioned as being representative of an environment which is seen to be comfortable and no health risk to occupants. The Building Research Establishment (BRE) states a temperature range of 18-21°C during winter for living rooms (BRE, 1995). This has also been adapted by the UK Government to create the Standard Assessment Procedure (SAP) when calculating the energy efficiency of a building which states an adequate temperature for living rooms is 21°C with the remaining rooms within the dwelling being 18°C (BRE, 2010). The Chartered Institution of Building Services Engineers (CIBSE) state that a temperature range of 19-20°C should be used in winter for dwellings which have continuous occupancy and for those with transient occupancy, a temperature range of 16-18°C should be used (CIBSE, 2006). Many studies have referenced the World Health Organisation (WHO) recommendation that heating a home to an adequate standard of warmth means living rooms should be heated to a temperature of 21°C and other occupied rooms to a temperature of 18°C, to ensure and promote the health and wellbeing of occupants (Kane et al, 2015, Jones et al, 2016, Vadodaria et al, 2014, Collins, 1986, Jevons et al, 2016). However a review by the WHO into housing, energy and thermal comfort in 2007 identified that the recommendation of 18-22°C as a safe temperature range for indoor environments was weak and that the evidence and awareness of appropriate recommendations needed to be strengthened (WHO, 2007). When tracing the source of this temperature range recommendations can be found dating back to 1982 when a WHO working group reported on the health impacts of indoor housing temperature for the elderly found that temperatures ranging between 18-24°C posed no risk to healthy sedentary people (WHO, 1987). Ormandy and Ezratty (2012) reports that the WHO set an initial range of 15-25°C back in 1968 and although it is not clear why it was then later changed to 18-24°C it is noted that the latter recommendation was supported by evidence and has now since been used in reference to thermal comfort temperature ranges.

Fanger (1970) proposed an equation for calculating the predicted mean vote (PMV) using the factors identified in Table 2.5. This equation has since become part of various international standards relating to thermal comfort. An occupants' thermal sensation can also be measured using the seven point ASHRAE thermal sensation scale. This seven point scale can be seen in Figure 2.6.

+3	**+2**	**+1**	**0**	**-1**	**-2**	**-3**
HOT	WARM	SLIGHTLY WARM	NEUTRAL	SLIGHTLY COOL	COOL	COLD

Figure 2.6 ASHRAE seven point thermal sensation scale

The neutral or 0 interval on the thermal sensation scale is often referred to as the optimum temperature. However studies have found that there are discrepancies between PMV calculations and reported thermal sensation votes. Oseland (1995) report that discrepancies come from the fact that the PMV model is based on "artificial environments of climate chambers out of context with usual environmental settings" resulting in contextual effects. This was further seen in Oseland's results showing very poor correlations between thermal sensation votes recorded and those which were predicted, highlighting the issue of difference of peoples' perceptions of thermal sensations.

Devine-Wright et al (2014) reports that peoples' perception of thermal comfort can also be influenced by a feeling of cosiness where the feeling of warmth experienced by occupants is as much down to psychological feelings as physiological feelings. Devine-Wright et al found that occupants seek a visible glow alongside warmth to ensure a state of thermal comfort satisfaction. The use of secondary heating sources such as wood-burning stoves incited positive emotions and have connections to sociability with occupants particularly during seasonal holidays or with visitors. Therefore thermal comfort may also be influenced by the participants' value of cosiness and expectation of a visible glow from their use of heating.

Questions raised around what is perceived as comfortable include: What temperatures do people find comfortable? Do perceptions of comfortable temperatures change with time? (Darby, 2005). In particular the latter question brings up issues surrounding people's sensitivity to temperature, particularly older people, children and those that are ill. What are our own ideas relating to comfort and use of heating? Do we dress to fit our expectations of comfort within homes or do we expect the thermal environment to be at a suitable level regardless of additional effort (e.g. changing clothing levels)? These sorts of questions relate to how adaptive people are within their homes to achieve a comfortable thermal sensation.

2.4.2 Adaptive actions

Adaptive behaviours can come in various forms (Karjalainen, 2009), such as the addition or removal of layers of clothing, opening or closing windows to allow cool air in or to keep warm air inside, occupants using blinds to shade rooms from solar rays. Occupants can also improve their comfort from more active actions such as drinking a hot or cold beverage or moving to a different part of a dwelling. All of these adaptive actions will undoubtedly impact on the occupant's use of their heating controls therefore it will be vital to know how adaptive the households within this doctoral research are, to determine the adaptive opportunity in their homes.

Adaptive behaviours can also be investigated through measuring adaptive thermal comfort (ATC), an alternative approach to understanding thermal comfort where people are considered to be active participants with their ambient thermal environment, moving away from the conventional heat balance approach where people are seen as being passive participants. ATC first came about as a reaction to the oil crisis of 1973 where it became apparent that people are more likely to respond differently if a situation causes them a source of discomfort so that they react in a way to re-establish their comfort perceptions (Brager, 1998). ATC categorises adaption into three main types: physiological adaption (the body's response to any thermal environment changes – includes genetic adaptation and acclimatisation), psychological adaptation (adaption due to previous thermal experiences and expectations, however it is hard to evaluate due to discrepancies from thermal perception criteria), and behavioural adaptation (conscious or unconscious adaptation of behaviour in relation to thermal environment and can be classified as personal, technological or cultural behaviour adaptations). Liu et al (2012) developed a method to weight these three adaptive categories by developing a four-stratum hierarchy developed from the analytic hierarchy process where multi-criteria problems are split into both quantitative and qualitative dimensions giving a hierarchical structure. Figure 2.7 shows the thermal comfort analytic hierarchy developed by Liu which expands the conventional three adaptation categories into six subsequent categories covering indoor and outdoor environments, personal physical and thermal expectation factors, physiological parameters and environmental controls.

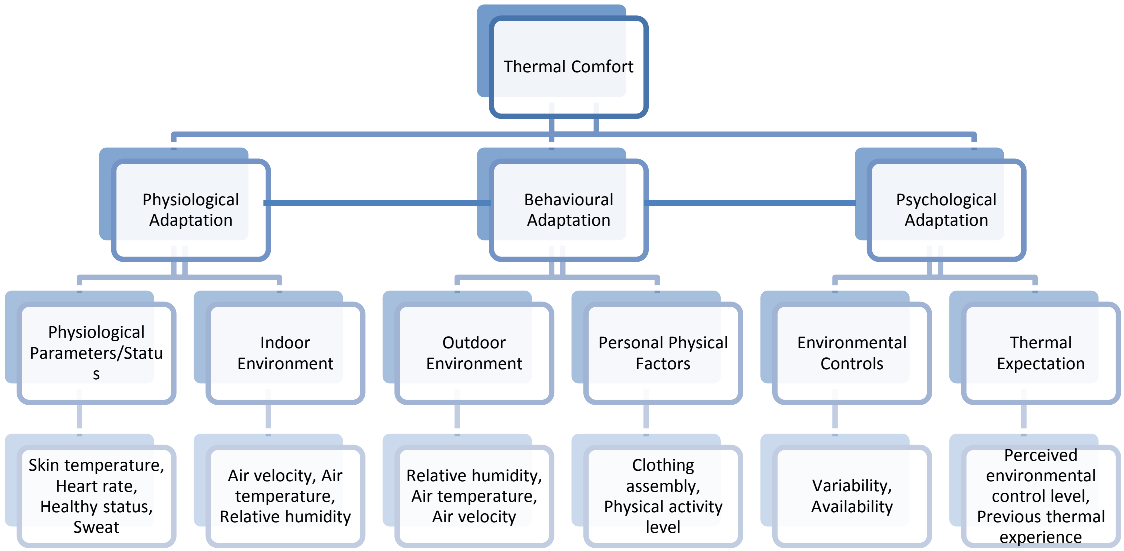


Figure 2.7 Four-stratum thermal comfort analytical hierarchy developed by Liu et al (2012)

Occupants' use of adaptive behaviour impacts their use of heating within homes and as such may result in different heating behaviours due to the driving factors behind their desire to use adaptive actions. However, it is currently unknown if specific adaptive actions are only found in certain heating user types. This doctoral research investigates adaptive actions within a sample of UK homes and therefore the drivers behind heating use and any recorded adaptive behaviours can be matched.

2.4.3 Mental models

There have been a number of researchers looking at mental models as a way of understanding energy use. Mental models as an approach has been identified as being one which can have some confusion over its exact meaning as different research domains consider them to represent different constructs (Wilson and Rutherford, 1989). It is also a method which has been around for quite a while with many examples dating back to the 1980s. Recent work by Revell and Stanton (2014) has considered the different understandings of mental models across research domains and tried to clearly outline an approach to understand occupants' mental models of their heating systems. This approach built on work by Kempton (1986) who used mental models to characterise occupants' use of thermostats into two types – the feedback theory and the valve theory. The feedback theory involves occupants seeing their thermostat as a device which senses the temperature and turns the boiler (or furnace as Kempton describes) on and off to maintain an even temperature. The valve theory is that occupants' believe the thermostat to be more of a device similar to a valve or tap in that the higher the setting the larger the rate of flow (or essentially the higher the thermostat setting the more gas or fuel the system is using).

Revell and Stanton (2014) develop this further by looking at occupants' mental models of their whole heating system and showed there to be an obvious difference between how the system is engineered to work and how occupants believe it to work. However it is worth noting that Revell and Stanton's work studied a very specific user group in that the sample was University employees/researchers who were all overseas family households therefore the disconnect between how the occupants thought their heating system worked compared to how it was engineered to work could be down to the lack of familiarity with the type of central heating systems common to the UK. This is obviously an area where work can be built upon and clearly a very active method of understanding occupants' heating use within future work. By expanding the sample demographic it may allow differences in heating control use to be characterised by how the occupants understand their controls to work in relation to the heating system as a whole. Misconceptions of complex heating systems and how they work may impact how those occupants then use their heating.

2.4.4 Usability

Currently there is little research on digital controls changing occupants' behaviours with regard to the heating practices. However, there has been extensive research in the area of occupant usability with thermostat controls and optimum interface designs. By understanding more regarding the usability of heating controls it allows for better design to save energy. Usability studies can also uncover any issues with occupants using heating controls that may limit the potential of the controls saving energy. Suggestions regarding the inclusion of feedback to occupants, increased functionalities and targeted functions to specific demographics, the design on user interfaces and even intelligent automated systems, removing much of the occupant interaction need have all been presented. Yet many of these suggestions still have issues surrounding possible user misconceptions and occupants not adapting to these new heating control technologies once installed. (Lu, 2010, Yun, 2011, Combe at al, 2012, Peffer, 2011, Rathouse & Young, 2004, Karjalainen, 2007b, Freudenthal and Mook, 2003, Sauer et al, 2009). Voice activation of thermostats has even been developed with the usability aimed at those who are disabled and may struggle to change thermostat settings due to restricted movement or sight (Carvalho, 1999). Many studies found that the effectiveness of installing programmable thermostats or feedback on effective interface displays needed to be clear for occupants to understand. Peffer (2011) reports that studies show nearly half of homes with programmable thermostats do not use the programme function. It has been reported that often the misconceptions of occupants and use of thermostats comes from not understanding how to use them, confusing operating manuals, not understanding that the thermostat is in fact not like a valve (in that the higher it is turned the faster a space will heat up) and displays being too complicated or buttons being far too small (Meier, 2011).

There has also been research into making domestic heating fully automatic (Boait & Rylatt, 2010) where the input from the occupant is simplified and the system essentially learns and adjusts time periods from patterns of hot water and electricity use and the temperature set-point is adjusted for external weather conditions and user activity levels. This level of control does have market potential, however the success may not be as the developer would hope as occupants may feel a loss of control with a fully automatic system and feel restricted to changing settings. It is also unclear how well this type of control would deal with constant variations in occupants' patterns of electricity use and level of activity. However this level of a system learning from occupants has massive potential for developing ways of encouraging users to reduce their energy consumption or even reduce temperatures slightly until an occupant feels uncomfortable and takes the action to use a temperature 'boost' – essentially finding a comfortable set-point for the occupant that may not be as high as a temperature as the occupant believes they need to be comfortable.

Guerra-Santin (2010) link households with programmable thermostats to be those which were more likely to have radiators constantly on compared to households with manual thermostats or manual radiator valves. Shipworth et al (2010) report similar findings and found that those centrally heated homes which had system controls accessible to the occupants showed no lower demand temperatures or heating duration lengths compared to homes without the system controls. Meier found that during a study of programmable thermostat use in the US that energy savings were often less than predicted or some cases resulted in increased energy use (Meier, 2011). These studies may suggest that installing digital controls may not change occupants heating behaviours, however the studies did not factor in measuring or analysing occupants' practices before and after to see whether installing these controls may change occupants heating behaviours and essentially create new heating habits.

2.4.5 Categorising heating behaviour user types

There have only been a handful of studies which have attempted to categorise user types in relation to heating use within homes. Research within the Netherlands reported five categories of behavioural patterns in relation to home temperatures and ventilation: conservers, spenders, cool, warm and average. These behavioural patterns were based on a total of 17 self-reported energy-related behaviours such as thermostat settings and occupancy (Raaij and Verhallen, 1983b). More recent work, still within the Netherlands identifies similar behavioural patterns relating to heating use behaviours. These are identified as: spenders, affluent-cool, conscious-warm, comfort and convenience-cool. The behavioural patterns are then matched with four identified user profiles: family, seniors, singles and low-income couples (Guerra-Santin, 2011). However, similar to the Raaij and Verhallen the findings were based upon survey data and therefore self-reported behaviours, with Guerra-Santin (2011) not taking the reported thermostat setting into account within the analysis due to the lack of variation across the sample. These studies however based the user types/profiles on behaviours themselves i.e. actions relating directly to heating use but did not account for the causes and influences behind these actions. Paauw et al (2009) identified four groups of potential drivers for energy consumption and/or conservation which they named: convenience/ease, conscious, costs and climate/environment from household interviews, which were then applied to different groups of household type, which neglected potential cross-overs between similar drivers within different household types.

Within the UK the Department of Energy and Climate Change (DECC) published work as part of a smarter heating controls research program, aimed at uncovering whether improved heating controls reduces energy consumption, understanding how to utilise new technologies whilst understanding the socio-technical role of heating (DECC, 2013d). As part of the research programme outputs, a report on "What people want from their heating controls" was published and reports a classification of heating behaviours within a UK sample (Rubens and Knowles, 2013). These behaviour categories are summarised in Table 2.6. This is the first work where different heating behaviours have attempted to be categorised within the UK, however the behaviour types are quite broad and the method of categorising the sample used in the study is quite vague. To identify the heating behaviours, a sliding scale method was used which included: comfort versus spend, one zone versus multiple zones, regular versus irregular routines, predictable versus unpredictable routines and self-versus others. The difference between regular/irregular routines and predictable/unpredictable routines was not made clear. The sample consisted of 43 households split between Manchester and London which both have very different external climates, dwelling types and cultural diversity. Yet there is no mention as to how the behaviour categories were split across the locations, i.e. were all ego-centric households in London or a mix etc. Out of all categories, only one was linked to household characteristics with reactors being categorised as those typically in larger, less energy efficient family homes often where the children have since moved out. Similarly to the works of Raaij and Verhallen (1983b) and Guerra-Santin (2011), this research focused on the behaviours themselves and neglected to take into consideration the influences behind these behaviours.

Table 2.6 Heating behaviour categories as reported by DECC (Rubens and Knowles, 2013)

Behaviour Type	Summary of heating behaviour
Rationers	Occupants who want to save money therefore keep their heating use to a minimum and are more likely to control their heating manually for that reason.
Ego-centric	These occupants use their heating in relation to their own comfort regardless of how others may feel and similarly to rationers most likely to control the heating manually.
Hands-off	Occupants who would rather not interact with their heating system or change regularly yet still desire their home to be warm with the option to demand different temperatures if they had to.
Planners	Occupants who think in advance about their heating needs and tried to avoid use when not needed. More likely to change their heating through the timer or thermostatic radiator valves.
Reactors	Occupants who 'react' to variations in internal and external temperatures either through changing settings on their heating controls or through use of secondary heating.

One of the objectives of this doctoral research, as mentioned in Chapter 1, was to develop a taxonomy of heating behaviour types. Although this is no longer a novel idea, the author still believes that a more detailed approach focusing on the drivers behind heating behaviours could help show that it may be far more complex than suggested with just five heating behaviour types. Therefore a taxonomy developed within this doctoral research could be seen as novel for identifying heating user types based on the drivers and/or reasons why households adopt specific heating behaviours.

2.5. Conclusions

This literature review has shown the energy research field, in particular relating to domestic energy has been focused on technical advancements and techno-economic energy saving potential studies. There has been acknowledgement of the need for more socio-technical studies, however few studies have combined both social and technical aspects, and therefore those which report occupant behaviour in homes tend to be more from the social science discipline. There is currently a lack of interdisciplinary research regarding heating use within UK homes. This literature review has identified there is a lack of information available on heating control use within UK homes and in particular the drivers for heating use and the level of interaction from occupants.

With the volume of factors influencing energy use and temperatures seen within homes, there were very few studies found during this literature search which have managed to characterise individual household heating practices. However it should be noted that this is a very active area of research and that this may change very soon as household heating has been identified as one of the main areas which could help reduce energy use within the residential sector, so in order to save energy through recommendations or actions, it is vital to understand the current heating practices of householders.

Chapter 3: Methodology

This chapter reaffirms the aim of this thesis and explains the considerations taken to shape the research in order to achieve the research aims. The chapter introduces the methodological approaches taken and explains the background to the philosophical and theoretical stance to the research.

3.1 Research purpose

3.1.1 Introduction

Research purpose has historically been described as being either to explore, to explain or to describe, though these purposes could also be classed as to understand, to develop and to discover (Marshall, 1999). Since doctoral research requires research which is novel and unique within the area of investigation in order to contribute something new to that research field, it could be argued that the purpose of all doctoral research is exploratory. As shown in the literature review, the research on occupant behaviour relating to heating use in homes is limited and a fairly new field within UK focused research. Therefore understanding how people use their heating in homes and identifying heating behaviour types, especially in relation to new heating control technologies is relatively un-researched to the level of detail and in the context to which it is presented within this thesis.

Exploration of heating use is an important and key purpose of this research from which a better understanding could help inform the design of new heating control technology and make recommendations about the assumptions currently made by energy models regarding occupant use of heating, heating durations and demand temperatures. Furthermore this doctoral research aims to go beyond just reporting heating use by looking to explain and describe heating behaviours. Layder (2012) suggests that in order to produce rigorous research it needs to "move away from the question *how* (or a description of what is happening) to *why* (an explanation or set of reasons for why this is happening)". This doctoral research has been designed in a way which attempts to uncover the 'why' relating to heating use behaviours as well as describing how people currently use their heating in UK homes.

3.1.2 Research aims and objectives

The purpose behind the research and the research questions influences the design of the research study. The research purpose or overall aim of this thesis as presented in Chapter 1 is reiterated:

To examine household space heating use and to identify the reasons behind heating use in UK homes.

It is this purpose and the context from the literature review which determined the following research questions:

1. *How do people currently heat their homes – what controls do they have and what do they use?*
2. *What are the reasons behind occupants' reported heating use?*
3. *Can heating behaviours be categorised by understanding how occupants use their heating, why occupants heat their homes in a particular way and what occupants use to control their heating?*
4. *How varied are household heating patterns regarding demand temperatures, heating period durations, household temperatures achieved and the household interaction level with heating controls?*
5. *How does heating use in UK houses evolve during seasonal shifts from autumn into winter and how does this compare with moving from winter into spring?*
6. *Do many households keep the default settings after installation of new controls?*
7. *Do new heating controls lead to a reported change in heating use for households?*
8. *Is how occupants report using their heating different to measured heating use?*
9. *How does the combination of qualitative and quantitative heating data add to the understanding of heating use?*

These research questions can be categorised by the research purpose using the four classic types of research purpose (Marshall, 1999) as shown in Table 3.1.

Table 3.1 Doctoral research questions matched with classical research purpose types

Purpose of research	Example	Doctoral research questions with this purpose
Exploratory	• To investigate little understood phenomena • To identify or discover important categories of meaning • To generate hypotheses for future research	• Q1: How do people currently heat their homes – what controls do they have and what do they use? • Q2: What are the reasons behind occupants' reported heating use? • Q5: How does heating use in UK households evolve during seasonal shifts from autumn into winter and how does this compare with moving from winter into spring? • Q8: Is how occupants report using their heating different to measured heating use? • Q9: How does the combination of qualitative and quantitative heating data add to the understanding of heating use?
Explanatory	• To explain the patterns related to the phenomena in question • To identify plausible relationships shaping the phenomena	• Q3: Can heating behaviours be categorised by understanding how occupants use their heating, why occupants heat their homes in a particular way and what occupants use to control their heating?
Descriptive	• To document and describe the phenomena of interest	• Q4: How varied are household heating patterns regarding demand temperatures, heating period durations, household temperatures achieved and the household interaction level with heating controls? • Q6: Do many households keep the default settings after installation of new controls? • Q7: Do new heating controls lead to a reported change in heating use for households?
Emancipatory	• To create opportunities and the will to engage in social action	

From these research questions the design of the research process for this thesis was determined and, as such, the relevant research questions are highlighted throughout this thesis to show clearly how parts of the study were designed and executed in relation to answering the relevant research question(s). However before any research design methodology is chosen a decision must be taken as to what perspective the research will be based on, the theory behind it and whether or not that theory is developed further through the research (Gray, 2009).

3.1.3 Philosophical stance

The philosophical stance adopted by researchers typically falls into one of two main philosophical approaches, ontology or epistemology (Ritchie, 2014). Ontology considers the nature of the social world and can be referred to as the study of being. Ontological research can take a realism position or an idealism position to it. Epistemology considers the possibilities of how things can be known (Robson, 2011). Similar to ontology, epistemological research can take different positions to it, objectivism, constructivism or subjectivism (Gray, 2009). However, often the term epistemology is used in reference to both ontological and epistemological research, as it can be referred to as the theory of knowledge (Gomm, 2004).

The nature of this doctoral research takes an epistemological stance with a constructivism position. A constructivism position allows the researcher to take a research approach which allows for the understanding of multiple perspectives. Therefore within this doctoral research this constructivism epistemological stance allows for the understanding of householders' heating use by collecting multiple perspectives.

3.1.4 Research type and approach

The type of research carried out typically falls into one of two categories relating to the type of data collected. Qualitative research is based on collecting data in the form of words and phrases and focuses on researching 'meanings'. Quantitative research is based on collecting data in the form of numbers and focuses on researching ‘facts’. Therefore qualitative and quantitative research differs in many aspects from the focus or purpose of the research to the epistemological position, the differences between the two are summarised in Table 3.2 (Gray, 2009).

Table 3.2 Differences between qualitative and quantitative research methods (Gray, 2009)

	Qualitative methods	**Quantitative methods**
Epistemological positions	Constructivist	Objectivist
Relationship between researcher and subject	Close/insider	Distant/outsider
Research focus	‘Meanings’	‘Facts’
Relationship between theory/concepts and research	Induction/emergent	Deduction/confirmation
Scope of findings	Ideographic	Nomothetic
The nature of data	Data based upon text	Data based on numbers

Even though the two research methods are seen as being distinctly different, a third research method has become more popular recently, mixed methods. Mixed methods is a combination of both qualitative and quantitative methods however it is still fairly new and therefore its philosophy, design approaches, methodology and analysis techniques have caused arguments and controversy (Gray, 2009).

A mixed methods approach was chosen for this study to allow for the combination of both qualitative and quantitative measurements to provide a more detailed picture of heating use in homes and to explore the different reasons behind various heating behaviours. The combination of both research methods allowed for all of the research questions to be tackled and can often be referred to as taking a pragmatic approach. Pragmatic research allows the researcher to be flexible in investigation techniques used, cover a broad range of research questions, likely to promote collaboration between researchers, and have a positive attitude towards both approaches (Robson, 2011).

Obviously combining both methodological approaches has the risk of discrepancies between results. However Moffatt (2006) lists how to deal with any discrepancies between the two approaches as:

- treat both approaches as fundamentally different;
- explore the methodological rigour of each approach;
- explore data set comparability;
- collect additional data to make further comparisons; and,
- explore whether the outcomes of both approaches match.

For mixed method design to be successful the research needs to be analysed, interpreted and written in a way which the two components are illuminated together (Robson, 2011). To ensure that the mixed-method approach is successful for this doctoral research, Chapter 6 combines both qualitative and quantitative data collected for Phase 2 together to highlight the importance of mixed-method research. This combination involves data reduction, displaying both sets of data, data transformation, correlation of data, consolidation of data and then finally comparison and integration of both data sets.

It should also be considered that the research method is influenced by whether the study is underpinned by a known theory or whether new theory is being formed from the study. This refers to whether the study is inductive or deductive. Inductive research involves data being collected then analysed to see if a relationship is found between variables which can then be used to construct theory (Gray, 2009). Deductive research tests hypothesis to see if it can be confirmed, modified or refuted (Gray, 2009). However, similar to the research methods, inductive and deductive approaches are not mutually exclusive. Within this doctoral research a primarily inductive approach is taken as a heating use taxonomy was developed from the data collected, however it is acknowledged that a deductive approach was also used when designing the study around the literature available on what is currently known about heating use in homes and heating user types.

3.1.5 Theoretical perspective

Theoretical perspectives give direction to the research relating to what assumption the research is based upon. There are two main theoretical perspectives which can influence the research approach, positivism and interpretivism, although there are other less common theoretical perspectives. Positivism takes the assumption that the truth can be distinguished from untruth and that the truth can be determined by either deduction or by empirical support. It takes the perspective that the social world exists externally to the researcher and can be measured through observation (Gray, 2009). Interpretivism takes the assumption that interpretations of the world are culturally derived and historically situated. It takes the perspective that subjects and the world have no direct one-to-one relationship. Interpretivism approaches can be found with symbolic interactionism, phenomenology, naturalistic inquiry, hermeneutics or realism (Gray, 2009).

This doctoral research takes an interpretive approach, by focusing on understanding heating use within homes and interpreting the drivers behind heating use within a sample of households. Classifying heating use also requires a degree of interpretation by the author regarding the different heating characters found.

3.2 Research Methods

The research design is an important element of any study as it focuses the research and forms a plan of action to carry out the research. Robson (2011) summarises research design into a framework shown in Figure 3.1.

Figure 3.1 Robson (2011, p71) research design framework

To tackle the purpose of this thesis research, as presented in section 3.1, more effectively this doctoral research was designed to include two separate phases of research to be undertaken, referred to as Phase 1 and Phase 2. Phase 1 was an exploratory and explanatory based study which aimed to address research questions 1, 2 and 3. Phase 2 was a more exploratory and descriptive based study aimed at addressing the research questions 4, 5, 6, 7, 8 and 9. Figure 3.2 shows the research objectives of this thesis and how they fit into the two separate research phases and the corresponding data collection methods chosen for each study.

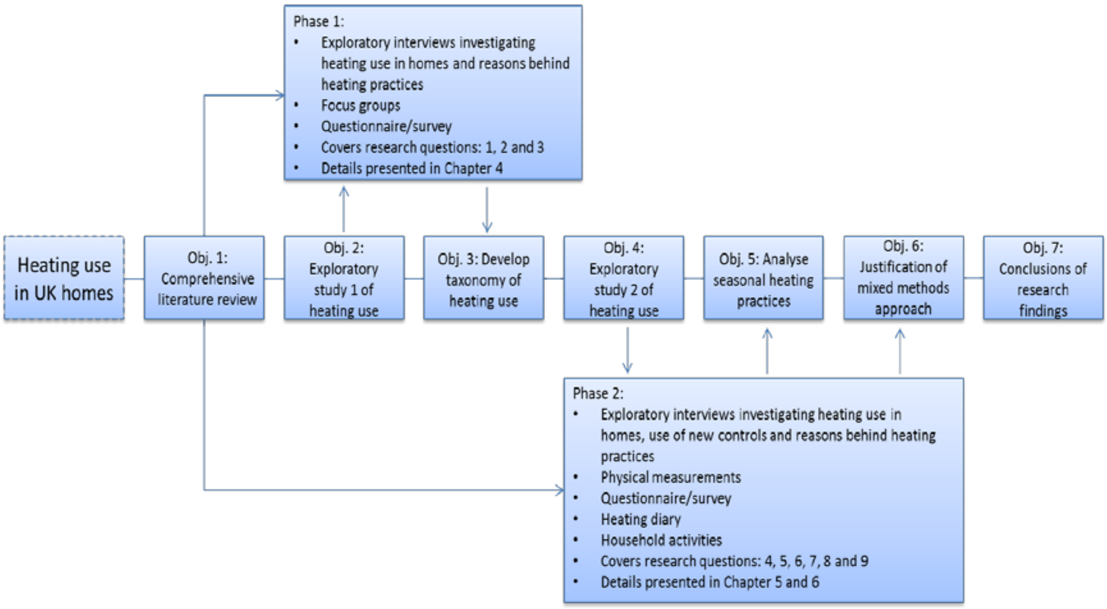


Figure 3.2 Research design focused around research objectives and the data collection methods chosen for each study

3.2.1 Phase 1 study

Phase 1 (reported in Chapter 4) was an exploratory empirical study with a total of 30 participants, in order to 'understand how and why people currently heat their homes'. The study was an exploration carried out through use of semi-structured interviews with household occupants covering a range of different demographics. Through this exploratory research, heating behaviour types and key issues influencing heating use are identified.

3.2.2 Phase 2 study

Phase 2 (reported in Chapter 5 and Chapter 6) was a separate exploratory study to that carried out for Phase 1, with a smaller sample of twelve households, in order to describe how people use their heating in homes and whether the reported heating use differed from measurements of heating use in homes. The study used the households which were recruited as part of the DEFACTO project's Go Digital study and therefore there was some overlap between the needs of this doctoral research and the needs of the DEFACTO project. This overlap of shared participant data from this study is shown in Figure 3.3.

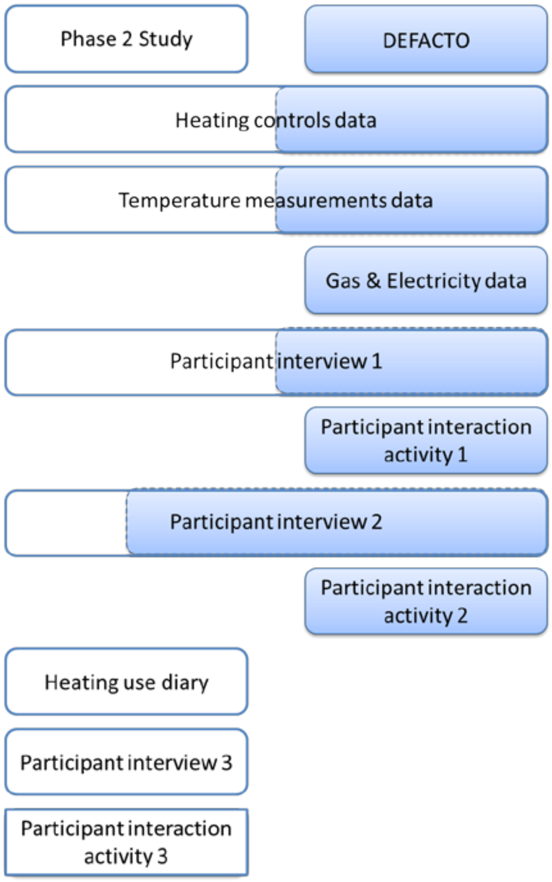


Figure 3.3 Phase 2 study and overlap of shared data with DEFACTO project

Details of the author's involvement with the Go Digital study regarding the study design and data collection are summarised in Table 3.3.

Table 3.3 Author and DEFACTO team involvement in Go Digital study as part of Phase 2 of this doctoral research

	Solely author	Collaboration between author and DEFACTO team members	No input from author	Details
Selection of monitoring kit to be installed in households			✓	All monitoring equipment was chosen by the DEFACTO project and the author had no say in any of the equipment used
Information packs given to householders regarding study		✓		Author helped with putting the information packs together and made suggestions on wording used and designed an initial leaflet for sensor placement. Final design was carried out by DEFACTO team member.
First interview		✓		Author worked in collaboration with DEFACTO team member to design all interview questions used, although was not present at any of the first interviews with households.
Participant interaction activity 1			✓	Author had no input with this activity.
Monitoring kit installation			✓	All monitoring kit was installed by a third party and therefore author and DEFACTO team had no control of installations.
Second interview		✓		Author worked in collaboration with DEFACTO team member regarding the design of the interview questions and attended all interviews.
Participant interaction activity 2			✓	Author had no input in the design of this activity but helped film the participants carrying out the tasks.
Heating diary	✓			Heating diary was designed solely by the author using the Go Digital branding.
Interview 3	✓			Author designed all interview questions and carried out all interviews without any collaboration from DEFACTO team members
Participant interaction activity 3	✓			Author designed and carried out the activity without any collaboration.
Data downloads	✓			Data downloads for all monitoring kit was done by DEFACTO team members however author downloaded all data relevant for this doctoral research separately to control how it was cleaned and analysed.

3.3 Data collection techniques and tools

Having established the design of this doctoral research from consideration of the research purpose, research type and both the philosophical and theoretical stance, the data collection techniques and tools selected to be used for this doctoral research are explained here. Further in-depth details of these data collection methods for each of the two study phases are presented in the relevant chapters, Chapter 4, 5 and 6.

3.3.1 Interviews

The basis of interviews is simply the researcher asking questions of interest to participants and hopefully getting answers which can then contribute to the research study (Robson, 2011). Interviews formed a large part of the data collection for both the Phase 1 and Phase 2 studies. Interviews can be in three different formats, a face to face interview, a telephone interview or a focus group interview. Telephone interviews may be less expensive, quicker and relatively easy to carry out but many participants do not like to partake in them due to the increase of cold-calling and the lack of any connect to the interviewer as it often feels impersonal. As such face to face interviews tend to get a better response from participants as they are more likely to agree to take part. Therefore face to face interviews were used for the majority of the qualitative data collection carried out during this doctoral research.

Both Phase 1 and Phase 2 used semi-structured interviews. Semi-structured interviews have a predetermined interview guide which acts as a checklist for topics to be covered and a default wording and order to questions, however it also gives researchers the ability to be flexible in how they order them or if they want to ask additional questions to follow up any responses given by participants. For all interviews carried out during this research interview scripts were made in advance. The interview scripts also included probes to use with the questions should they be needed. The prompts or probes helped to expand participant's responses to questions. The interview structure for Phase 1 and the initial Phase 2 interview consisted of an introduction where the researcher(s) introduced themselves and the study, a warm up question which was an easy non-threatening question to help settle the participant and start the conservation. This was then followed by the main body of interview questions before the use of a cool off question/activity was used to wrap up the interview before thanking them for participating.

The advantages and disadvantages of using face to face interviews over telephone interviews are summarised in Table 3.4 (Robson, 2011).

Table 3.4 Advantages and disadvantages of using face to face interviews over telephone interviews (adapted from Robson, 2011)

Advantages	Disadvantages
Easier to get participants to agree to being interviewed face to face	Telephone interviews can use computer-assisted technology to simplify process
Face to face interviews can be of longer duration therefore gather more information and cover more topics and also give flexibility to the researcher	More expensive and time consuming than telephone interviews
Face to face interviews allow the potential to use visual cues to help understanding	Potential for more interviewer bias in face to face
Contextual information can be gathered	More ethical and risk considerations with face to face interaction
A rapport can be built with participants	

Interview questions can be focused to ask questions about people's attitudes and beliefs, people's past/current and future behaviours, facts about people or their demographic information. However care must be taken by researchers when wording questions so to avoid any difficulty in participants understanding the question correctly. Therefore interview questions were kept relatively simple, easy to understand and easy to respond to and avoided any negative wording. The semi-structured format meant that should a participant not understand a question then the researcher(s) could give a description or explanation of a term or the focus of the question to ensure that the question was correctly understood. Care was taken to avoid questions containing emotionally charged wording which could impact responses and result in biased conclusions (Cozby, 2009). A mixture of both open-ended and close-ended questions formed part of the interviews. Open-ended questions allow participants freedom to answer however they like however it does mean that the researcher may have a harder task when trying to analyse responses. Closed-ended questions limit the possible responses a participant can give therefore often makes the analysis of responses easier in comparison.

All of the interview scripts were first piloted prior to carrying out the study interviews. This allows the order of questions to be checked to ensure that the order flows and there are no sticking points or jumps in topics being discussed. The structure of each question was also checked, are they clear to understand, do they use easily to understand terminology? Piloting the interview script also allowed the researcher to estimate the duration of the interview itself to give participants a rough guide of how much time they would be committing to and allowed the interviewer to plan their timings.

3.3.2 Physical measurements

The majority of the quantitative data collected within this doctoral research came from physical measurements. Monitoring of physical measurements formed a large part of the Phase 2 study. The physical measurements included internal room temperatures, use of the new heating controls, demanded set-point temperatures, gas usage, electricity usage and the heating schedules set. The monitoring equipment used for these physical measurements are detailed within Chapter 5.

3.3.3 Focus Groups

Focus groups are a type of interview that involves a group of people being brought together for a focused discussion. Focus groups tend to be used as an initial study to help design main data collection methods or often they can be used in conjunction with other methods such as observations or questionnaires. Therefore focus groups were included in the design of the Phase 1 study to gather information surrounding the general understanding of heating use in homes and help design the interview questions for the main study.

Focus groups typically involve between 6-10 participants and can last between 1-3 hours in length which therefore limits the amount of questions which can be discussed. The focus group was audio and video recorded (with participant permission) so that it could be transcribed and analysed later. It is recommended that two researchers carry out focus groups so that one can act as a note taker and one as a moderator. The note taker ensures that any points of interest raised during the discussion are not missed and can help decide areas of interest to analyse. The author adopted the moderator role which involved the facilitation of the main discussion and dealing with any issues such as one or two participants dominating the discussion or if any hostility developed between participants. The advantages and disadvantages of using focus groups are summarised in Table 3.5 (Robson, 2011).

Table 3.5 Advantages and disadvantages to focus groups (adapted from Robson, 2011)

Advantages	Disadvantages
Efficient technique for data collection by collecting data from numerous people at the same time	Limited in number of questions which can be covered
Participants tend to enjoy the experience	Researchers require a level of experience to facilitate the group process
Contribution from those that may be reluctant to vocalise their opinion individually can be encouraged within a group discussion environment	If group discussion is not managed effectively then some participants may not articulate their views or could be overpowered by other participants dominating
Method relatively inexpensive, flexible and easy to arrange	Potential for conflicts between personalities
Participants who cannot read or write are not discriminated against	Confidentiality issues depending on topic being discussed
Group dynamics help focus on the most important topics	Results often difficult to generalize

3.3.4 Self-reported diaries

The use of diaries as a data collection technique can be appealing as on paper they are the opportunity to generate a wealth of data using a minimum amount of effort from the researcher as it can often be viewed as a type of self-administered questionnaire (Robson, 2011). Diaries can be used as an observation tool, as typically they require participants to note actions which would typically be those actions that a researcher would record as part of an observation study. Due to this they can be used in situations where direct observations may be too difficult or impossible to occur. Within this doctoral research a heating diary was used within Phase 2 to gather information regarding daily interaction with the heating system/controls, household behaviours regarding who interacts with the heating and also the demanded temperatures and heating schedules. However using diaries requires a lot of responsibility from participants and often the researcher risks participants not completing the diary as desired. To limit this, the heating diary used a specific set of questions which participants could easily understand, quickly complete and note down the information required. Participants were also rewarded for completing and returning the heating diary via a voucher as a token of thanks. The advantages and disadvantages of using self-reported diaries is summarised in Table 3.6. To increase the validity of findings from diaries it is recommended that researchers use them in combination with another data collection method so that cross-checks can be carried out on the diary entries. This was achieved in the study by comparing the reported data with the physical measurements recorded.

Table 3.6 Advantages and disadvantages of using self-reported diaries

Advantages	Disadvantages
Relatively unobtrusive – can 'observe' behaviours without being observed	Data may be limited
Low cost to carry out	Pressure on participant to record their behaviour/actions
Captures behaviour 'in-situ'	High risk of inconsistency in quality
Provides in-depth information regarding routines and activities	Researcher has no control over the data collection situation and cannot guarantee 100% response

3.3.5 Questionnaire/Survey

Questionnaires and surveys can typically be used for all research purposes, exploratory, descriptive, explanatory or emancipatory, however they are not recommended for exploratory research as a sole method. Both studies used questionnaires and surveys within this research. Standardised questions within questionnaires and surveys helps to increase confidence in reported findings due to standardised questions meaning the same thing to different participants. Therefore questionnaires and surveys were seen to be a good method for gathering demographic information from participants in both studies. Typically surveys involve use of a questionnaire which can be administered as either a self-completed questionnaire, as part of a face to face interview, as part of a telephone interview or as an internet survey. During this doctoral research questionnaires were used in the format of self-completed questionnaires and those used during face to face interviews. The process involved in carrying out an interview questionnaire is shown in Figure 3.4.

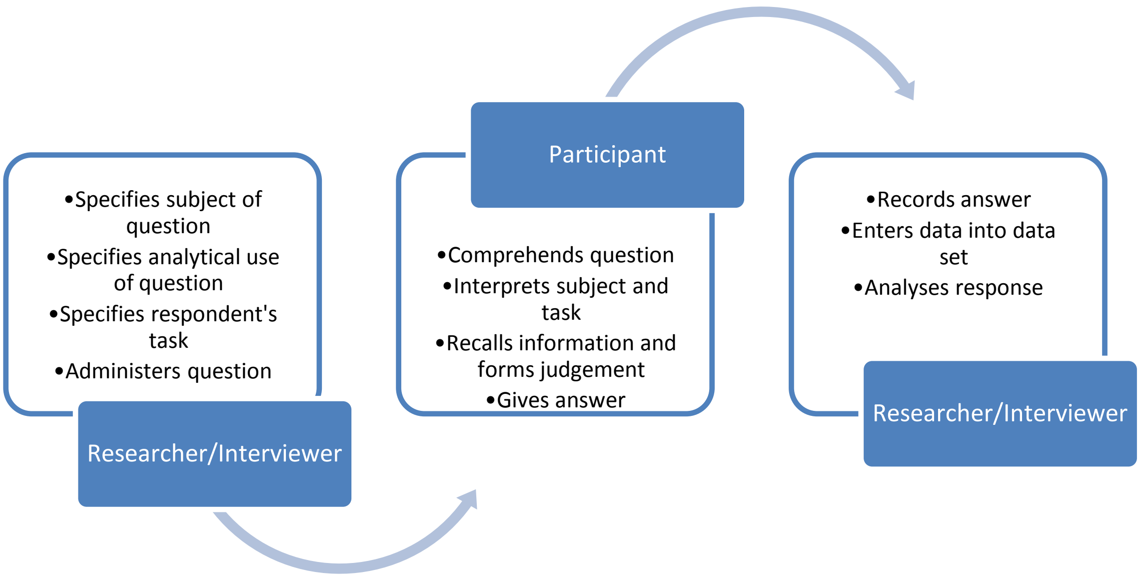


Figure 3.4 Model of questionnaire-survey data collection process (adapted from Robson, 2011)

Self-completed questionnaires were used within both Phase 1 and Phase 2 to gather demographic information and were therefore kept simple and easy to fill out. Closed-ended questions were used within these self-completed questionnaires. When using self-completed questionnaires there is a risk that the participant may answer the questions in any order they see fit and as such later questions may impact their answer on other questions.

Questionnaires/surveys during face to face interviews were used during Phase 2 as open-ended questions could be used which allowed participants the chance to expand on their answer. The questionnaire/survey was used to double check some demographic information, building characteristics and get answers to any unanswered questions within the self-completed questionnaire. They also gave the author the opportunity to check if any changes had occurred during the study duration such as changes to the household composition or if any energy efficiency improvements had been made, both of which could influence the heating use within the household.

The advantages and disadvantages of using questionnaire-survey methods in research are summarised in Table 3.7 (Robson, 2011).

Table 3.7 Advantages and disadvantages of using questionnaire-based surveys (adapted from Robson, 2011)

Advantages	Disadvantages
Provide relatively simple and straightforward approach in gathering participants attitudes, values, beliefs and motives	Data affected by participant characteristics such as memory, knowledge, experience, motivation and personality
Can be easily adapted to collect generalizable information	Participants may not record their beliefs or attitudes accurately
High data standardization	Potential for low response rate
Potential to generate large amounts of data at relatively low cost and over a short period of time	Ambiguities or misunderstandings may not be detected

3.3.6 Participant interaction activities

Increasingly, researchers are using additional activities during data collection methods which require participant interaction. For example, 'getting to know you' activities (Buswell et al, 2015) can be used as a way to build trust and rapport with participants but also as an observational method of getting insights into general attitudes and beliefs on a topic area. Within this doctoral research participant interaction activities were used within the Phase 2 study. The use of 'exercises' help to gain more data regarding participants' use of energy in their home which may not have been uncovered simply from an interview or diary. As part of this doctoral work participants were asked to rank the order of the rooms within their home from the warmest to the coolest using magnets to represent each room and a temperature scale. Magnets were also used for participants to describe their heating user types. Mallaband et al (2013) used a timeline tool to get participants to disclose information in a storytelling format. A timeline for participants to use as a method to identify events and explain in more detail using magnets to represent specific events was developed. This additional activity ensured that more information was gathered from householders than an interview may have exposed as the timeline creation allowed participant's memories to be jogged by other events being discussed. During the final interviews participants were shown data traces of their heating use to allow for additional information gathering from occupants memory of their heating use being jogged by seeing the data.

3.4 Data analysis

Before any data can be interpreted and reported, the type of data analysis to conduct needs to be decided. This section explains the data analysis approaches used with the qualitative and quantitative data collected. Further details of the data analysis carried out of relevance for each of the two study phases are outlined in each of the study chapters, Chapter 4, 5 and 6.

3.4.1 Qualitative data analysis

The core of qualitative data analysis is shown in Figure 3.5, where the phenomena being researched is described, classified and studied for connections between the concepts identified within a circular process (Dey, 1993).

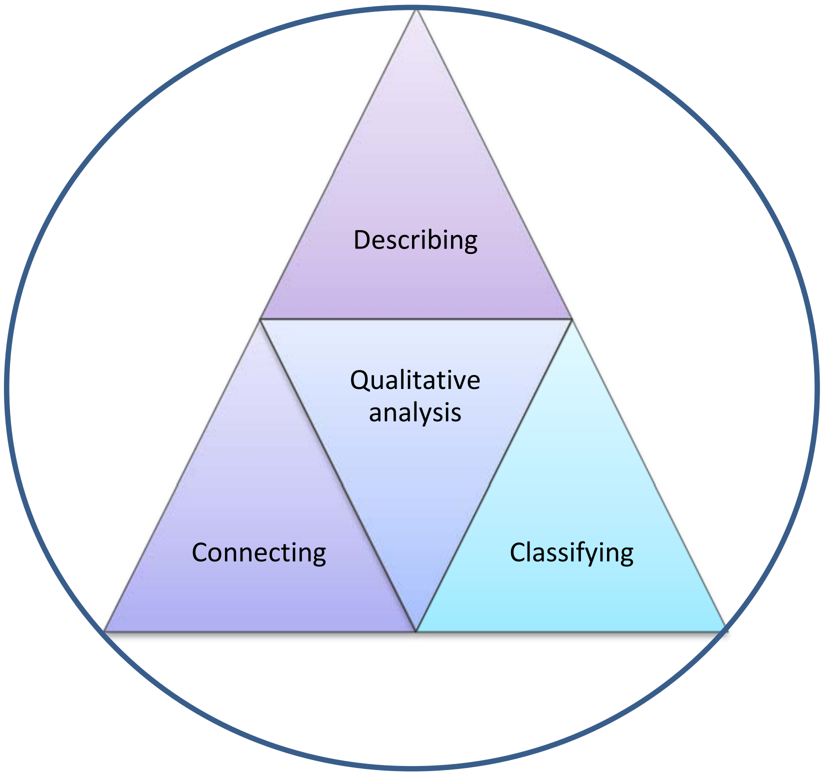


Figure 3.5 Circular process of qualitative analysis (Dey, 1993)

To undertake qualitative data analysis there are three main approaches of importance for this doctoral research; quasi-statistical methods, thematic coding and grounded theory methods (Dey, 1993). A quasi-statistical method is where qualitative data is treated in a quantitative data format to carry out simple statistical tests. For this doctoral research a thematic analysis and grounded theory approach was taken when analysing qualitative interview data. Thematic coding is a general approach that is not linked to a specific theoretical perspective. Grounded theory is a version of thematic coding where codes come from interacting with the data (Robson, 2011).

3.4.1.1 Thematic Analysis

By using a thematic analysis approach within this doctoral research, items of particular interest within the qualitative data were coded by the author. Themes are created by collecting all data with the same label together. These themes and, to an extent, the codes used were determined inductively from research questions and previous research. Themes allow for further data analysis to be carried out gaining further interpretations from the data collected which leads to the potential to create matrices, maps, flow charts and diagrams (Robson, 2011). This data analysis process was therefore seen to be best suited for categorising heating use and drivers from the interview data in order to create a heating use taxonomy of heating characters. The process involved for carrying out thematic analysis is summarised in Figure 3.6.

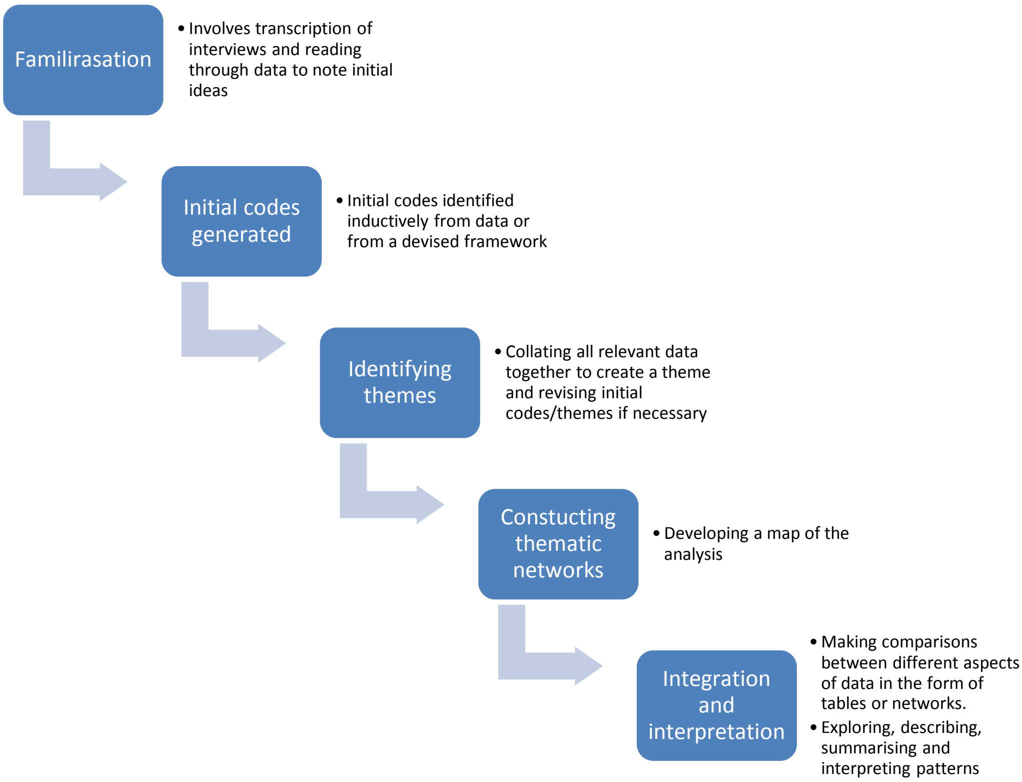


Figure 3.6 Phases of thematic coding (adapted from Robson, 2011)

Generating codes during thematic analysis can be done for various categories depending on what the research requires. Categories include the following; specific behaviours, activities and events, meanings to participants, relationships or interactions, consequences, settings and reflexive (Robson, 2011). Within this research categories were selected based on the research questions and first interpretations by the author following the interviews. Therefore initial coding of data was focused on descriptive (i.e. what participants say) but this was then coded further for more theoretical oriented themes. The advantages and disadvantage of using thematic coding are summarized in Table 3.8 below (Robson, 2011).

Table 3.8 Advantages and disadvantages of using thematic coding (Robson, 2011)

Advantages	Disadvantages
Flexible as can be used on most qualitative date forms	Flexibility of using thematic coding means a broad range of topics may be found and inhibit the researchers decision on what data to focus on
Relatively quick and easy method to learn and use, especially beneficial for researchers carrying out mixed-methods	Can be limited to description or exploratory analysis
Results can be communicated easily to practitioners, policy makers and the educated general public	Exact details of the process of thematic coding is often eliminated from reports
Can summarise key features of large amounts of qualitative data	Sometimes not appreciated as an analytical method as much as other forms of analysis such as grounded theory, interpretative phenomenological analysis, discourse analysis or conversational analysis

3.4.1.2 Grounded Theory analysis

Grounded theory analysis aims to generate theory which can explain what is central to the data collected at both a grounded level and at a high level of abstraction (Robson, 2011). Grounded theory analysis comprises of the following; initial coding and categorising of data, concurrent data generation, writing memos, theoretical sampling, comparative analysis, theoretical saturation and theoretical integration (Birks, 2011). Therefore grounded theory analysis was seen to suit the Phase 2 study of this doctoral research, as this study had numerous data collection points and as such concurrent data generation could be taken into consideration. Birks summarised these essential elements of grounded theory in the diagram shown in

Figure 3.7 where three cogs are representative to what can be used to drive grounded theory. The three cogs are used to represent methods to refine and generate data and the concepts and techniques involved, with continuous generation of memos for all three cogs to achieve the overall grounded theory.

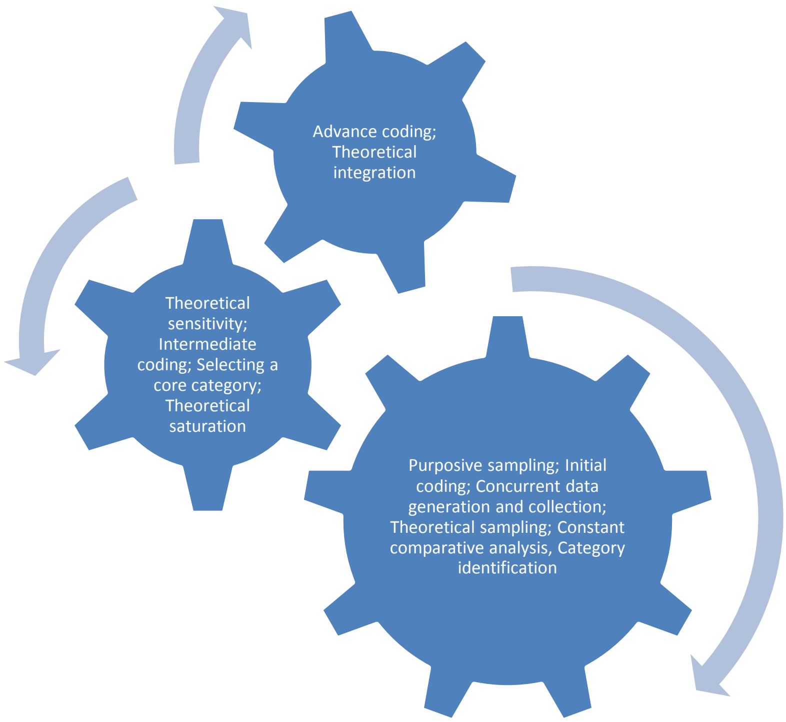


Figure 3.7 Essential grounded theory methods (Birks, 2011)

Robson (2011) summarises these methods into three stages; finding conceptual categories, finding relationships between categories and then conceptualising these relationships by finding core categories.

3.4.2 Quantitative data analysis

Quantitative data was collected during both Phase 1 and Phase 2 of this doctoral research however formed a much larger part of the Phase 2 study due to the physical measurements of heating use and temperatures within the study. There are two main stages in quantitative data analysis which involves looking at the data collected either in a graphical format or statistically (Field, 2013). Graphical displays of quantitative data are often the initial analysis stage to see what the general trends are within the data and help determine what statistical analysis may be used on the data. Within this doctoral research both graphical visualisations and statistical analysis were used to better understand the data collected.

3.4.2.1 Graphical visualisation of data

There are a number of graphical representations of collected research data which can be made during quantitative analysis. The most common one being frequency distribution graphs which show how many times a certain value is recorded, otherwise known as a type of histogram. Within the Phase 2 study this sort of analysis was seen to be beneficial for looking at recorded set-point temperatures and heating durations. From the distribution of the data the following measurements can also be achieved; the mean (measurement of the central tendency otherwise known as the average score), the median (the middle score in the data when ordered in an increasing magnitude) and the mode (most frequently occurring score). The distribution can also be analysed for its dispersion or spread, otherwise known as the range of scores within the data. This analysis often helps with initial descriptives of the dataset which can then determine what statistical tests should be carried out, many of which are dependent on the type of distribution the data set has. Graphical visualisation of the data was also used to plot temperature traces, allowing differences between rooms within each dwelling to be observed as well as comparisons to be made between the different households.

3.4.2.2 Statistical analysis

Various software packages are available to run statistical analysis of quantitative data however for this doctoral research Microsoft Excel and IBM SPSS packages were used. This allowed for all the graphical visualisation of data sets to be carried out and then descriptive statistics to be generated initially. To use SPSS an initial data set was generated in Microsoft Excel of the data that was to be analysed together before this was then imported into SPSS. Here it was possible to classify the variables depending on what type of measurement they were. The different measurements possible for variables included nominal variables which typical referred to classification categories, ordinal variables which referred to categories which could be ordered in a specific way, and scale which referred to variables which had a distinct order. Table 3.9 summarises the statistics of relevance that can be carried out using SPSS and what they measure (Robson, 2011).

Table 3.9 Statistical analysis and what they measure

Statistical analysis	Measurement of
Frequency distributions	Frequency of scores and distribution of data set
Descriptive statistics	Measures of central tendency (mean, median, mode), measures of variability (range, inter-quartile range, mean deviation, variance, standard deviation, standard error)
Cross-tabulation	Relationship between two variables
Chi-square test	Degree of association or linkage between two variables
Correlation coefficients	Correlation between two variables (the co-relationship)
Multiple regression	R-squared (multiple coefficient of determination), t-value of coefficients, standard error of coefficients, analysis of variance (ANOVA)

3.5 Reliability & Validity

Reliability of research refers to its consistency and stability of measurements. However this can be particularly problematic in qualitative research as it often involves the use of non-standardized research instruments. Robson (2011) identifies common issues with all types of data collection (including qualitative research) as being equipment failure, environmental distractions and interruptions, and errors in transcription.

For this doctoral research a key focus was made to improve the reliability of measurements taken during the study. This involved reducing the risk of equipment failures by always testing all equipment prior to visits to participant households and ensuring spare batteries and a spare dictaphone was taken along for interviews. To limit any transcription errors the author transcribed all Phase 1 interviews using a slowed down audio recording within NVivo, and transcribed each question in turn repeating the audio recording if needed until the full conversation had been transcribed. With those interviews that the author did not transcribe the transcription script was checked against the original audio recording, with any missing parts added to the transcription by the researcher. For the physical measurements recorded as part of the Phase 2 study, care was taken to ensure all data files were cleaned to remove any erroneous data points before any analysis was carried out, details of which can be found in Chapter 5.

Validity in qualitative research is different to quantitative research due to the subjective, interpretive and contextual nature of data collected within qualitative research (Thomson, 2011). Maxwell (2012) identified five factors which could be used to insure validity in qualitative research; descriptive validity, interpretive validity, theoretical validity, generalizability and evaluative validity. This research met two of these validity factors. The first being “descriptive validity”, which refers to the data accurately reflecting what the participant has said or done, and therefore nothing should be omitted from the transcription process. Within this research all transcripts were checked multiple times to ensure nothing was missed and emphasis was made if participants put emphasis on anything in particular. The second factor is “interpretive validity” referring to the researcher’s ability to capture a true reflection of what the participants have meant. In order to ensure this, researcher’s approached all interviews with an open mind and made no preconceptions or judgements about participants’ answers and use of heating. To try and reduce any bias from participants during interviews researchers ensured them at the beginning of all interviews that there were no right or wrong answers and that the study was simply interested in how people did use their heating.

Methods can be applied to qualitative research in order to improve its validity, triangulation and member checking. Triangulation can come in various forms from using more than one data collection method (data triangulation), using more than one observer during the study (observer triangulation) or using more than one theory (theory triangulation). Triangulation can also be achieved by combining both qualitative and quantitative methods which is often referred to as methodological triangulation. Within this doctoral research methodological and data triangulation was used for research validity. An element of member checking was also used during the final interviews for the Phase 2 study by presenting participants with data traces and the assumptions made from the data by the researcher. Member checking is where participants have research materials such as transcripts, accounts or the researcher's interpretations from measurement data or other recorded measurements sent to them, therefore helping to reduce any researcher bias or misinterpretation of what participants meant to be highlighted (Robson, 2011).

3.6 Ethical considerations

Ethical consideration is important prior to any research being carried out especially any studies involving human participants and so should be factored into any research planning and evaluation. Ethical considerations should help reduce/eliminate the risk of harm, stress and anxiety to participants. Questionable practices that would raise ethical considerations include (Robson, 2011):

- involving people without their knowledge or consent;
- coercing participation;
- deceiving participants;
- exposure to physical or mental stress; and,
- withholding benefits from some participants.

Cozby (2009) identified three basic principles to consider for ethics; beneficence, autonomy and justice. Beneficence refers to maximising benefits to participants and minimising any possible harm, which may include psychological or physical harm. Autonomy refers to respecting human participants, such as insuring that they are treated with confidentiality and allowing participants to make the deliberate decision to participant in the research study. Justice refers to issues of fairness when participants receive benefits of the research being carried out and also bearing the burden of risks associated with the research (Cozby, 2009).

This doctoral research was carried out in compliance with Loughborough University's ethics guidelines. The ethics guidelines ensure that the research would be carried out and managed in an ethical way that would not harm any participants. To ensure issues from potential risks were considered a risk assessment form was also completed for both phases of this thesis research, which could calculate whether formal approval was needed for the research study. Phase 1 did not require full ethical approval, however full ethical approval was sought from the Loughborough University Ethics Committee for carrying out research relating to Phase 2 of this study as part of the DEFACTO project. Full ethical approval was needed due to the nature of the DEFACTO project's research involving various monitoring equipment and interactions with households which could have potentially contained vulnerable people. This ethics submission was made by the DEFACTO project team but listed any involvement this thesis work had in addition to the project's needs. In addition to the ethics submission all research project members had a Criminal Records Bureau check completed and certification obtained providing evidence that each project member posed no risk to participants in that study.

To reduce any harm to participants or any misinterpretation by participants to what the research involves informed consent was sought by the author for the Phase 1 study and formed part of the information packs given to participants for the Phase 2 study. This involved giving participants information for the research project and the researcher's name, and getting the participant's to formally sign saying that they agree to take part. An informed consent form typically includes statements that the participants need to agree to such as, they can ask the researcher any questions they have about the research study prior to consenting, that they know their participation is voluntary and as such can withdraw from the study at any point, that their data may be used in reports, publications or presentations, and that they have read and understood the information provided about the study. These statements were included in both the Phase 1 and Phase 2 study consent and participant information materials.

To further protect participants within both research studies anonymity was given to those participating in the research. This meant that researchers also avoided disclosing any personal details which could result in a participant's identity being exposed. To ensure anonymity, any identifiers to participants have been removed when presenting the results of both studies. Due to both studies involving interviews being carried out in participant's homes care was taken to avoid any invasion of the participant's privacy.

On top of ethical issues for participants, researchers must also consider their own safety and any risks to them when carrying out the research. Boynton (2005) provides detailed potential risks to researchers that should be considered and the actions which should be ensured to limit those risks. These risks and actions have been summarised in Table 3.10.

Table 3.10 Potential risks and implications for researchers (summarised from Boynton, 2005)

Risk	Implications
Buildings	Ensure access well light, clear paths with no potential safety issues from machinery etc.
Own property	Keep belongings close and in a safe place. Do not take valuables unless absolutely necessary
Well-being	Aware of fire exits, emergency contact numbers
Equipment	Be correctly trained to use any equipment
People	Anticipate and know how to respond to potential racist/sexist/homophobic remarks or abuse from participants
Environment	Likely to have to work or travel in adverse weather conditions. Have planned routes
Lone working	Is risk posed high, medium or low? Is it possible to work in pairs? Record location, route and timings of any visits to participants
Setup	Designed study to avoid cold-calling? Have identity badges.

To ensure the safety of the researcher during the Phase 1 study, a Loughborough University risk assessment form was completed. Following this, protocols were put in place where the researcher would attend interviews with a chaperone. This was also further supported by arranging a contact within the University who had access to the interview details (location, time etc.) and was texted prior to the interview and as soon as the interview ended. Should neither the interviewer nor chaperone text the contact person within ten minutes of the scheduled end time of the visit, then the contact person would call to get confirmation everything was ok. Should confirmation fail to be made after numerous attempts then the contact person was instructed to get in touch with the police. The researcher was also aware of how to quickly end the interview should they feel uncomfortable or threatened by any participant during the interviews.

A detailed risk assessment was completed for the DEFACTO project which included the involvement of the Phase 2 study that formed part of this doctoral research.

Similar protocols were put in place as to the Phase 1 study where both the first and second household interviews were attended by two team members. As a good rapport had been established with the households by the third interviews, these were attended by only the author. Therefore to ensure the safety of the researcher a contact protocol was put in place where a team member knew all details of the household visits and was texted prior and following any visit to confirm all was ok. If contact was not made then the chosen team member would get in touch with the researcher, failing this raise the alarm.

3.7 Summary

The research within this thesis takes a constructivism epistemological approach and is interpretive in nature. The research incorporates mixed methods with a primarily inductive design. Various qualitative and quantitative data collections techniques and tools are used including: interviews, physical measurements, a heating diary, focus groups, participant interactive activities and questionnaires/surveys. Detailed information regarding the specific data analysis carried out on this collected data can be found in the relevant chapters, Chapter 4, 5 and 6.

The doctoral research was designed into two different phases, Phase 1 and Phase 2. Phase 1 of the research used primarily qualitative methods to develop an understanding of the variation of current heating use in homes, how people heat their homes and the reasons behind why they adopt certain heating behaviours. Phase 2 of the research used a multi-staged, mixed methods approach where quantitative methods were used to investigate what people did to heat their homes, how people interacted with new heating controls and how varied the heating behaviours were within the sample regarding set-point temperatures, heating durations and the heating schedules set. The qualitative methods used within the Phase 2 research investigated why people used their heating a particular way and whether any issues impacted their use of heating within their homes. This doctoral research also investigated the benefit of combining both qualitative and quantitative research methods for investigating heating behaviour in homes. The ethical and safety considerations taken for both the Phase 1 and Phase 2 are described in detail within this chapter ensuring the safety of all participants and researchers.

Chapter 4: How do householders heat their homes and why?

This chapter focuses on the research carried out for the Phase 1 of this thesis, an exploratory study to understand why and how householders heat their homes. The study was a qualitative focused investigation therefore this chapter presents householders' self-reported use of heating. The chapter details the aims and objectives of the Phase 1 study along with how it was carried out and the findings found, before discussing the implications of these findings.

4.1 Introduction

As identified within the literature review in Chapter 2, research into occupant behaviour within homes is typically focused on identifying behaviour traits towards energy use in homes as a whole. However it has also been recognised that heating use within homes can be extremely diverse and that occupants heating preferences are likely to vary significantly, including within the same home (ETI, 2015). Yet little research currently focuses on investigating domestic heating use solely to develop a better understanding of the level of variation and ultimately the factors behind such heating behaviours.

Since the start of this doctoral research the Department of Climate Change (DECC) published a report which presented various heating user types (Rubens and Knowles, 2013), which are referred in this thesis as "heating characters". Although these characters elucidate on a level of variation for heating use within homes, they do not touch on the reasons why occupants may exhibit these heating behaviours. This chapter describes an exploratory investigation into how people heat their homes, based on their self-reported comments and the reasons behind heating their homes in a particular fashion. It is therefore able to expand on the heating characters identified within the literature already and suggest an alternative taxonomy which takes into consideration influential factors on heating behaviours, factors which may also influence whether energy savings would be possible by changing an occupant's heating character.

4.2 Aims of study

The aim of this study is to help answer the following research questions of this thesis;

1. *How do people currently heat their homes – what controls do they have and what do they use?*
2. *What are the reasons behind occupants' reported heating use?*
3. *Can heating behaviours be categorised by understanding how occupants use their heating, why occupants heat their homes in a particular way and what occupants use to control their heating?*

The answers to these questions then helped to create a taxonomy of heating behaviours relating to the preferential heating practices identified and built on the current heating behaviour categories already identified in the literature, therefore, completing Objectives 2 and 3 of this thesis.

Conduct a qualitative focused exploratory study to investigate how people currently use their heating within their home and the reasons behind why they have such heating practices

Objective 2

Develop a taxonomy of heating behaviours relating to preferential heating practices identified through Objective 2 and building on current heating behaviour types identified in the literature.

Objective 3

4.3 Methods

4.3.1 Study methods

The study, referred to as Phase 1, was focused on understanding the context behind how and why people use their heating systems in their homes, however it also uncovered many misconceptions and adaptations householders had regarding the heating system in their homes. The study was a qualitative focused exploratory and explanatory based investigation. The main approach for the study was the use of semi-structured interviews to record reported heating use in homes in a way which allowed the researcher to probe areas of interest further if needed. This study initially used focus groups to contribute to the design of the interview questions and structure. The use of focus groups was seen as a quick and inexpensive way to gather information regarding public understanding of heating use terms and help guide the construction of clear and easy to understand interview questions.

There was the obvious awareness that this study was reporting individual's views and interpretations of their own heating use behaviours and as such may not be a completely accurate representation. However, an emphasis for this study was to investigate the level of variation in heating use and to uncover issues or factors influencing heating use within homes. As part of the semi-structured interviews a questionnaire survey document was also produced to collect information about participants such as the household composition, dwelling type, dwelling age and income levels.

All of this Phase 1 study was carried out independently by the author and was not in any way related to the DEFACTO project. Therefore, the focus was to keep the study location based locally.

4.3.2 Sample recruitment

Random sampling technique was used initially to recruit households so that the sample covered a broad range of demographics and dwelling types. Recruitment of the sample was initially carried out through an advert within the local weekly newspaper, the Loughborough Echo, shown in Figure 4.1.

Figure 4.1 Local newspaper recruitment advertisement

This newspaper advertisement was further supported with a total of 1,000 leaflets containing the same advertisement, being distributed around the local area using a random selection of streets. The random selection of streets to leaflet was carried out by listing all streets within Loughborough alphabetically in MS Excel and then using a random number generator to select specific streets. The identified street was then checked on Google maps to estimate the number of households on that street and to remove any streets that were industrial units, until a total of 1,000 households had been selected. The random streets selected can be seen in Figure 4.2 by the stars representing the residential streets selected.

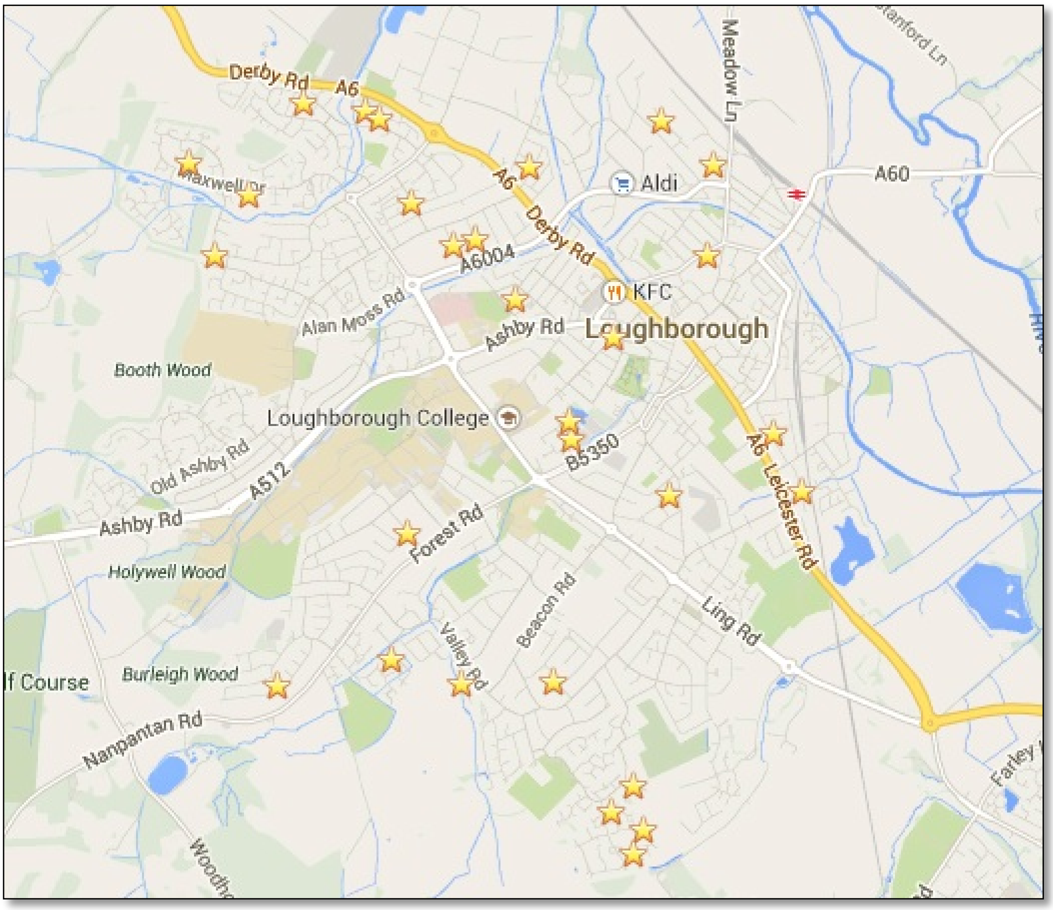


Figure 4.2 Map showing locations of randomly selected streets for leafleting

The leafleting was carried out during the two weeks following the advert first appearing in the local newspaper. When these initial attempts failed to recruit enough households a further advert was run in the local newspaper which coincided with an energy special issue. However, this recruitment approach also failed to recruit a satisfactory sample size. The leaflet design was then turned into a recruitment poster with a rip-off section containing contact information (Figure 4.3) to attempt to recruit more participants through a snowball sampling technique. Snowball sampling is when a researcher interviews a participant from a demographic of interest and then uses those participants as informants to identify further participants of interest and so on, hence called snowballing (Robson, 2011, p275). Therefore, during interviews the author also told the participants to feel free to pass on information about the study to those who they thought may be interested in participating.

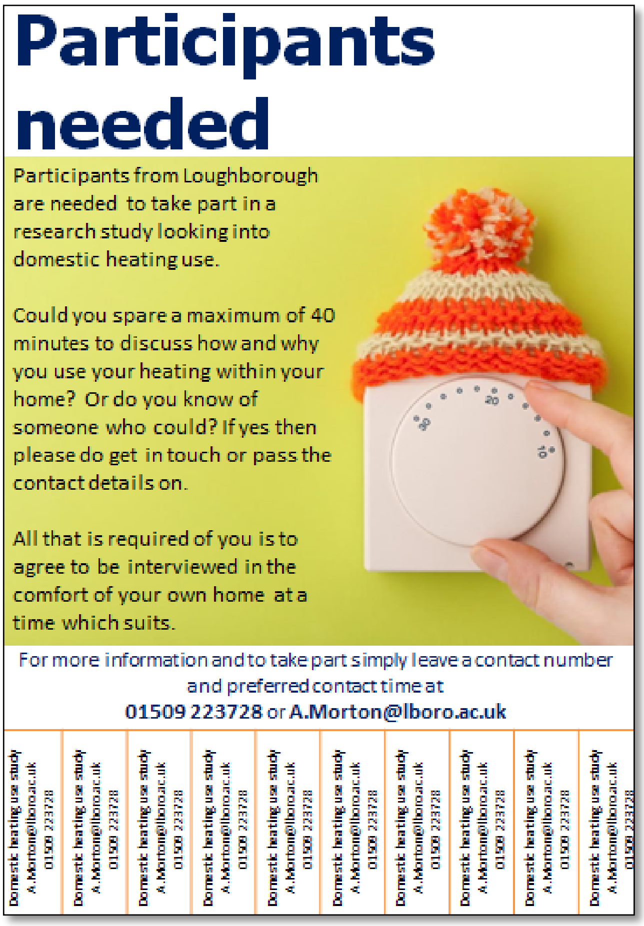


Figure 4.3 Recruitment poster

The number of participants successfully recruited is summarised in Table 4.1, although more households showed interest in participating an interview date was never confirmed due to them changing their mind about taking part.

Table 4.1 Number of participants recruited from each recruitment method

Recruitment method	Number of participants successfully recruited
First newspaper advert	8
Leaflets	2
Second newspaper advert	7
Posters	8
Snowballing	5

A high level review of the data collected was carried out as the interviews progressed in order to identify key themes emerging from the interviews. Recruitment continued until saturation was reached which meant that no new key findings were being found during the interviews. Once the recruitment ended the sample was checked to ensure that there was a good spread of key demographic variables. Demographic information was collected when participants first showed interest in the study using a call script, as shown in Appendix 4-A, and in more detail during the interview. In the end a total of 30 households were recruited therefore meeting the "rule of thumb" for comparisons involving "relations in a single group" (Robson, 2011, p128) relating to qualitative research studies.

4.3.3 Sample distribution

The 30 recruited households within the sample covered a range of dwelling types and household demographics (Table 4.2). As the table shows, the sample recruited covered a mixture of dwelling types and dwelling ages which will impact the rate of heat loss from that home and as such how occupants may heat their homes. There was a higher percentage of 45-54 year old age group participating in the study. However, this is likely to be due to elderly populations being more apprehensive about taking part in research studies, although over 10% of the sample recruited fell into the 65+ age bracket so the elderly were still represented within this study. The snowball sampling approach may have also been a factor, with participants in the 45-54 year old age group suggesting others in the same age group also participate. Those recruited also covered a range of income brackets, heating system types and tenure, all things identified as potential influence factors for energy use in homes within the literature review.

Comparing the sample demographics with data describing the English housing stock (DCLG, 2016) shows that there was a higher percentage of detached and semi-detached dwellings within this study compared with the split within the current housing stock in England. However, the study sample is a much better match to the housing stock for the East Midlands, with the 2011 census showing 32% detached, 35% semi-detached, 21% terraces and 12% flats (ONS, 2012a). Therefore the study sample can be seen as being representative to the East Midlands region but not representative to the whole of the UK.

Table 4.2 Sample demographics

	Sample characteristic	n, % of sample	% of English housing stock (DCLG, 2016), % of East Midlands population (ONS, 2012)*
Dwelling type	Detached (inc. bungalows)	11, 37%	27%
	Semi-detached	9, 30%	25%
	Terrace	6, 20%	29%
	Flat	4, 13%	20%
Dwelling age	Pre 1919	8, 27%	20%
	1919 – 1944	7, 23%	17%
	1945 – 1964	3, 10%	19%
	1965 – 1980	4, 13%	20%
	1981 – 1990	2, 7%	8%
	Post 1990	6, 20%	16%
Age of interviewee	25 – 34	6, 20%	12%
	35 – 44	4, 13%	7%
	45 – 54	9, 30%	14%
	55 – 64	7, 23%	12%
	65 – 74	2, 7%	9%
	75 +	2, 7%	8%
Income bracket	Low (< £15,600 p/a)	7, 23%	
	Medium (£15,600 - £31,199 p/a)	11, 37%	
	High (> £32,000 p/a)	12, 40%	

*Dwelling type and age summary data from English housing stock 2014-2015 report data (DCLG, 2016) and age of interviewee comparison made against East Midlands population census 2011 data (ONS, 2012a). All percentages have been rounded to nearest whole number

The sample included households which had between 1 or 6 occupants living within the property. The majority of the sample was either sole occupant households or two person households, both representing 33% of the sample each. However, the East Midlands has been reported as having the highest proportion of two person households within England and Wales (ONS, 2012b), therefore the sample may be reflecting this. It is also likely that the use of a snowballing sampling technique could have influenced this. 17% of the sample had three occupants, 7% had four occupants, and 7% had five occupants with the final 3% of the sample having a total of six occupants within the property. Within the sample there were a total of nine households (30%) which contained a child under the age of 16. The sample consisted of 20% rented accommodation and the remaining 80% being owner occupied.

Within the sample, 90% of participants had gas central heating and 10% had electric heating within their properties (both electric heaters and storage heaters within those). Out of the remaining participants, 50% had a combination boiler as part of their gas central heating, 30% had a regular boiler. The remaining 10% of participants had gas central heating but did not specify within the interview if it was a combination boiler or a regular boiler.

4.3.4 Design of Interview Questions

Focus groups were used initially to understand the level of comprehension towards heating use and heating system terminology by members of the general public. By gaining a better appreciation of how people interpreted questions on heating use and behaviours it allowed the design of the interview questions to be more informed and structured.

Three focus groups were arranged to be held within Loughborough town library and advertised via a poster which was placed in local cafes, museums, shops and the library itself. The advertisement asked participants to book a place on a session due to the limited capacity of 8-10 people per focus group to ensure that they were successfully facilitated. Before undertaking the focus groups, ethical approval was sought, a script was made with relevant discussion topics and prompts and a short questionnaire to gain information about the types of demographics represented was produced. Due to a poor response rate of participants (even with a token of gratitude being offered) only one of the three focus groups occurred. However this lone focus group was still extremely beneficial and due to it being carried out at full capacity it resulted in a thoughtful discussion. The focus group demographics are summarised in Table 4.3:

Table 4.3 Focus group demographics covered

Participant	Gender	Age Group	Household composition	Tenure
1	Female	60 - 69	2 adults	Buying with mortgage
2	Male	50 - 59	2 adults	Buying with mortgage
3	Female	30 – 39	2 adults 2 children	Own outright
4	Male	50 - 59	Only occupant	Own outright
5	Male	50 - 59	Only occupant	Own outright
6	Female	60 - 69	3 adults	Own outright
7	Female	60 - 69	Only occupant	Renting
8	Male	20 - 29	Shared	Renting

The focus group demographic spread matched up reasonably with the Phase 1 study sample. Sole or two person households made up 75% of the focus group sample and 66% of the main study sample. The split in tenure was similar also with the focus group having 25% in rented accommodation compared to the 20% of the Phase 1 sample, and the remaining being owner occupied. Not so well matched was the fact only 1 participant in the focus group was from a household with children, which made up 30% of the main Phase 1 study sample. The focus group was made up of 75% of participants falling into the 50-69 year old age band which was higher than the representation of those ages within the Phase 1 study. However, the match between both samples meant that the focus group findings gave a good indication of what sort of findings may have been uncovered within the main Phase 1 study.

The following topics were discussed during the focus group with the use of open ended questions being directed towards the group as a whole with encouragement given to ensure each participant had an equal opportunity to contribute their views and experiences to each point;

- most important factors for heating a home;
- influences on heating use;
- heating control strategies;
- supplementary heating use;
- heating use negotiations;
- different heating use for different parts of the home; and,
- heating used for other reasons aside from providing warmth.

Occasionally prompts were used to ensure that the participants understood the questions. These occurrences were then noted as being issues concerning the level of comprehension that question had with the participants, which was vital regarding the development of questions for the main study interviews, ensuring that there was no ambiguity with what the questions regarded and therefore ensuring the responses gained were not as a result of misunderstandings.

Initial analysis of the data gained during the focus group uncovered intriguing quotes relating to the topics being discussed, some of which are included below:

"I'm a cold blooded person so heating is important to me. I'd ***stint on food before I'd stint on heating****"* – Participant 7

"It's just all on the thermostat and that's in the hall so I'm probably ***just under 15˚C at night*** *as the kids don't like it hot and then you've got all the duvets so don't really need it warmer"* – Participant 3

"I love to be warm I really hate to be cold so I ***probably live in an overheated house*** *but that is just how I like to live"* – Participant 4

These quotes of interest led to the desire to include questions within the interview which covered priorities in relation to heating i.e. cost, comfort or health. The findings also resulted in a probe being included within the interviews relating to the temperatures which participants felt comfortable with or typically set their thermostats to. Interview questions were then formatted using the same topics covered for the focus group and with any additional topics that may have been covered or raised from the responses during the focus group. The final interview script can be found in Appendix 4-B.

4.3.5 Piloting

The interview script was piloted in two separate test interviews with participants from a non-academic background. During this pilot phase, if questions were not clear enough, alternative options were given to see what the participants felt to be the clearest and easiest question format to understand. The ordering of the questions was also changed following the pilot phase to ensure that the interview flowed well and that participants did not feel like they were being asked the same question twice. Prompts used during the pilot interviews were also noted down on the interview script so that those which resulted in participants successfully answering what the question initially aimed for could be used again. Finally the pilot interviews allowed for the time taken to complete the interview to be measured so that interested participants for the main interview could be informed of the expected duration of the interview.

4.3.6 Interview procedure

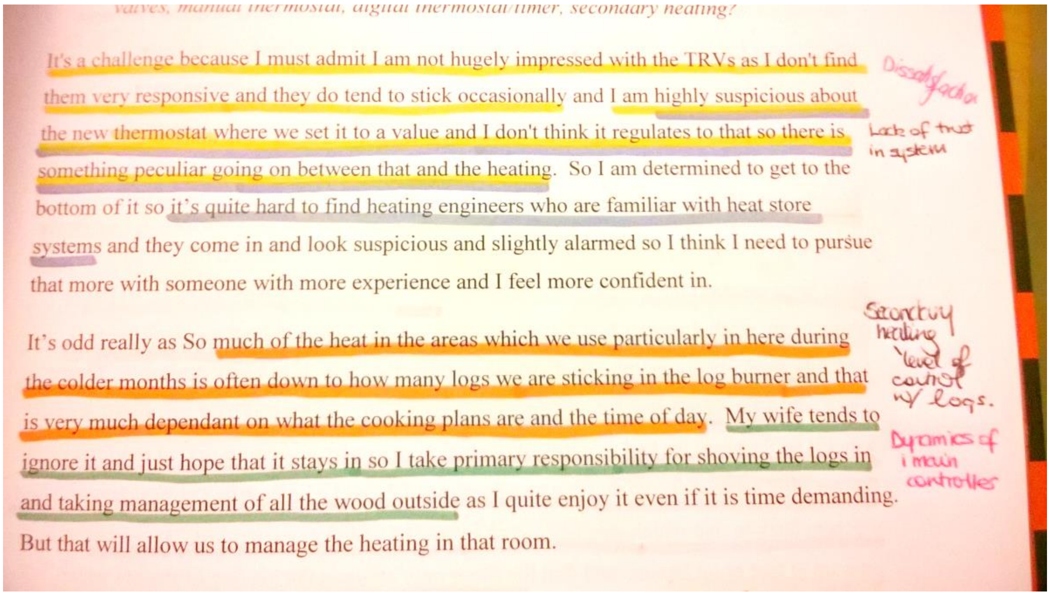
All householders took part in a face to face interview which was held in their own home and typically lasted 30 to 45 minutes in duration. The participants were told about the reasons behind the study and the type of interview questions were explained to participants. Participants were then given an information sheet containing more details about the study before they were asked to sign an informed consent form, both shown in Appendix 4-C. The participants were also asked if they consented to the interview being audio recorded for transcription purposes. All of this was completed before the interview began. The interview script used can be found in Appendix 4-B, which was followed as closely to the order printed. Due to the nature of the topic often participants may have mentioned answers to later questions when expanding on earlier question topics, however in these cases the participants were just asked to reconfirm the answer to the question. Prompts had also been noted from the pilot stage so that the interviewer could expand on participant's answers if needed or of interest. At the end of the interview participants were then asked to complete a short questionnaire, found in Appendix 4-D, which aimed to gain more demographic information about the whole household. This short questionnaire was seen as a way of rounding off the interview and gave the participant opportunity to ask any questions that they had which may have arisen from the interview.

4.4 Data Analysis

All demographic information gathered via the questionnaire survey was compiled within an individual Microsoft Excel spreadsheet. All 30 interviews were transcribed by the author using Microsoft Word and NVivo 10 software. NVivo 10 software was used to slow the audio recordings down to a manageable pace which allowed the author to transcribe into Microsoft Word quickly and efficiently. Once the interviews were transcribed the word documents were imported into NVivo to allow formatting and analysis to be carried out. The interviews were analysed to uncover the variation in heating behaviours within homes and the reason behind those heating habits. To do this, exploratory questions were compiled in advance inductively from the high level review of the data as interviews were being carried out. The transcriptions were then analysed to answer each one, therefore uncovering more detail on heating use and occupant behaviour. The questions were as follows:

- What heating controls do people have in their homes?
- What controls do people use in their homes?
- How do people tend to adjust the heating in their home?
- Do people have/use secondary heating and why?
- Are there different types of users for heating?
- Do people change patterns of heating due to issues with their heating system (work around)?
- What are the main drivers for how people use their heating?
- Do household dynamics effect how a home is heated?
- Is there any link between types of heating users and other characteristics (such as dwelling type, demographics or income)?

These exploratory questions were then used to create node categories within NVivo to help code the interview scripts for each of the corresponding exploratory analysis topic. Chunks from each individual interview script which related to each of the exploratory questions were highlighted and coded to the relevant node within the NVivo software. The coded interview data for each node was then printed off so that the researcher could further code/analyse the full sample findings by hand, allowing for easy annotation of any points of interest and to highlight key terms used. This was done due to the unstable nature with the NVivo 10 software during analysis, with multiple instances of the software crashing and therefore loss of analysis data. Figure 4.4 shows how different colours were used to separate any points of interest for different exploratory questions when some highlighted interview data was relevant to more than one of the exploratory questions. The figure also shows how the researcher kept annotations and notes to help analyse the interviews.


It's a challenge because I must admit I am not hugely impressed with the TRVs as I don't find them very responsive and they do tend to stick occasionally and I am highly suspicious about the new thermostat where we set it to a value and I don't think it regulates to that so there is something peculiar going on between that and the heating. So I am determined to get to the bottom of it so it's quite hard to find heating engineers who are familiar with heat store systems and they come in and look suspicious and slightly alarmed so I think I need to pursue that more with someone with more experience and I feel more confident in.

It's odd really as So much of the heat in the areas which we use particularly in here during the colder months is often down to how many logs we are sticking in the log burner and that is very much dependant on what the cooking plans are and the time of day. My wife tends to ignore it and just hope that it stays in so I take primary responsibility for shoving the logs in and taking management of all the wood outside as I quite enjoy it even if it is time demanding. But that will allow us to manage the heating in that room.

Figure 4.4 Example of coding

4.5 Findings

4.5.1 Heating controls present and heating controls used

Within the sample it was found that numerous different heating controls were present within the households, these are summarised in Table 4.4.

Table 4.4 Heating controls present within sample

Participant	Wall thermostat	Wall timer/programmer	Boiler timer/clock	Boiler temperature control	Electric heater control	Thermostatic radiator valves (TRVs)
P1			✓	✓		
P2	✓	✓				
P3				✓		
P4	✓	✓		✓		✓
P5	✓	✓		✓		✓
P6	✓	✓		✓		✓
P7	✓		✓			✓
P8	✓	✓				✓
P9			✓	✓		✓
P10			✓			✓
P11	✓		✓			✓
P12	✓		✓			✓
P13	✓	✓				✓
P14			✓			✓
P15	✓		✓			✓
P16	✓	✓				✓
P17	✓	✓				✓
P18	✓	✓				✓
P19					✓	
P20	✓	✓				✓
P21	✓	✓				✓
P22					✓	
P23	✓	✓				✓
P24	✓	✓				
P25	✓	✓		✓		✓
P26					✓	
P27	✓	✓		✓		
P28	✓		✓			✓
P29			✓			✓
P30			✓			
Total number and % of sample	20, 67%	15, 50%	11, 37%	8, 27%	3, 10%	21, 70%

Within the sample 67% reported having a wall thermostat controller within their homes, and 47% reported having a timer/programmer fitted. However when looking at those households which had a form of time control on their heating, either through a timer unit or a clock/timer on the boiler itself, they accounted for 87% of the sample. The 13% with no timer control included the households with electric heating. Of the households which had either a regular or combi boiler, 33% reported not having any form of control on the boiler itself. This could however be due to householders being unaware of the controls on the boiler itself when there is also separate room thermostats and/or timers present within the property. Out of the sample 70% reported they had thermostatic radiator valves within the home, however this varied from the majority of radiators within the household having them to just a couple. The households which only had a couple of radiators with TRVs were living in the older properties where occupants had replaced old radiators and installed new ones with TRVs on them.

Of those households with more than one method for controlling the heating, 46% of those households mentioned using more than one method to control the heating within their home. Table 4.5 summarises which controls each participant identifies as actively using to control their heating within their home. From the reported heating behaviours it showed that 70% of those with wall thermostats used them as a means to control their heating, 60% with a separate timer/programmer to the boiler used it to control the heating, 64% of those with a timer on the boiler used it, 25% of the households which could control the temperature from the boiler chose to do so and finally 38% of the households with TRVs used them for controlling the heating within their homes.

Table 4.5 Heating controls used within households (x represents those controls present in property but not used by participants)

Participant	Wall thermostat	Wall timer/programmer	Boiler timer/clock	Boiler temperature control	Electric heater control	Thermostatic radiator valves (TRVs)
P1			✓	✓		
P2	✓	✓				
P3				✓		
P4	✓	✓		✗		✗
P5	✗	✓		✗		✓
P6	✗	✓		✗		✓
P7	✓		✗			✗
P8	✗	✓				✓
P9			✓	✗		✗
P10			✗			✗
P11	✓		✓			✗
P12	✓		✗			✗
P13	✓	✗				✓
P14			✓			✗
P15	✗		✓			✗
P16	✗	✓				✗
P17	✓	✗				✓
P18	✓	✓				✓
P19					✓	
P20	✓	✓				✓
P21	✓	✗				✗
P22					✓	
P23	✓	✗				✓
P24	✗	✓				
P25	✓	✗		✗		✗
P26					✓	
P27	✓	✗		✗		
P28	✓		✗			✗
P29			✓			✗
P30			✓			
Total number, % of those with control actively using it	14, 70%	9, 60%	7, 64%	2, 25%	3, 100%	8, 38%
Total number, % of those with control and not actively using it	6, 30%	6, 40%	4, 36%	6, 75%	0, 0%	13, 62%

Participant P10 was an exception within the sample as they did not use either of the available control options. They had access to a timer on the boiler itself and TRVs within numerous rooms round the household; however it was reported that the timer on the boiler was broken, therefore not possible to use and there had been issues with numerous radiators in the property resulting in the TRVs not being changed after a heating engineer had been to try and fix the issues. This left the occupant with the only way to control their heating as simply switching the heating on and off at the boiler itself every day. Issues such as these are presented in further detail in Section 4.5.6.

4.5.2 How heating is adjusted

During the interviews participants were asked to describe how they typically adjusted their heating as well as being asked about their use of each of the individual control methods they had available to them in their home. As mentioned previously not all participants reported using all the methods of controlling their heating available to them. The majority of the sample reported using one key control method regularly and perhaps one or two additional methods occasionally or rarely.

Factors which related to how householders controlled their heating included the location and accessibility of controls. Many participants stated that their choice of control for adjusting their heating was related to the convenience of one control option over another, with some stating that often the other method(s) of control was inaccessible to them or that it was 'hidden away', such that they typically forgot all about being able to control the heating using that method.

"The thermostat is just a lot easier for me to get to" *(Participant P12, Female, Aged 47)*

Surprisingly 30% of the sample stated they typically adjusted their heating by simply switching their heating on and off as needed. This was either due to it being the only option the householders had to control their heating or it was down to the participants' desire not to change any of their heating settings. Typically with these participants they had reached their ideal timing schedules and set-point temperature through previous experimentation and felt their home was warm and comfortable so did not see the point with messing with those settings. Therefore these participants either switched the boiler on, leaving their timer to turn the heating on and off as needed or they switched the boiler on so the heating is always on and cycles on and off depending on whenever the temperature drops below the desired set-point.

"Adjusting it is just going to be switching it on or off more than changing the set-point" *(Participant P20, Male, Aged 32)*

"I would say we tend to switch on or off because all the radiators I would say are set to about three, we don't turn them up or down now because there doesn't seem to be any need" *(Participant P14, Female, Aged 45)*

There was a definite split between participants reported use of their radiator valves (TRVs or manual radiator valves) within homes as a means of controlling their heating. A number of participants did mention typically leaving their heating settings alone and simply adjusting the radiator valves as needed in their individual rooms. However other participants stated that they preferred to leave the radiator settings as they were after numerous adjustments to get them on the right setting for each room in the past. There were a couple of participants who stated they rarely used them due to the valves being stiff or difficult to get to.

"We interact a lot with the radiator valves" *(Participant P23, Female, Aged 46)*

"We tend to fiddle around with the radiator valves if we are in a room and it feels a bit chilly…yeah we do tend to control the environment through them frequently" *(Participant P6, Female, Aged 59)*

Many participants reported only adjusting certain controls depending on the season, for example turning radiators on or off, turning the boiler on or off and adjusting the set-point temperature or heating schedule in relation to the season. This seasonal change is something which the Phase 2 study of this doctoral research explores in more detail through measurements of heating use in a different sample. Although the majority of the participants noted changing their heating schedules and set-point temperatures seasonally, most said that they preferred to use boost or advance functions on their heating controls instead of constantly changing their heating settings during the winter months. This demand interaction by participants, where they only interact with the heating system when additional heat is needed may be down to the participants' lifestyles being varied and day to day use of the home constantly changing. In fact one participant reported not using the programmable functions on their heating for that exact reason:

"We override it if we are in all day and the heating has gone off at say 8am and the house cools down by around 9am then we will override it" *(Participant P11, Female, Aged 62)*

"If it is cold I will tend to put it on for like, you know there is a manual button where you can press it and have an extra hour, well that is what I do to heat it for an extra hour" *(Participant P16, Female, Aged 48)*

"Never set any schedule for the programmer thermostat because I think my lifestyle is very flexible so I don't know when I am home or when I am out so I don't think there is much use for me setting a profile for my room thermostat" *(Participant P25, Male, Aged 27)*

Numerous participants did however state that their main frustration with their heating system was feeling that they couldn't control or adjust their heating in a way that they would like, often stating the controls they did have were difficult to use. Usability of controls was reported by many participants when discussing thermostats. Participants mentioned either not being able to work them without the help of the user manual, or mentioned giving up on trying to set them due to time consuming processes or overly complicated programmer functions. One participant mentioned that their system allowed for two time periods to be programmed daily, however reported that it had a minimum duration which it could be set for. This minimum setting was two hours therefore the participant did not see the point in programming the heating to be on twice daily. This was due to the participant feeling that two hours of additional heating was not what they need, therefore just switched it on/off instead.

"We had a problem with that time clock and that is when they gave us this really super-duper digital thing that neither of us could work…we couldn't even make sense of that (manual)…ended up asking for the old controls back…all I want was a button that I could press and it comes on!" (*Participant P5, Female, Aged 62*)

Numerous participants also reported that they felt the system did not heat their home to the same level throughout or that in comparison to a heating system they had previously the one they had now just didn't match up to their expectations. However, those interviewed that had fairly modern heating systems installed reported a much higher satisfaction level, often stating that it was a vast improvement to their previous older boilers. Those with older systems were more likely to report using secondary heating as a way of adjusting the warmth within their home instead of changing the settings on the central heating system.

4.5.3 Secondary heating sources and use of

Participants were asked during the interviews if there was any secondary heating sources besides from the main heating system within the household, and whether these secondary heating sources were used and if so how often and by who. Secondary heating sources are a particularly difficult factor to measure as they are often in only one or two rooms in the dwelling, can be portable, their use is often intermittent and it is extremely difficult to pinpoint secondary heating from temperature measurements alone. It is possible to monitor the use of secondary heating systems through the application of measurement devices. However, these were not implemented in the suite of equipment used on the DEFACTO project and so self-reported use was utilised in the study. Within the sample only five participants reported not having any sources of secondary heating, the remaining participants reported having various secondary heating sources, which are summarised in Table 4.6.

Table 4.6 Number of participants with secondary heating sources and those using them during winter

Secondary heating source	n	Used during winter		
		Regularly	Occasionally	Rarely
Wood burning stove/fire	8	7	1	
Gas fire	8	3		5
Electric fire	3	1		2
Electric fan heater	8	2	2	4
Portable oil filled radiators	4		1	3
Plinth heater	1		1	
Halogen heater	1	1		

As the figures show, those that reported having a wood burning stove/fire as a secondary heating source were also most likely to be those who reported using it regularly throughout winter. Many participants stated that they preferred the heat from these alternative solid fuel heat sources, that it felt more homely and that the residual heat stayed around for a substantial period of time after using it therefore often turned the central heating system off.

"It is sort of a pleasurable thing" *(Participant P9, Female, Aged 52)*

"It is a nice heat to have because it had more interaction with it and a radiator has no emotional relation to it" *(Participant P21, Male, Aged 55)*

The connection many participants made with using the wood burning stove/fire to create heat on cold wintery days could be in line with the Danish use of the word 'Hygge' which represents a feeling of cosiness, creating a warm environment and a sense of well-being, similar to the research identified in Chapter 2 by Devine-Wright et al (2014) on the idea of cosiness. Therefore participants may be using the secondary heating for a psychological benefit as well as the physical warmth benefit.

The remaining participants that regularly used secondary heating throughout winter stated that they often did it as a means of heating a space they were using within their homes instead of putting the whole heating system on.

"During the day I will happily put that on (gas fire) instead of putting the heating on" *(Participant P6, Female, Aged 59)*

Or they were often used as a means to give a certain room (within the sample bedrooms, studies and kitchens were reported as being rooms of use) an extra boost of warmth to ensure the participant felt more comfortable within the room.

A high proportion of those with secondary heating in the form of gas/electric fires or electric fan heaters and portable radiators reported occasionally or rarely using them as additional sources of heat. Of these participants most referred to the secondary heating sources as back-ups if there was ever an instance that the main heating system no longer worked or if there was a power cut. However participants also reported choosing not to use them due to the perceived costs involved with running them.

"They are more decorative and waste so much energy in comparison" *(P8, Male, Aged 55)*

In one instance a participant mentioned that the reason behind not using their gas fire for secondary heating was in fact down to it being deemed unsafe to use following a gas inspection and therefore they saw it more of a decorative feature rather than getting it fixed or replaced. However use of secondary heating will ultimately be driven by what factors influence the participant to use their heating in the first place, those using secondary heating regularly may be influenced by cost factors and believe it works out cheaper to heat an individual room over the whole household using the main heating system.

4.5.4 Main drivers for heating use

Occupants' use of their heating system can be driven by various factors and this study aimed at identifying those which influenced the sample in how they used their heating system. Participants were asked what their main priority was when it came to heating their homes and often their answers were probed further by the interviewer to delve deeper into the reasons behind using their heating system a specific way.

4.5.4.1 Comfort

Unsurprisingly the overriding factor which was identified to influence heating use within homes most was the occupants' desire for comfort. Within the sample 83% identified it to be their main priority. Many participants stated that they would hate to feel uncomfortable in their own home and touched on the psychological feeling of being able to live in a warm and comfortable environment and not wanting to see their own home as somewhere which is cold. It did become apparent that even with the participants in agreement that comfort is a main priority, the level at which people feel comfortable in their own homes varies greatly. Some participants stated they knew their level of comfort was high and even realised that they were probably going slightly overboard with their heating use, however this was also matched by participants stating that they viewed their level of comfort to be below that of "most people". This comparison by participants to other people or what is considered a social norm is an interesting concept as people most likely base these assumptions on their past experiences. So they could be surrounded by friends and family that like to have very warm homes or work in offices which are overheated due to poor building energy management. Similarly those who stated a high comfort setting may have past experiences of colder environments. Ultimately everyone's perceived level of comfort will vary greatly and may not just be down to the physical attributes of that person, be that weight, gender, age or activity levels but could be influenced by what thermal experiences they have had/grown accustom to.

"I have no idea how much we spend so it's not really cost as it is mainly my comfort. I'd rather spend money on heating and rather do without other things than be cold." *(Participant P5, Female, Aged 62)*

"I am one of those people who likes to feel warm and I am fortunate enough to afford the cost of the energy, so I probably tend to overheat the house rather than heat particularly you know to improve the temperature" *(Participant P27, Male, Aged 58)*

"I refuse to be cold in my home…I need to be comfortable in my own home, that is all I ask really." *(Participant P4, Female, Aged 86)*

4.5.4.2 Cost

Alongside comfort, cost was another main factor affecting how participants would heat their homes and a couple of participants stated that it was often a balance between comfort and cost, with some even suggesting it was a 50/50 balance. Although the majority of the participants stated that cost wasn't an overriding factor as they could comfortably afford the energy currently, numerous participants did state that should energy prices continue to rise then cost would certainly become more of an impact on how they would heat their homes.

"Comfort and cost are probably equal priorities as I think I have probably adapted my comfort levels to what I can afford" *(Participant P10, Female, Aged 35)*

One participant also stated that her husband had recently been diagnosed with rheumatoid arthritis and felt that as that progressed and he became less mobile then cost would need to be factored into how they used their heating, mentioning that they may just be more frugal with something else as heating would still be a priority to them. Within the sample there was one participant whose heating use was directly influenced by cost alone and the participant described herself as being too scared to have the heating on due to the fear of receiving a bill which she could not afford to pay. This meant that the participant reported that she would only put the central heating on for a very short period of time each morning which was done as a precaution so that the system didn't break or pipes did not freeze in winter. The participant believed that the only way for her to afford to heat her home was to heat each room as it was used through secondary heating sources, however stated she would keep this to a minimum by adopting adaptive methods such as putting extra layers on or using blankets as a first resort before switching a heater on.

"In terms of not having it (heating) on during the day then yes that is cost" *(Participant P15, Female, Aged 48)*

Within the sample, 23% rented the property and within them three participants had the heating bills included within the rent which presented a different dynamic in relation to occupants' attitudes towards heating use. Typically all-inclusive rent is seen to mean that the occupant will not care about how much energy/heating they are using as they are not the ones paying the energy bill directly and therefore can often be considered to be wasteful of energy. However within the interviews an opposite view was found, with those concerned being careful regarding their energy use within the property to protect the rental price they currently pay.

"I am conscious of trying to minimise the bill for my landlady so it doesn't impact her too much" *(Participant P20, Male, Aged 32)*

However, this could be biased due to those interested in participating within the study were most likely to be energy conscious and therefore might not be representative of all those paying an all-inclusive rent.

4.5.4.3 Energy savings

One third of the participants interviewed mentioned being driven by the desire or preference to save energy and to not be wasteful in their use of heating within their homes. Often these participants mentioned that cost was not a driving factor and they saw comfort as their main priority. However they did not want to be seen or feel to be wasteful of the energy they used to heat their homes. Often these participants went on to list various energy saving actions not relating to heating directly but showing their desire to reduce their overall whole household energy use.

> "It doesn't have to be hot all the time so I try and minimise that…for an environmental perspective" *(Participant P20, Male, Aged 32)*

> "Why would I spend the money if I don't need to and why would I behave that unsustainably if I don't need to?" *(Participant P18, Female, Aged 54)*

> "I don't want to spend money needlessly…I think we are quite conscious about trying to save energy here and there" *(Participant P6, Female, Aged 59)*

4.5.4.4 Health reasons

One driver of heating use which is out with participants' control is the need for heating due to health issues relating to one of the household occupants. One participant reported that due to their late wife they often used to have the heating still running throughout the summer to ensure she was comfortable and prevent further illness. Another participant reported being disabled and therefore only occupied two rooms other than her bedroom. Therefore only these rooms were heated to her requirements but she did have access to the heating controls should she need to change any settings. A further participant, although healthy, reported health being a concern when heating her property as they were aware of the health implications that living in a damp property could cause and therefore, to reduce the risk of falling ill due to damp, ensured that the whole property was heated to an adequate level. However it was not just the health of adults that was reported as being a driver towards how the heating system was used but also mentioned was ensuring that a baby was in a warm environment. Babies and young children were often reported as the cause of changing heating behaviours within the sample to ensure that they don't fall ill at such a young age from being in a cold environment.

4.5.4.5 Clothing levels and expectations

As previously mentioned comfort often drives occupants to heat their homes a specific way and as such influences their heating use. However, occupants' levels of comfort may also be influenced by their desired clothing level and/or their comfort expectations. Within the study there were both those who expected to be able to wander around their own homes in shorts and t-shirts and others who thought that that was a bit wasteful and expected those within their household to know to put on a jumper or additional layers when cold. The need to wear shorts and t-shirts by one occupant was a direct influence in a difference of comfort expectations/activity levels between household members. Therefore it was seen as more of a compromise so that the occupant who felt the cold more could be comfortable within the home. These quotes illustrate the scope of attitudes:

"I don't like wearing heavy clothes at my house, even during the winter I prefer to sit in shorts" *(Participant P25, Male, Aged 27)*

"I live at a level that is not uncomfortable, just enough to be comfortable enough to be in one layer but not wasteful" *(Participant P22, Male, Aged 39)*

"I'm not one of those people who feels like they need to walk around wearing a t-shirt" *(Participant P18, Female, Aged 54)*

4.5.4.6 Additional uses

Use of the heating system in homes for reasons besides providing warmth also became apparent as potential influences on the use of heating systems. The most common example mentioned during the interviews was the use of the heating system to help with drying clothes. Although the majority of those who mentioned this stated they would never put the heating on solely to dry clothes and would rather utilise the heating whilst it was already programmed to be on, however four participants did mention that they may switch the heating system on briefly for this depending on the weather or how urgently the clothes were needed. One participant on a prepayment meter also mentioned how they would prioritise being able to have a hot shower in the morning instead of putting the heating on depending on the amount of money left on the gas meter.

4.5.4.7 Advice given

The last remaining identified driver for heating use in homes was the advice which occupants had been given for recommended heating or general energy use in homes. One occupant reported hearing advice on the radio regarding how it was more energy efficient to use heating systems on a demand only basis. The participant reported that he felt this advice went against the previous advice of using a timer to control the heating and that in general there is a lot of contradicting advice. The availability and the source of information regarding how to correctly use heating systems within homes may have a big impact on how occupants' heat their homes. People may follow advice they are given as being the best or most efficient way to heat their home, without questioning the facts. Advice could be used to save heating energy within the domestic sector, however it needs to be accurate and from a source which occupants would trust. Regardless if it is accurate and trustworthy there is still the risk it may not be as effective as it could be due to the volume of conflicting advice already confusing consumers, therefore any new advice may need to debunk current assumptions and provide clear and easy to understand advice.

4.5.5 Household dynamics and heating use

As mentioned in the sample demographics (Section 4.3.3) 67% of the sample was multi-person households, therefore the dynamics between household occupants can dictate how the heating within the household is used and controlled. Within the sample the majority of participants reported one member of the household typically taking more control over the heating, however this can be due to differences in preferred comfort levels or due to indifference to the heating itself.

"He is usually hot and I'm cold…I am the time controller for that thing (thermostat)"

(Participant P5, Female, Aged 62)

"My wife tends to ignore it and just hope that it stays on so I take primary responsibility" *(Participant P21, Male, Aged 55)*

Those participants that mentioned typically one person taking the control over the heating due to differences in personal comfort were those that felt the cold more than other household members. As such most participants in this situation reported other household members typically wearing lighter or fewer layers, with the example of shorts and t-shirts often popping up.

"I tend to turn it down more, normally we are fine but he does like to wear short sleeves and no jumper whereas I am quite happy in a jumper, but generally we agree" *(Participant P11, Female, Aged 62)*

However it should also be noted that there were five participants who reported telling other household members to wear more layers or to use blankets and jumpers as a solution instead of resorting to switching the heating on for longer or to a higher temperature.

Often sole control of the heating by one occupant was due to other household members having a lack of interest in the heating controls or just a general sense of indifference towards them.

"My husband tends to sort out the controls on the boiler and I know how to switch it on but I tend not to be that interested" *(Participant P15, Female, Aged 48)*

The participants who reported these behaviours previously described their heating controls as being difficult to understand and lacking the knowledge of the location of a thermostat therefore preferred to switch the boiler on or off instead of working out how to change the boiler settings themselves. This indicates that the usability of the controls themselves can put off certain members of the household from interacting with heating.

Within rented accommodation the dynamic between those sharing the property can influence the heating use with potential tension arising from disagreements surrounding temperatures and durations. Within the sample one of the participants was living in shared accommodation and stated that they felt unsettled about wanting to change the heating as they seen it to be a shared resource within the household. To avoid any disagreement the participant took the effort to discuss the heating schedule and temperature with those other tenants to come to an agreed solution. However during the interview the participant mentioned the current heating settings not being ideal and felt a lack of control given differences in personal comfort levels.

"I have no control over the heating in the other rooms that are rented out, or the other lodgers" *(Participant P20, Male, Aged 32)*

However another participant admitted that they were probably quite controlling of the heating but did not see any need to change the current heating behaviour within that shared property as the other tenant had not raised any issues with how the heating was currently being used, even with the participant often switching the boiler off whilst they were still in bed.

"Embarrassingly I usually leave the house earlier and I turn off the boiler completely…so I guess I am a bit of a boiler Hitler" *(Participant P13, Female, Aged 36)*

The presence of children within the household creates a slightly different household dynamic especially when those children are very small. Participants reported that they wanted to ensure the child was kept in a warm environment.

"I do use the heating a lot more than what I used to with the wee one" *(P29, Female, Aged 26)*

However those with slightly older children reported the desire not to have the children messing with the heating controls or simply that the children themselves were not really interested in knowing how to control the heating. Therefore those households with older children stated that often the children knew how to switch the heating on or off if needed however it was on rare occasions that the child would have to interact with the heating.

"I was hesitating because of my son…we don't encourage him to just going and changing the thermostat" *(Participant P23, Female, Aged 46)*

"Two of the three (children) know how to switch the heating off or put it on if they were cold or left on their own so they would know how to put it on if needed" *(Participant P14, Female, Aged 45)*

One participant did report that their children tended to be the ones in disagreement regarding the heating within the home, often demanding that it should be warmer yet the parents typically disagreed that it was cold. In contrast another participant stated that their children had been raised so that they put on a jumper before requesting the heating was adjusted within the household. Often those households that reported a child having a significantly different level of comfort than the rest of the household were the ones that reported the child taking control of their own room through use of radiator valves or having the availability of a secondary heating source to use if very cold.

From the participants within this sample it shows the presence of a child impacting the heating use within a household. Typically those with very young children reported longer periods of heating use. Then when the children are older and have developed their own level of comfort expectations there might be further disagreement regarding the heating within a home. This was found more in homes where adaptive heating behaviours were not reported as having been instilled into them. Tensions within households can then become apparent when the children start interacting with the heating system but not owning up to changing the settings.

"I tweak it (thermostat) down sometimes also when I notice someone has tweaked it up" *(Participant P8, Male, Aged 55)*

"No one ever tends to own up to doing it" *(Participant P15, Female, Aged 48)*

A further dynamic that was mentioned by numerous participants was the households' reaction to having visitors. Interestingly a couple of participants within the sample mentioned having a different view on heating due to the presence of visitors to the household.

"If we do have visitors coming over we will boost it up more than normal so the house is warmer" *(Participant P8, Male, Aged 55)*

"If we have people round we often think we better light the fire or better put the heating on, but when it is just us we will be a bit stingy" *(Participant P9, Female, Aged 52)*

This shows that often occupants will put the heating on out with their normal heating behaviour for visitors ensuring that they are welcomed by a warm environment. This could also indicate that the households which 'boost' the warmth within the home may believe that it is a social expectation to have a warm home or that the participants feel that their level of acceptable comfort is lower than their guests and as such make an exception to meet their visitors comfort levels.

4.5.6 Problems with heating systems impacting heating behaviours

Within the sample only 13% of the participants mentioned having no problems with their heating system which impacted on their use of it. The problems reported during the interviews ranged from issues with parts of the heating system such as the radiators or thermostats, issues from the original installation of the heating system, overly complicated controls, issues with the building fabric or issues which are holding occupants back from replacing their current system.

Issues relating to the thermostat with households fell into two main categories, occupants reporting that they believed their thermostats to be inaccurate and the thermostat locations. Numerous participants reported being suspicious of the accuracy of the thermostat itself either having to have the set-point extremely high to get a comfortable environment within the home (*Participant P21, Male, Aged 55*), or having to only move it the smallest of degree to get the heating to switch on *(Participant P7, Male, Aged 26)*.

"The thermostat control…bugs me as I have to have mine set quite high to get a temperature…don't think the temperature on the thermostat matches the temperatures we get as I have to have that set to 25-27 degrees to get a nice ambient temperature in the bedrooms." *(Participant P12, Female, Aged 47]*

However there was also cases where the inaccuracy was believed to be due to the location of the thermostat itself. One example included a thermostat located on an external uninsulated wall of a 1600's building where the participant believed, it was reading a much colder temperature. This participant could move the thermostat to a new location due to it being a wireless thermostat controller, however not all participants were able to do this and the location of their thermostat caused problems. Some participants reported being unable to locate their thermostat,

"It might be in the hall, yeah I think it is but not sure where really" (Participant P16, Female, Aged 48)

Some reported that they believed the thermostat was not located in the best place. This was often due to it either being located extremely close to a heat source such as a radiator or in the warmest or coldest room in the household therefore giving a false reading to represent the rest of the dwelling.

"Rather unfortunately situated in the little sitting room, which is possibly one of the warmest rooms in the house" (Participant P18, Female, Aged 54)

Participants also had problems with their radiators within their homes which affected the use of the heating system. Some participants felt that the radiators did not add anything to the warmth of a room when switched on even when switched to the maximum. Similarly some occupants reported their radiators not being adequate any more due to their age and often felt that they were undersized for the room. Not all issues surrounding radiators was down to inadequate systems in fact two participants mentioned not using radiators within their home, one due to the need to locate a sofa directly in front of the radiator therefore switched it off, and another who mentioned having three radiators in a large open plan kitchen diner, but felt two provided more than enough heat so never got the third radiator connected to the system.

Some participants reported having to deal with broken parts of their heating system and mentioned how they adapted their heating use around these issues. One participant mentioned that they discovered their thermostat had been damaged one day and the temperature selection pin had been broken so to ensure it did not happen again they had stuck the temperature selection pin to the maximum setting on the thermostat with blutak and then adjusted the room TRV's to suit. One participant mentioned that when they tried to switch their boiler onto just hot water, the pressure gauge on the boiler dropped dramatically and to stop it happening again they simply left the boiler set to heating and hot water all year round and relied on switching the thermostat to the lowest temperature setting during the summer months. Two participants in rented accommodation mentioned problems with their boilers. One had a broken timer on the boiler so controlled their boiler by switching it on and off as needed. The second participant reported the problem with their boiler was that it was only heating half of the dwelling due to issues with the pipe work in the property, therefore relies on heating the remainder of the dwelling through the use of electric heaters.

"The timer on the boiler is broken, which has been broken since I moved in and apparently they can't fix it because the boiler is too old…or they just can't be bothered!" *(Participant P10, Female, Aged 35)*

"The radiator system, the pipes and all are very old…they told us there wasn't much they could do as the pipes were really really old so it would just keep happening every time they were to clean them all out…thing with the pipes is not something that you can really ask your landlord to buy new ones” *(Participant P13, Female, Aged 36)*

Problems reported also arose from installation of the heating system itself. One participant reported having trouble with their heating which stemmed from the installer fitting an outlet pipe which was far too small for the boiler which meant that water vapour was condensing back into the boiler. This meant that the thermostat inside of the boiler was then affected which resulted in having to get another engineer out to not only fix the boiler but also install a correctly sized outlet pipe. Another participant reported that the radiators were not installed where they wanted them to be fitted as the installer said it would save on pipework and gave a lot of different excuses which the participant just accepted. However the participant is now left unable to afford moving them and just has to accept their location. One participant mentioned that the location of their gas meter was extremely difficult to get to but the engineers refused to move it when installing a new one unless the participant paid a cost of £500 to move it. The location of installed controls has already been mentioned however one participant also mentioned how their boiler had been installed in an extremely difficult to access cupboard and therefore they did not change any of the settings on their boiler and simply controlled their heating through the controls which were accessible to them.

Although not technically problems with the heating system itself four participants did mention the building itself impacting their heating use. One of these reported their kitchen to be the coldest room and made sure to close the doors leading from the kitchen to the hall and living room to stop heat escaping. The reason the kitchen was the coldest room was due to a hole in the external wall in the kitchen which had been left unfixed for some time and therefore let cold air into the kitchen, particularly on windy evenings. The remaining three participants all mentioned issues with damp in their properties. This meant that rooms which were not used regularly still had to be heated even when the occupants preferred that the radiators were switched off completely in those rooms.

"When we try turning the radiator off entirely…we got a bloom on the furniture…so actually we do keep it warm due to that" *(Participant P9, Female, Aged 52)*

"It is a very damp house so I do it (open windows) to get the damp out" *(Participant P13, Female, Aged 36)*

While many participants stated they knew that their heating system was old and very inefficient now most of them had the view that replacing the system was either going to cost far too much money for them to really consider investing in a better system, although they mentioned they would obviously need to if it was to break. However some also mentioned "if it's not broke don't try and fix it". Participants viewed replacing the system before it was at the end of its lifespan as being wasteful. Replacing the system in old homes was also viewed as being quite a disruptive process and one that not everyone, especially elderly participants, would really be pushing to happen until it was an absolute necessity.

"I turned it down (new boiler), which may sound foolish but the upheaval!" *(Participant P4, Female, Aged 86)*

"At my age I don't want to have to start ripping up floorboards" *(Participant P1, Male, Aged 80)*

4.5.7 Different types of heating user/behaviour

Participants within the study were characterised, using their interview responses, by the heating user types suggested by Rubens and Knowles (2013) where five main user types were reported; rationers, ego-centric, hands off, planners and reactors, as reported in more detail previously in Chapter 2. Rubens and Knowles identify five scales (Figure 4.5) with different criteria. By using these scales and identifying the placement of defining features or variability on these scales, the user types can be identified.

However when looking more closely at the reasons why people used their heating a specific way it was found that although a number of participants could be easily classified as one of the five main user types by Rubens and Knowles (2013) it may not be an accurate description of how they would prefer to use their heating. This is due to problems with their heating system restricting their use and participants resorting to other methods. Participants reported that they would like to use it in a different way if it was possible. Therefore their desired use of the heating system would mean they were classified as a different heating user type. This is shown by an example below:

"I am frustrated that the timer doesn't seem to work on the boiler as it would be nice to know I could have the heating off when I am out and on when I am in because at the moment it is just left to one temperature and only turned right down when we are away for a few days." *(Participant P7, Male, Aged 26)*

This participant would be characterised to be showing a hands off behaviour according to Rubens and Knowles (2013) where they typically just left their heating set at one setting and only interacted with it when they needed, however the participant stated that had the timer been working on their boiler then they would use that to reflect when they were in and out of their home, a characteristic more in line with the planners behaviour type. This cross over between user types was found for a number of participants where they showed characteristics of one user type but in fact desired to act like another user type.

Figure 4.5 DECC heating user type and scales (Rubens and Knowles, 2013)

Table 4.7 represents how the sample would be classified using the framework scales suggested by Rubens and Knowles and shown in Figure 4.5. The scales used to determine which user type a participant is, have either one or a number of defining features which refers to a characteristic that the participant classes to be of importance. For instance rationers defining feature is saving money and therefore are further to the spend side of the comfort vs spend scale. The double headed arrows represent instances where there may be variation between other users with similar defining features or there was variation in the preference of that scale. These scales have been applied to the sample to identify which user type they belong to. This was done by categorising their defining features which were stated as important from the interview transcripts. Where participants exhibited more than one user type, when defining features are identified which fall into different user characteristics, these are indicated by selecting all relevant user types to that participant.

Table 4.7 Heating user types identified

	Rationer	Ego-centric	Hands off	Planner	Reactor
P01			✓		✓
P02			✓		✓
P03	✓				
P04		✓	✓		
P05		✓			✓
P06					✓
P07				✓	
P08				✓	✓
P09					✓
P10					✓
P11	✓				✓
P12			✓		✓
P13	✓				✓
P14			✓		✓
P15	✓		✓		
P16			✓		✓
P17			✓		✓
P18	✓	✓			
P19		✓		✓	
P20			✓		
P21					✓
P22					✓
P23				✓	
P24			✓		
P25		✓			✓
P26				✓	✓
P27		✓			
P28	✓			✓	✓
P29				✓	
P30			✓		
% of sample	20%	20%	37%	23%	60%

As can be seen by the results, 57% of the sample are categorised as being more than one heating user type as a result of exhibiting defining features in more than one of the user type scales. One participant even exhibited behaviour relating to three of the different user types. The remaining 43% of the sample were classified as belonging to only one user type. 60% of the sample exhibited characteristics of the reactor user type, which correlates with the high proportion of participants reporting their main heating use driver as being comfort.

The user types however do not factor in differences in desired levels of comfort through thermal expectations so preferred clothing levels etc. Nor do they factor in the reasons behind heating use which might require the heating to be left on such as damp. Although the author acknowledges that the framework provided by Ruben and Knowles is just that, a framework, the findings from this study allow it to be expanded to create a heating taxonomy or heating "characters" which take into account some of the factors that may restrict heating users, and therefore attempts to reduce participants being categorised in multiple heating user/character type.

4.6 Heating behaviour taxonomy

From the findings from this study a new heating behaviour taxonomy was developed resulting in ten heating characters, shown in Figure 4.6. This heating behaviour taxonomy focused on the drivers behind heating use and, unlike Rubens and Knowles (2013), took into consideration limitations occupants may have which would impact how they use their heating system. By considering possible limitations in use of heating systems the taxonomy splits into two main overriding categories, those restricted in heating use behaviour by the heating system itself and those not restricted and as such driven by specific drivers.

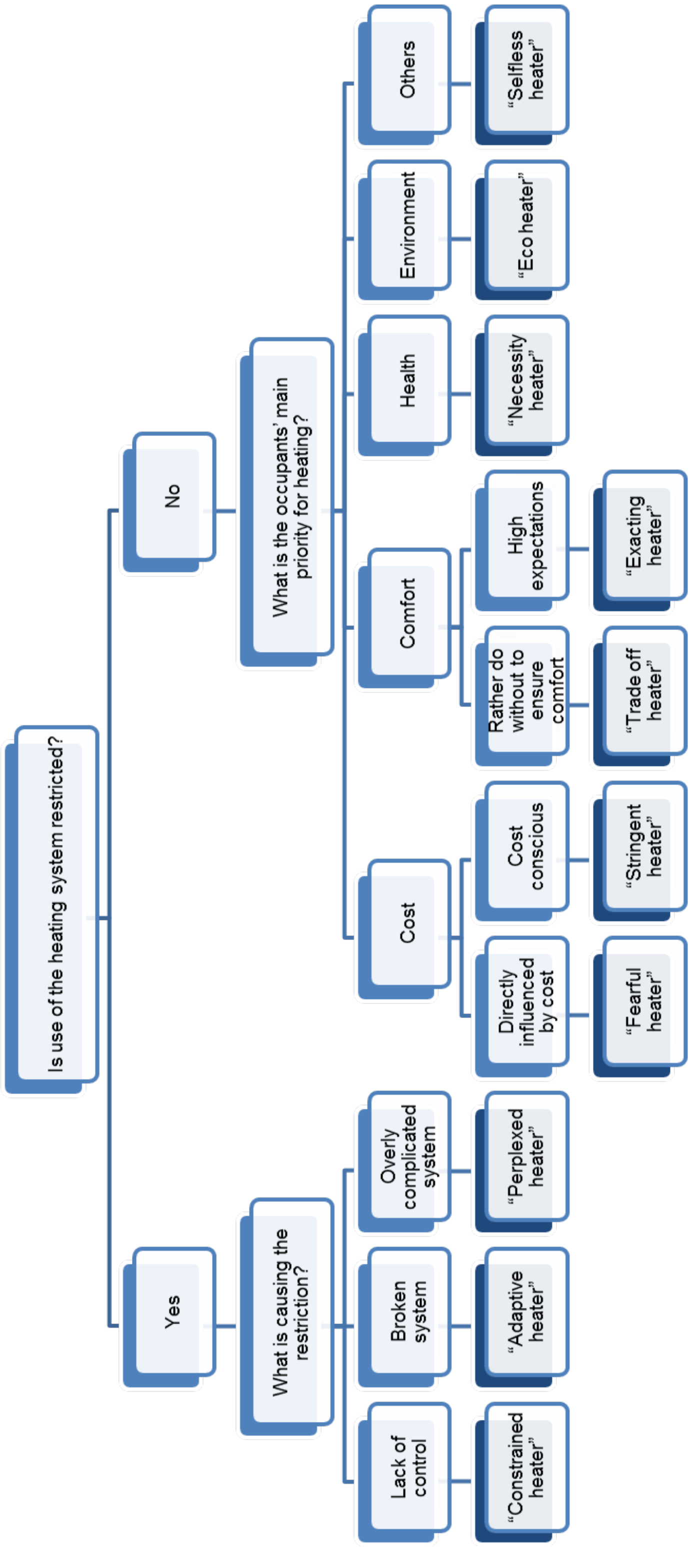


Figure 4.6 Heating taxonomy developed from interviews

4.6.1 Restricted by heating system

Those that were restricted by the heating system itself or parts of the heating system were divided into three different categories, those who had a lack of control over their heating, those who were dealing with broken heating systems and those who considered their heating system to be overly complicated. Each of the three types has different attitudes towards the use of their heating but all have a level of dissatisfaction towards how they have to use the heating within their homes.

4.6.1.1 Lack of control

Those who have no control over their system are referred to as "Constrained heaters". This is because the only way that the occupant can control their heating is by switching it on or off, therefore they are "constrained" from controlling it in any other manner. These sort of heating characters are likely to be unsatisfied with this situation but have no option other than to deal with it, or pay to upgrade their system to install new controls or a new central heating system. Therefore "constrained heaters" are likely to have secondary heating sources within their property and may regularly rely on them for more control of the heating or rely on adaptive measures to gain additional warmth. These heating characters may often resort to leaving their heating on a lot more than those with the ability to control the heating better and therefore there is an energy saving potential within this group.

4.6.1.2 Broken system

Those who are referred to as "Adaptive heaters" are dealing with a broken heating system or broken parts of their heating system and therefore chose to work around this and find more "adaptive" ways to heat their home, whether this be from using secondary heating, changing how they use rooms where the system may be broken, and using adaptive comfort methods such as blankets, further clothing layers, slippers etc. These heating characters may be restricted by costs to overcome these issues, or perhaps living in rental accommodation where problems with the heating system are not seen as an urgent matter as long as their heating is still working, even if not to its optimum condition. In rental accommodation occupants may have to get permission from the landlord for any problem to be fixed and therefore cannot just sort the problem straight away like they may want to. Owner occupied "adaptive heaters" may be held back by the financial costs or the upheaval of having any problems fixed.

4.6.1.3 Overly complicated system

Finally there are those who can be referred to as "Perplexed heaters", who are those whose use of their heating system is restricted due to overly complicated design and/or controls. These overly complicated heating system designs may result in these heating characters not being able to use their heating system efficiently, being unaware of the functionalities of their heating system and again being dissatisfied with the heating system. "Perplexed heaters" may be more likely to include elderly people who cannot understand how to work certain controls due to small displays or lettering, small buttons which may be too close together and with multiple menus to go through to get to set simple heating settings. These heating characters are therefore more likely to use their heating on an on/off basis or may leave the default settings as they are, even when not suited to their lifestyle. Like "constrained heaters" these "perplexed heaters" have the potential to save energy with new systems or controls which they understand a lot easier and can set to suit their day to day requirements.

4.6.2 Not restricted by heating system

Those who are not restricted by their heating system are categorised by their main priority and reasons behind their specific heating use behaviours. The identified priorities within the sample, which resulted in separate heating characters, included cost, comfort, health, environmental attitudes and prioritising others over themselves.

4.6.2.1 Cost

Those occupants who prioritise cost with their heating use are divided into two different heating characters dependant on whether their heating use is dictated by the cost or whether they are extremely conscious of costs. Those referred to as "fearful heaters" are those whose heating use is directly related to the cost associated with using the energy to heat the home and often these occupants are "fearful" of receiving a bill which they simply cannot afford. Therefore these occupants are most likely to keep their heating use to a minimum and may choose to only heat specific areas of the dwelling believing that this will reduce the cost. These occupants will often resort to putting on multiple layers of clothing and having hot drinks or moving around to try and improve their own thermal comfort before resorting to putting the heating on. Often they may also use secondary heating sources in replace of the main central heating system so that they can control the heat better and minimise their heating usage. Those referred to as "stringent heaters" are not dictated in their heating use by costs to the same extremes that "fearful heaters" are but they are extremely conscious of their heating use and the costs associated to this. Often these occupants may be on prepayment meters or lower incomes and want to try and minimise large bills however still expect to be able to use their heating system as normal, if not just "stringently". These occupants are likely to keep their heating use to a minimum and try and stick to the heating schedules they set and use adaptive measures in-between those scheduled heating periods to improve their comfort instead of putting the whole heating system on. These occupants may also make use of secondary heating sources to have localised heating during these non-scheduled heating periods.

4.6.2.2 Comfort

Comfort is a priority for many when heating their homes and is split into two different heating characters, "trade-off heaters" and "exacting heaters". Those referred to as "trade-off heaters" are those occupants who desire to be comfortable within their own home and see it to be a priority that their home is a warm environment that they are happy to live in. To ensure that they can reach this environment these occupants often make “trade-offs” between other items such as an expensive holiday or new TV. They are careful in maintaining a balance in what they expect in the rest of their day to day lives for the knowledge that they live in a comfortable and warm home. Alternatively the other heating character driven by comfort are those who have quite a high comfort expectation and as such may be referred to as “exacting heaters” due to their “exacting” comfort conditions. These occupants are those who like to “wander round their home in shorts and t-shirts in winter” and to ensure they can achieve this will often have their heating on for long periods of time and/or at much higher set-point temperatures.

4.6.2.3 Health

Some occupants are influenced by health issues with their use of heating within their home and these are referred to as “necessity heaters”. Occupants that fall into this heating character type are those who may be less mobile due to a disability, may have an illness which impacts their thermal comfort, or it may be homes with small babies/young children who require a warmer temperature. Often these occupants heat their homes to ensure they can prevent further illness and therefore it is a “necessity” to them to have it warm. This means that these homes may often have longer heating durations and/or a higher set-point temperature to ensure this comfortable environment lasts throughout the day. These households may also control their heating by the easiest method available to them, in particular if they are less mobile. Therefore they may be more likely to switch the controls on/off rather than use TRVs and more likely to heat the whole house instead of trying to adapt individual rooms to their needs. Similarly those who are less mobile may resort to leaving their heating on longer as they are unable to keep going to the controls to change settings when they feel like it. “Necessity heaters” may benefit from new heating control technologies that are portable and therefore can be placed in an easily accessed area, those with remote access, and those which have some form of temperature feedback so that occupants can see what the temperature within the dwelling is.

4.6.2.4 Environment

Those who prioritise the environment when heating their homes are referred to as "eco-heaters". These occupants are very aware of trying to reduce their energy use within their home, not just the energy used for heating and therefore they are very "eco" in their thinking and actions. "Eco-heaters" are more likely to have investigated how their heating system works and build up a mental model that lets them understand the impact of their actions on how much energy it equates to, although this may be more in a monetary value of energy rather than the kWh value. These households are likely to make use of solid fuel options with perhaps wood burners to use reclaimed or recycled wood in as they believe these to be more eco-friendly over central heating. "Eco-heaters" are likely to have more control options to ensure they use their heating system to its optimum efficiency and are likely to have considered or invested in renewable energy sources such as solar hot water heating or solar panels.

4.6.2.5 Others

Finally there are those where their heating character is influenced by prioritising others over themselves and therefore are referred to as "selfless heaters". These are occupants whose heating use is in relation to others within the household who may have different comfort levels, often resulting in higher temperatures than those which are their own comfort level and therefore they are often "selfless" in how they heat their home to ensure that other occupants are content. These occupants are most likely to take adaptive measures themselves to improve their own comfort such as lower clothing levels or set different areas of the home to different temperatures through use of radiator valves (TRVs or manual) or windows. Similarly "selfless heaters" may accept a lower comfort level to their own comfort preference, in favour of meeting the comfort needs of others, and again likely to use adaptive measures to improve their own comfort.

4.6.3 Summary of heating behaviour taxonomy

Although this heating character taxonomy is not definite, it provides an alternative insight into the reasons for heating use and the impact these have on how the heating system is then used within a property. By understanding the drivers behind heating use in homes it is clear to see how difficult reducing the energy used for space heating within the domestic sector is: certain heating characters may well respond better to new heating control technology than others; one solution or new technology will not fit all households'; and more research is needed into exactly how occupants adapt to new heating controls being installed.

4.7 Discussion

The aim of this study was to uncover how people use their heating in a sample of 30 homes and uncover the reasons, in particular, behind occupants' preferential method of controlling their heating when more than one option is available (i.e. thermostat, timer/programmer, radiator valves, thermostatic radiator valves or boiler controls). The main drivers influencing heating use, identified in this study, fell into four categories; comfort, cost, health and energy savings. These align with two of the categories identified by Wei et al, occupant related factors and other factors. Within the occupant related factors identified by Wei et al (2014), the occupants' own thermal sensation as well as health were identified as influencing factors, which agrees with this study's finding of comfort and health being driving factors towards heating use. Wei et al (2014) listed heating price and energy use awareness within the other factors category, agreeing with this study's finding that cost and energy savings can have an influence on occupants' use of heating in homes. Rathouse & Young (2004) reported the importance of understanding the drivers behind occupants' use of heating within their home and this study has presented just how varied these drivers can be.

The heating use drivers and heating use characteristics identified in this study were used to develop a new heating use taxonomy, building on the work of Rubens and

Knowles (2013) and their heating user types. The heating use taxonomy provides a framework to understand the heating use behaviours of specific characters linked with the driving factors towards heating use for those households. Those with a lack of control or broken systems used workaround solutions to try and achieve the best heating strategy for their home; consequences of these restricted systems have not previously been reported by Rubens and Knowles (2013), Raaij (1983b) or Guerra-Santin (2011). Policy measures aimed at improving energy efficiency may need to address restricted heating systems as a priority, before the energy saving potential of new technologies or retrofit options can be considered.

Participants in this study, despite having multiple methods to control their heating (wall thermostat, timer/programmer, boiler controls, TRVs etc.), reported using one predominant method for reasons of personal choice, usability and accessibility of control options. These findings agree with those reported by Rathouse & Young (2004) that poor positioning of controls (be that positioned too high, too low, somewhere dark, out of reach or hidden away), led to difficulty for occupants to use these heating controls. This has implications on energy use within these homes, as restricted access to control may lead to households heating unused spaces, or leaving their heating on for longer durations than needed. However it should be noted that within this study the interviews only focused on one participant within each household and therefore they may be unaware of how others in the household adjust the heating. Although the participants inferred as to how others within the household used the heating system, and often reported similar difficulties for them, it may not reflect exactly what other household members do with the heating system. This is a similar limitation found with previous work (Rubens and Knowles, 2013, Guerra-Santin, 2011, Raaij, 1983b) where the response mainly reflects one individual household member and as such may not show the full picture of heating use within the household.

By linking the heating use drivers with the characteristics of heating use, a diversity of drivers and heating use characteristics were uncovered, even within a small sample similar in size to that used by Rubens and Knowles (2013). This study may have identified a larger number of characters due to the level of detail in the taxonomy, however this level of detail about the characters can be used to understand how people are driven by certain factors when using their heating. This study found 30% of participants reported using their heating in an on/off manner rather than adjusting thermostat temperatures or heating schedules, possibly as a result of the controls being overly complicated for some participants. Controls not being used in an optimum way and changes rarely being made have been reported previously by Caird et al (2007) and Shipworth (2011).

In households with TRVs in this study, 62% reported barely touching them at all, due to participants never considering changing the settings or due to difficulties in the use of the physical device. This finding is similar to that reported by Rathouse & Young (2004) who reported occupants not interacting with radiator valves and TRVs due to badly located valves, restricting occupants' access to adjust the settings. However this study also found participants reporting not interacting with TRVs due to a preference of a uniform temperature throughout their home. This finding suggests that, in those homes, zonal heating control technology may be less likely to be adopted as those households may not see the need for it when content with a uniform temperature. However installing zonal control in households, where existing TRVs are difficult to use or badly located, could result in larger energy savings if householders are willing to set up the system appropriately.

In this study there were those who reported using secondary heating regularly during winter either instead of using the main heating system or in addition to the central heating. 88% of participants reporting the presence of wood burning stoves/fires within their homes also reported regularly using them over winter, often reporting a preference towards using them. This preference was often down to not only the warmth they provide but the sense of well-being which also came from the use of wood burning stoves/fires. This finding agrees with Devine-Wright et al (2014) who reported people's perception of thermal comfort can be influenced by a feeling of cosiness. Often those reporting using wood burning stoves within this study reported that the heat generated from the stove switched their central heating off due to the heat spreading to the hall where the thermostat was located; this could result in some energy savings. However, those using secondary heating sources such as portable radiators or gas fires are very room specific and their use is unlikely to cause the thermostat to switch the central heating off, and therefore may be using energy in addition to the energy used by the central heating system.

Due to the in-depth nature of the interviews carried out for this study, the sample size was small and therefore cannot be seen as being representative of the heating behaviours across the UK. However the sample covered a range of demographics, dwelling types and occupancy levels, therefore providing a perspective into the variation in heating use and the reasons behind such use within the sample. The study has presented a taxonomy of heating use which combines heating use behaviours and the influencing factors behind them which can be used as a framework to understand more about how different influencing factors impact heating use in homes to help target new heating policy and technology more effectively. In particular, the problem of some occupants dealing with ill-working heating systems highlights that some households may require a focus on fixing problems with the heating system first before trying to improve it with new technology. The study has also shown wood burning stoves/fires being used not just for additional warmth as secondary heating sources but also for achieving a sense of well-being and cosiness within the home. Overall this study has shown that heating use in homes is extremely varied and the reasons behind heating use behaviours are not necessarily always determined by user preference.

Chapter 5: How do people actually use their heating controls?

This chapter focuses on the research carried out for Phase 2 of this thesis, an in-depth study to understand how occupants use their heating system within their home following new controls being installed. This chapter details the aims and objectives of the study along with how the study was carried out and focuses on the quantitative results found and the implications these results have on heating use within UK households.

5.1 Introduction

As identified during the literature review in Chapter 2 domestic energy research is typically focused on whole household energy use, however the importance of research into space and water heating is taking precedence, as it accounts for the largest proportion of energy use in homes and so it is surprising that still little is known about occupants' use of their heating within homes. Although numerous studies, as identified in the literature review, have been carried out investigating heating durations, temperatures and whether energy models use a true reflection of heating characteristics for modelling energy use or not, the majority of these studies have based their findings on temperature measurements alone. Previous studies such as Kane et al (2015) put forward metrics to describe heating patterns in a large sample of households within Leicester, however these metrics were derived from temperature sensors being placed in the household's living room and main bedroom. Heating durations and set-points were then calculated from only these two internal temperature measurements. Similarly Martin et al (2006) reported on heating periods in 59 homes with insulation upgrades by calculating the heating duration from temperature sensors placed on radiators. The Carbon Reduction in Buildings (CaRB) study monitored 358 households (identified as having central heating out of a total sample of 427) and again derived the demand temperature and heating duration within these homes from temperature measurements in the living room and the main bedroom (Shipworth et al, 2010). These estimated findings on heating use were then compared to reported heating use from interviews with householders.

Relying on temperature measurements to identify heating use in homes may fail to take the influence of the occupants into consideration and therefore may miss detail relating to heating use. Various factors could be involved such as use of secondary heating or as identified in Chapter 4 unexpected situations that force occupants to use their heating in a specific way which may not be their preferred heating behaviour. By understanding this detail, characteristics of heating use in UK homes can be compared against the current assumptions made within tools such as energy models which have to factor in standard assumptions relating to factors such as occupant behaviour, demand temperatures and heating use durations.

This chapter describes an in-depth explorative study of how new heating controls were used. They were installed into a small sample of homes, giving the occupants a portable digital thermostat with the ability to programme individual daily heating schedules and had remote heating control access. Unlike the Phase 1 study presented in Chapter 4, this study investigates how occupants actually use their heating system through monitored data as well as their reported use through interviews. The purpose of this study was to explore heating use in homes by recording set-point temperatures, heating durations, manual overrides and how this varies during the shoulder months and winter months.

The structure of this chapter includes a recap of the aim of this study and its objectives contributing to the overall thesis. Section 5.2 details the data collection used within the study, the heating controls installed within the participating homes as well as detailing the remaining monitoring equipment and other data collecting techniques used. Section 5.3 details the data analysis that was carried out. Section 5.4 presents the results of this study which are separated into the results during the shoulder months and during winter, before detailing the results relating to the influences on heating use and characterisation of heating use within the sample, as well as comparing this study's results with current assumptions and studies. Section 5.5 contains the discussion element of this chapter which critiques the results and methods used for the shoulder months and winter months. Section 5.5 also discusses the impact of the different heating categories identified in this study have to a wider context, before detailing the author's view for future work in this area. Section 5.6 summarises this chapter by presenting the key findings in relation to the chapter's aim and objectives.

This study set out to answer the following research questions:

4. *How varied are household heating patterns regarding demand temperatures, heating period durations, household temperatures achieved and the household interaction level with heating controls?*
5. *How does heating use in UK houses evolve during seasonal shifts from autumn into winter and how does this compare with moving from winter into spring?*
6. *Do many households keep the default settings after installation of new controls?*

By answering these research questions this study met the following objectives of this doctoral research:

Conduct a second phase explorative study using both qualitative and quantitative methods to develop an in-depth understanding of heating use within a small sample of households with new heating controls installed.

Objective 4

Analyse the evolution of heating practices through seasonal shifts from use of quantitative data achieved from the new heating controls installed to see how occupants change their heating practices moving between seasons.

Objective 5

The findings from this study contribute to the overall aim of this research of uncovering heating use behaviours in UK homes through developing an in-depth understanding of heating use within a small sample of households with new heating controls installed.

5.2 Data collection

5.2.1 Overview

Phase 2 of this doctoral research, as described in Chapter 3, used the Go Digital pilot study, both in the design of the overall study and the data collected. The author's involvement in each element of the Go Digital pilot study and this Phase 2 research was outlined in Chapter 3, Table 3.3 (Page 95). The Phase 2 study was focused on researching the way different households used their heating systems and understanding how they adapted to new digital heating controls. Figure 5.1 summarises the different stages of involvement with the participating households and the order in which these occurred.

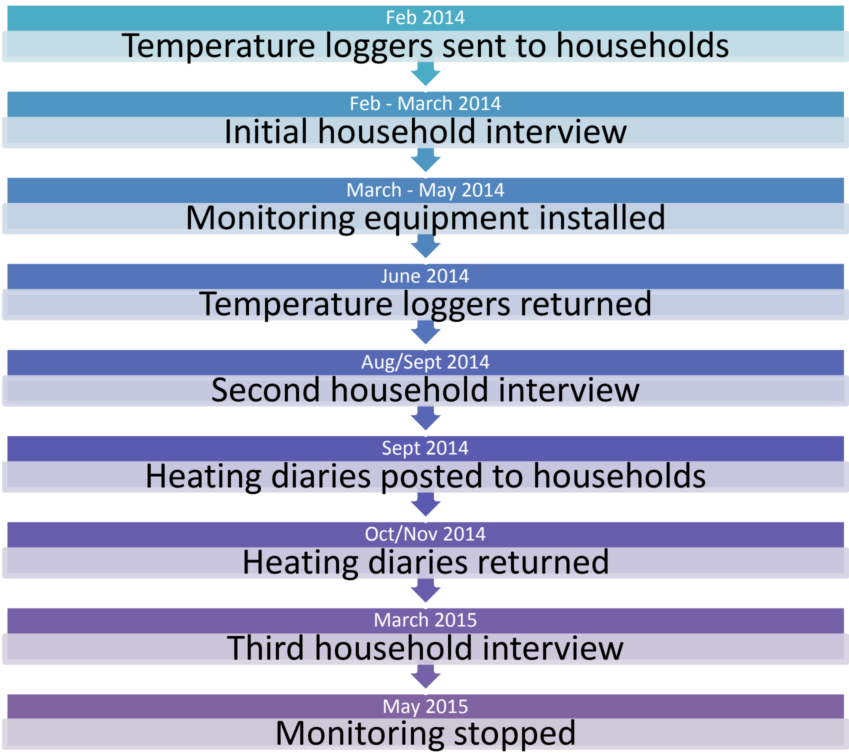


Figure 5.1 Order of participant involvement for Go Digital study and this thesis

The Phase 2 study of this doctoral research used a mixed method approach of both qualitative and quantitative research. This approach was used to ensure a detailed picture of heating use within the participating homes was gained to provide results that could expand on the previous quantitative research on heating use and the qualitative research on occupants' behaviour relating to energy use within homes identified within the literature review, therefore covering the following benefits of using a mixed methods research design as identified by Robson (2011, p167):

- triangulation;
- completeness;
- answering different research questions;
- ability to deal with complex phenomena and situations;
- explaining findings; and,
- illustration of data.

Quantitative methods within social research have typical features where measurements and quantification of a specific subject is central to the research design with measurements that are reliable and show validity of key importance (Robson, 2011, p18). To meet the aim of this study, physical measurement of heating use within homes was vital. To ensure originality, measurements other than just temperature had to be included. This study included measurements of temperatures in every room within households, electricity and gas usage, previous energy usage, set-point temperatures, use of heating controls and household characteristics. The quantitative research methods collecting numerical data allow for statistical analysis of the measured data to be carried out. However due to the small number of participant households within this study it is unlikely that the findings can be generalized to represent the wider UK household population.

Both the qualitative and quantitative data is used within this chapter and within chapter 6. This chapter focuses predominantly on the physical measured data. Chapter 6 predominantly focuses on the use of qualitative interviews within the Phase 2 study and corresponding quantitative measured data to describe the benefits of using a mixed method approach for this study.

5.2.2 Recruitment

Recruitment of participating households for the Go Digital pilot study occurred with the help of one of the project stakeholders, where a snowballing strategy was applied to staff, families and friends of the company. The focus of the Go Digital study meant that there were certain criteria which interested participants had to meet to be selected as part of the project. The main criteria were as follows:

- own the property;
- have gas central heating; and,
- have a broadband internet connection.

Participants were told from the start that they would get to keep the new heating controls installed as part of the study and were rewarded with gift vouchers at various stages for taking part in additional activities such as interviews or the heating diary.

The final sample totalled 12 households, described in Table 5.1.

Table 5.1 Phase 2 study sample demographics

Participant	Dwelling type	Year of construction	Boiler type	Number of adults	Number of children (under 16's)	Income bracket
P01	Semi-detached	1990	Combi	1	0	£20,000 - £29,999
P02	Semi-detached	1924	Regular	2	1	£60,000 - £69,999
P03	Detached		Combi	3	0	£40,000 - £49,999
P04	Detached	1985	Regular	4	0	£70,000 - £99,999
P05	Semi-detached	1905	Combi	2	1	£40,000 - £49,999
P06	Detached	2002	Regular	2	0	£40,000 - £49,999
P07	Detached	1936	Regular	4	2	£50,000 - £59,999
P08	Semi-detached	1952	Combi	2	1	£100,000 - £149,999
P09	Semi-detached	1965	Regular	3	1	£60,000 - £69,999
P10	Detached	1969	Regular	3	1	
P11	Detached	1990	Regular	2	1	
P12	Flat	1980	Combi	1	0	£15,000 - £19,999

The sample included 11 houses and 1 flat, and ranged from having 1 bedroom to 5 bedrooms and a total number of rooms between 4 and 10. There was a split between households with combi boilers (5 households) and those with a regular boiler and hot water tank (7 households). The total number of occupants within each property ranged from 1 to 6. A total of 5 of the households had children under the age of 3 years old, and a further 3 households had children under the age of 16 years old (one of these households included a child under 3 years old also).

5.2.3 Monitoring

The monitoring equipment installed in the households is summarised in Table 5.2.

Table 5.2 Summary of monitoring equipment installed into all households

Monitoring equipment	Measuring	Sampling interval	Details
Temperature loggers	Air temperature	30 minute intervals	HOBO temperature pendant sensors installed prior to new heating controls and remaining monitoring kit installation for pre-install data
Gateway	-	-	Acts as the hub to all data from sensors
Wireless temperature sensors	Air temperature	30 minute intervals	Up to 10 individual sensors installed to measure individual room air temperatures
Boiler relay switch	-	-	Signals for boiler to fire when needed/requested by controls
Signal booster	-	-	Boosts wireless signal within household to ensure all sensors send data
Electricity monitoring unit	Electricity use	10 minute intervals	Electricity data not used within this thesis
Gas pulse meter	Gas use	5 minute intervals	Gas data not used within this thesis
Heating controls	Demanded set-points	5 minute intervals	iQE Halo controls
	Thermostat temperature	5 minute intervals	
	Manual interactions	Instantaneous and 5 minute interval updates	
	Away heating	5 minute intervals	
	Energy saving heating	5 minute intervals	

The first monitoring equipment which was installed into the households was the stand-alone temperature loggers. These sensors were sent to the households with a leaflet detailing information about the best location to put these sensors which would avoid direct sunlight, drafts, away from sources of heat such as radiators and preferably around adult hip height to give a better representative temperature for each room. These sensors were sent prior to the main monitoring equipment and new heating controls being installed to give as much pre-installation data as possible about the temperatures within the participating households. The sensors were also left to continue recording for a period after the installation of the main monitoring equipment to check how closely the wireless temperature sensors correlated with the stand-alone temperature loggers. These temperature loggers were then returned by the participants and the data was manually downloaded once received back.

The main monitoring equipment installed with the new controls is shown in Figure 5.2, with the equipment shown in green. The main monitoring equipment was installed by a trained third party installer.

Figure 5.2 Schematic of monitoring equipment installed into sample households

The central piece of monitoring equipment installed in the households was a gateway (Figure 5.3). This gateway allowed the download of the monitoring data from the Halo, the gas (if applicable) and electricity meters, and from the additional temperature sensors. This gateway needed to be plugged into a mains supply and the broadband router so that the data could be sent to the web portal for access to download. Participants were asked to avoid switching this gateway off to limit any data loss. The gateway also allowed the householders to have remote access to the heating controls using a smart phone app. This remote access required participants to download the app onto their mobile phones and register the gateway to their account. Once this was registered households had the ability to change their heating schedules and temperatures as well as overriding any existing schedules.

Figure 5.3 Gateway equipment

Each household had up to 10 wireless temperature sensors (Figure 5.4) installed, with the instruction for the installer to place each numbered sensor with the correspondingly numbered stand-alone temperature logger. By placing the wireless temperature sensors in the same location as the temperature loggers it allowed for a comparison between the two different temperature sensors to give validity in the pre-installation temperatures recorded by the stand-alone temperature loggers. To limit any damage to fittings and fixtures within the participant households the wireless temperature sensors were not attached to any walls or surfaces but simply placed, which meant there was a risk of them being moved. One of the temperature sensors however was mounted securely to a wall as this replaced any existing thermostat and was linked to the Halo controls. The boiler relay switch (Figure 5.5) was connected to the boiler and enabled the control of the heating by switching the boiler on and off at the desired times set on the Halo control’s programming function or when the home reached the desired temperature, known by the wall mounted temperature sensor.

Figure 5.4 Wireless temperature sensor

Figure 5.5 Boiler relay switch

To ensure that the signal of all monitoring equipment was strong enough to be detected, a wireless signal booster plug (Figure 5.6) was installed in each household. These were typically located in upstairs landings or hallways to ensure that the signal was sufficient across the whole home.

Figure 5.6 Wireless signal booster plug

An electricity monitoring unit was also installed to measure the amount of electricity being consumed within the household. The gas consumption was also monitored via a Zmart link pulse meter or via a third party monitoring company, SMS plc. Both of which complete the monitoring equipment installed as shown earlier in Figure 5.2.

The web portal was provided by Seluxit, a provider of cloud-based IoT platform solutions allowing for remote monitoring, and this online server gave access to all of the participating households and the data sent back from them through the individual gateways. All participating households were given a different code on the server which related to the individual gateways. The main interface for each of the households on the server is shown in Figure 5.7, which lists all the different sensors monitoring in the households. The multilevel sensors relate to the individual box temperature sensors installed, and each of these has files for the temperature recorded in that location (available to be downloaded either daily or weekly) and the battery level of the sensor. Similarly, the electricity meter (shows on the server as Aeon) and gas pulse meter (shows on server as Meter Pulse, if applicable for that household) showed the recorded monitoring data and battery levels.

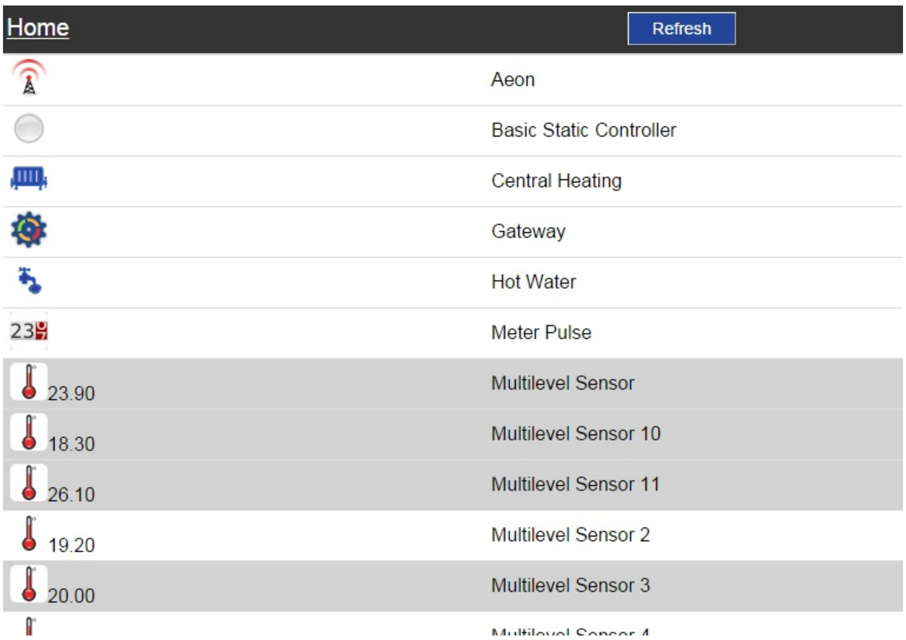


Figure 5.7 Screenshot example of interface seen on the online server

The main data recorded on the web portal and of interest for this study was found in the Central Heating category (as seen in Figure 5.7). Within this there were multiple data files to download, as shown in Figure 5.8. The "Heating" data file contained monitored data relating to the heating set-point, whereas the "Temperature sensor" contained the temperatures being recorded by the thermostat temperature sensor linked to the Halo control, therefore the temperature which would, depending on the set-point temperature, determine whether the heating came on or not. The "Multilevel Sensor" data files related to the individual wireless temperature sensors which had been placed in each room of the property. The "Advance" data file contained information to determine the manual interaction with the Halo controls, explained in more detail within section 5.2.4. To download the data from any of these files the "Show Log" button was pressed which presented the data in a graph format which could be set as a daily graph or weekly graph. These data were then exported as a .csv file which could be opened in Excel. Downloading of these data was therefore very time consuming as each week had to be downloaded individually and as an individual data files for each temperature sensor.

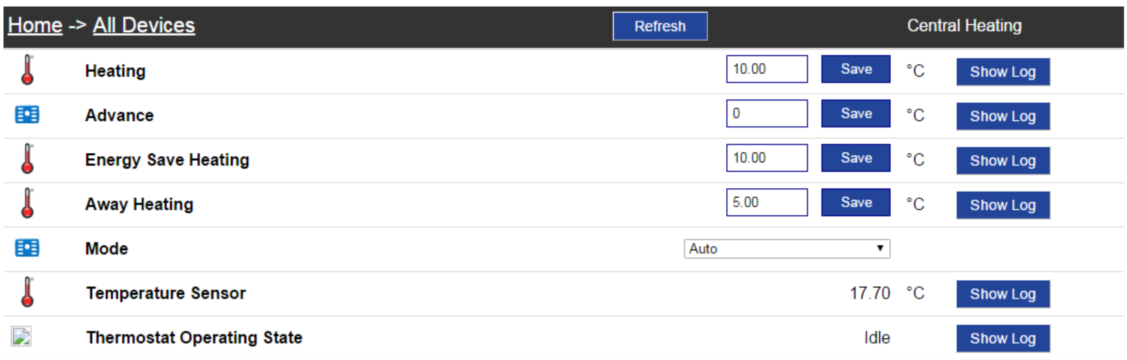


Figure 5.8 Example of household central heating interface on the online server

The "Away heating" data file was a log of the frost protection temperature setting. The "Energy Save Heating" related to the set-back temperature used by the controls when used on AUTO.

5.2.4 Heating controls

The new heating controls were iQE branded Halo controls (Figure 5.9). They gave householders the ability to control the temperature and heating schedule for their home with the addition of remote access to the heating system via a mobile phone app. The Halo controls have a digital interface which has the ability to control both the heating and hot water within a property should it be a household with a regular boiler and hot water tank central heating system. The Halo control itself was portable and could be moved from room to room as per the householders preferences as to its location. It had a docking station which allowed the Halo control to be charged as needed.

Figure 5.9 iQE Halo controls and display screen

The Halo had a touch screen interface which could be used to change the heating and hot water settings as shown in Figure 5.9. The heating could be programmed to be switched to ON, OFF or AUTO, as seen in Figure 5.10. By selecting the controls to be switched OFF, the frost protection temperature is displayed, as seen in Figure 5.11. This could be changed from the default of 5^{o}C by the householders via 5 steps; accessing the main menu, putting in the passcode, selecting heating settings option, changing the frost protection temperature as desired before pressing the home button in the bottom right hand corner, as shown in Figure 5.12.

Figure 5.10 On, Off or Auto control settings

Figure 5.11 Off and frost protection screen

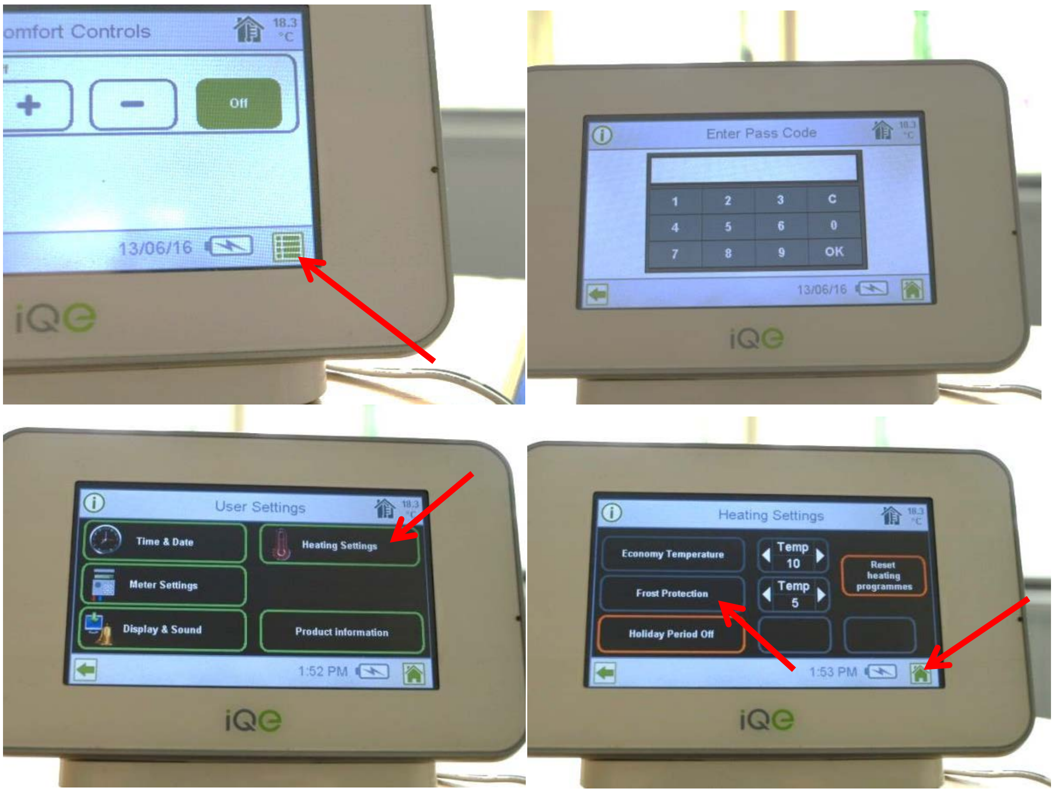


Figure 5.12 Process for occupants to change frost protection temperature on heating controls

When the householders select the heating controls to be switched to ON, the default thermostat temperature of 21^{o}C comes on as shown in Figure 5.13, this can however be easily changed by the householder by simply selecting the '+' or '-' buttons on the screen.

Figure 5.13 Heating controls switched to ON and default temperature setting

When the occupant selects the controls to be on AUTO this switches the heating on to whatever schedule the occupant has inputted for the controls. To program the heating schedule the occupant must select the radiator icon to bring up the main screen for setting heating schedules, as shown in Figure 5.14, which contains two separate clocks for morning and evening, temperature options and the days which the schedule has to apply to. This process can then be repeated again by pressing the radiator icon again to select different schedules and temperatures for different days and then saved again through the same means.

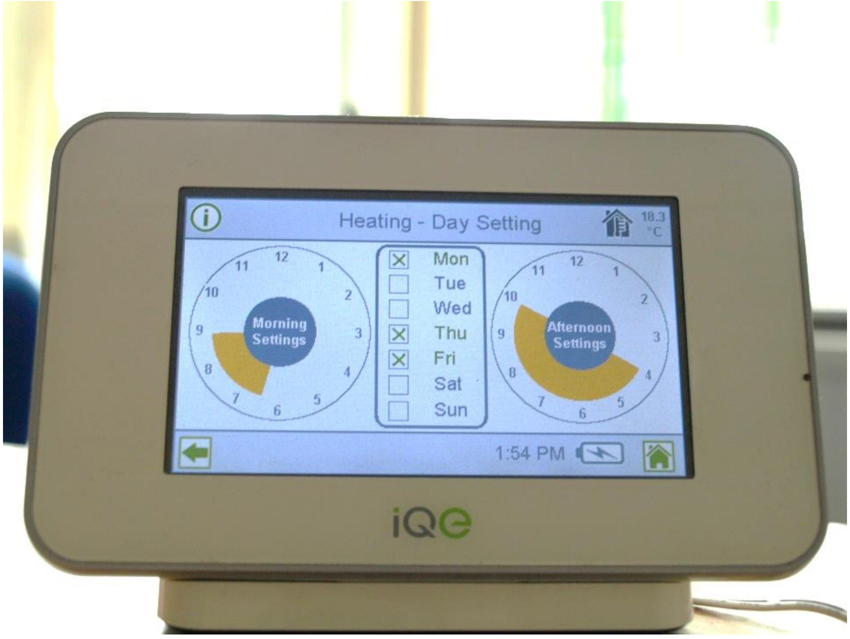


Figure 5.14 Main screen for heating schedule settings

Should occupants' needs assistance they could also press the information icon in the top left hand corner on the controls, which brought up contract details and website for the iQE Halo controls, as shown in Figure 5.15.

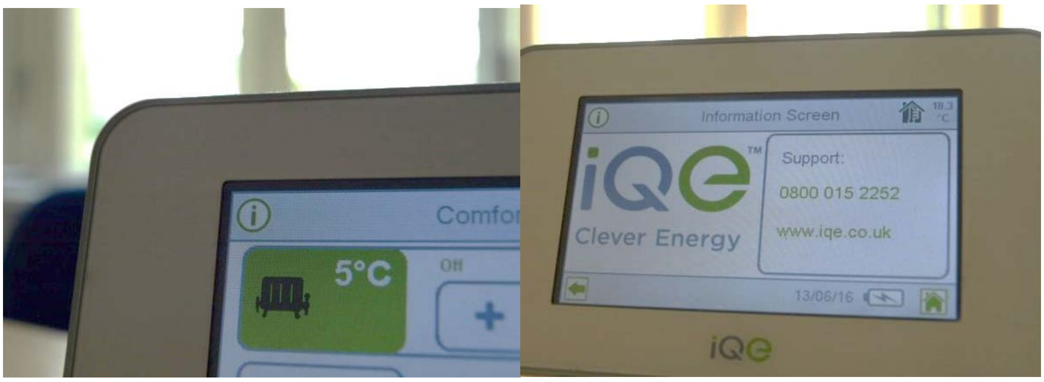
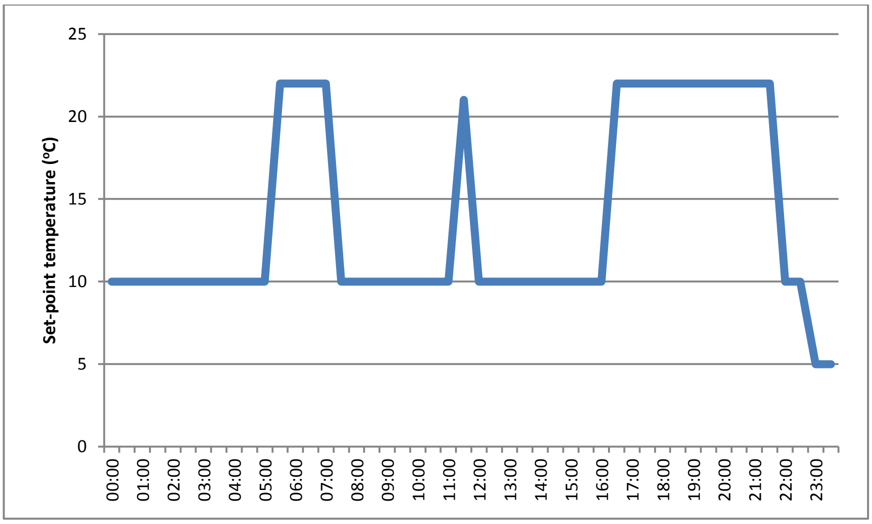


Figure 5.15 Information button and contact information screen

To determine how to use the data to determine interactions with the heating controls, an experimental study was carried out within a test house facility. The test house was an unoccupied 1930's semi-detached building. This allowed for the controls to be tested within a controlled environment with no potential outside interference with the heating system. The controls were installed in the same manner they were set up in the main study with the main Halo controls being left in the living room. As to replicate the Go Digital study further stand-alone temperature loggers were also installed next to the individual room wireless temperature sensors which were connected to the data server.

The aim of carrying out these experimental tests with the Halo was to determine if it was possible to identify specific interactions with the Halo device from the data collected by the controls e.g. manually adjusting the set-point temperature or overriding a set heating schedule. Therefore numerous “tests” were carried out over a six week period, where each test was essentially a likely interaction with the heating controls. Firstly the Halo was set up to a standard, twice daily, heating schedule at 22^{o}C from 6.30am till 8.30am and from 5.30pm till 11pm. Subsequent tests to this included changing the heating settings via the remote access app, changing set-points during heating periods, manually switching on or off, changing the heating schedules, using the holiday mode, changing default settings and any other potential uses expected as a result of the author’s previous work in this area, all of which are detailed in Appendix 5-A. This lists any changes made to the schedule, what manual interaction occurred with the Halo controls and what remote access interaction occurred via the mobile phone app. The data recorded by the heating controls was then analysed to see which data files recorded what and how to unpick the different uses of the controls apart. To ensure the analysis did unpick certain actions the same action was carried out on multiple occasions with the controls therefore allowing the same data patterns to be seen and therefore ensure that this study could confidently report the exact heating use actions by the study participants.

The findings from the test house experiments made it possible to confirm that manual interaction with the heating controls can be identified separately from automatic schedules therefore allowing any manual overriding of the set heating patterns to be identified. The Halo recorded data in numerous files, however the experiments uncovered two of particular interest to separate manual use from scheduled heating. The first file of interest was the “Heating” data file which showed the demanded set-point at that moment in time whether that be from a set schedule or from manual interaction with the controls. This demanded set-point data would show a temperature recording even when the controls were switched to OFF due to the frost protection temperature having a default of 5^{o}C. The second file of interest was the “Advance” file which, from analysing the data recorded during the test house experiments, was found that any manual interaction with the heating controls would only show up in the “Advance” data file. This meant that whenever the heating controls were set to AUTO (i.e. the occupant had set a heating schedule and left this to switch the heating on and off when programmed) the Advance data file recorded a temperature of 0^{o}C as the heating was being controlled by the schedule and not manually. If the controls were then switched OFF this also showed up in the Advance data file and the Heating data file recorded as 5^{o}C, which related to the default frost protection temperature. The data recorded by these two main files could also be supported with data from two further data files, “Away heating” and “Energy Save Heating”. The “Away Heating” data file recorded the frost protection temperature, so this could be then used to check the temperature being demanded when the controls were switched to OFF. The “Energy Save Heating” data file recorded the set-back temperature set, which had a default temperature of 10^{o}C, which relates to the set-back temperature demanded when the controls are switched to AUTO. Figure 5.16 shows plots of the data recorded within the “Heating” data file and the data file recorded for the “Advance” data file and by comparing the two plots it is easy to unpick the manual use of the controls when the controls are switched from AUTO to ON even for a short period of time.



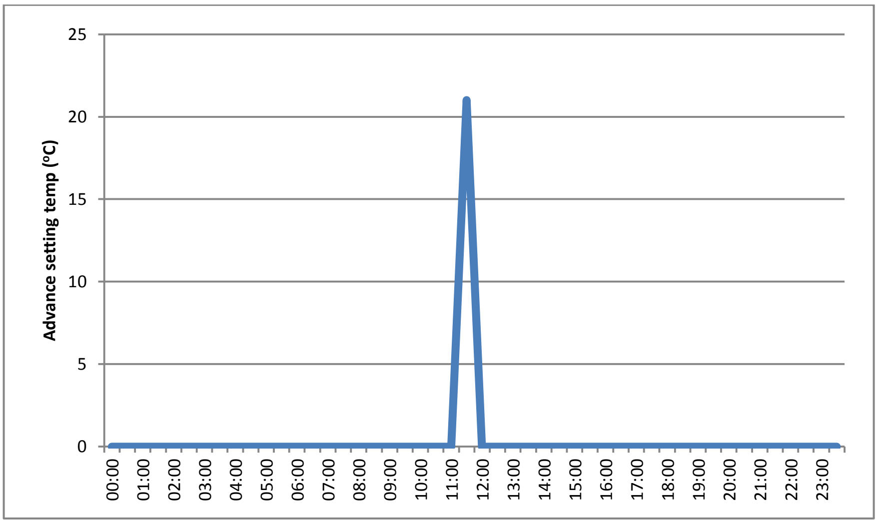


Figure 5.16 Top trace shows the data recorded in the "Heating" data file and the bottom trace shows the data recorded in the "Advance" data file

Figure 5.16 shows that the heating had been left on a schedule for two periods of heating and whilst setting the controls to go into “Holiday” mode the following day the heating was switched from AUTO to ON, which has the default temperature setting of 21^{o}C which can be clearly seen in the Advance data plot. This also showed that when the heating is scheduled to be left on “Holiday” mode the controls treat this as scheduled heating and therefore does not get recorded in the Advance data file, hence why the drop to 5^{o}C due to holiday mode at 11pm only shows in one data trace in Figure 5.16. This is obviously different however when the controls are switched to OFF this will then record in the “Advance” data file. Therefore even though both OFF and Holiday mode resort to the frost protection temperature, it is possible to distinguish between the two through use of various data files recorded by the heating controls.

The test experiments also uncovered a timing problem with the gateway, in that it would change the time on the data sent to the server to one hour behind the time an interaction had occurred. This was then discovered to be due to the Gateway not being in the correct time zone format. To get correct this the date and time data was adjusted appropriately within Excel using a formula which added one hour onto the time listed in the data file.

5.2.5 Monitoring period

Although households had monitoring equipment installed from March 2014, this Phase 2 study focused on monitored data from the start of July 2014 until the end of April 2015, so to have the same start date for all twelve homes (removing the staggered installation of the new controls). Also by analysing data from July onwards it was possible to identify any households which were using their heating during the summer. For this doctoral research the shoulder months were taken to be August and September representing the autumn shoulder months and March and April representing the spring shoulder months. Therefore the winter months was taken to run from October to February. The selection of which months represented which season came from previous studies within the area, with October being monitored as part of winter analysis. However, the author recognises there is a lack of clarity over exactly what months should be included in each season. The inclusion of both shoulder months seasons and winter analysis was done to uncover how the participant households used their heating in the lead up to winter and when they decided to stop or change their heating patterns after the main heating season, as well as how this differed to the heating use during winter. The data from monitoring the households coincided with the period when the households completed their heating diaries and when two out of the three interviews were completed (the first interview being done pre-installation of the new controls).

Once the data were downloaded there were some gaps in the recordings within some of the homes. Figure 5.17 summarises the gaps in heating set-point data being sent to the online server. These gaps in data were caused by a number of unforeseen circumstances out with the control of the researcher. Sensors went offline occasionally as indicated by being greyed out on the server screen (as can be seen in Figure 5.7, Page 187), however it was during the second interview visit to households that it became apparent the reason for this was due to batteries within some sensors becoming loose, as the installer had not screwed the backing on tight enough. In the rare case of those offline sensors that had the backing secured properly, it was often the case that the sensor had been dropped which dislodged the batteries. These issues were easily solved during the second visit and the sensor reactivated on the server after the visit, but resulted in gaps within the data. Other issues which caused data loss included households turning the gateway off and some households having weak wireless signal. Reminder emails and signal boosters were used with these households. Finally the last issue relating to data loss was caused by the online server itself being upgraded without any notice to the researcher.

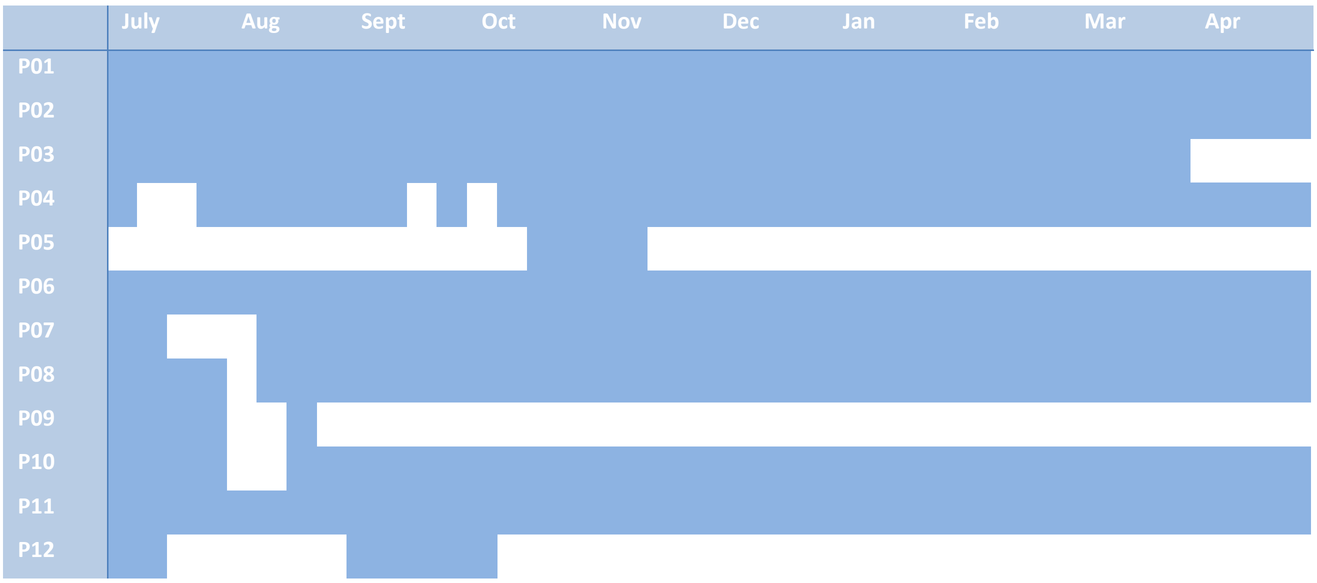


Figure 5.17 Availability of heating set-point temperature monitoring data (white gaps indicating missing data)

There were particular households which had more data recording issues than others. For example, shortly after the installation had occurred within P12, the system went offline which was likely due to the owner switching the gateway off. Then it came back online in September, however the owner the decided to rent out the property in October, after which the system went offline. So it is likely it was switched back on to get the property ready to rent and then once the new tenant moved in switched off again. P05 had issues with the signal within their home making it difficult for all sensors to be recorded, however there were further problems with the server meaning only a small amount of their set-point data were recorded. It was decided to accept this for this household so not to become a nuisance to the household as the system had already been completely rebuilt during the second interview visit, which took over 2 hours to complete. However, despite the rebuild, the sensors then went offline again a few weeks later so no further data were recorded.

A further issue was discovered during the second interview visits when trying to get sensors back online. It seemed the numbering on the room sensor did not necessarily match the number of that sensor on the server, allocated by the installer. Although in most instances this numbering was only 1 out, there were a number of occasions where the numbering was completely random, where it was possible the installer paired all sensors to the server then randomly placed them into the rooms of the household. This meant that identifying the exact room each sensor on the server came from was not possible with complete certainty. Since the only way to discover which sensor was which was to un-pair them from the server individually it was accepted that although all rooms were monitored it would be too difficult to correctly identify each room, and therefore no analysis was carried out on individual rooms for comparison between the sample. However it was still possible to analyse a whole multi-room average temperature for each household for comparison, however this was limited to a simple average instead of a weighted average due to the room locations being unknown and therefore the individual space floor area being unknown.

5.3 Data Analysis

An overview of the process behind creation of the data set and initial steps taken to clean and plot the data is presented. This is followed by details of the monitoring period and the analysis carried out on the specific areas where results are presented from this study, such as set-point temperatures, internal temperatures, scheduled heating use, changes to default settings, manual use of controls, heating durations, placing this study into context and categorising heating use types.

5.3.1 Overview

A data set was created for each individual household within Microsoft Excel which contained the following data from the online server:

- set-point temperatures – these were the demanded set-point temperatures either from the Halo control default and scheduled settings or from manual interactions of the participants;
- individual room temperatures – these were the temperatures recorded by the individual wireless temperature sensors placed into all rooms in the household. These were not connected to the Halo controls only to the online server. There were up to ten individual wireless temperature sensors for each household, so the number of individual room temperature files varied depending on the total number of rooms in each of the sample households;
- thermostat temperature – this recorded the thermostat temperature sensor which was installed to replace the occupant's existing thermostat;
- energy save heating – this refers to the baseline set-point temperature the heating control sets whenever left on AUTO, the default is 10^{o}C therefore the boiler would fire outside of the heating schedule if the temperature dropped below this;
- away heating – this refers to the temperature set as the frost protection setting, therefore the heating controls refer to this setting whenever set to OFF or Holiday mode; and,

- advance heating (manual interaction) – this records demanded set-points from any manual interaction with the controls outside of being left on AUTO.

The data set was created by compiling all the individual weekly .csv files which were downloaded from the server into MS Excel.

5.3.1.1 Cleaning the data set

Before any analysis of the data was started, the data sets first had to be cleaned to remove any errors or abnormalities. This data cleaning was done within Excel. The two main issues uncovered when cleaning the data were errors with the timestamp on the data and erroneous temperatures being reported.

As uncovered at the start of this study the reported time within the data file was one hour behind the correct time. To check that this was the same with the participating households the data were checked at the time of the second household visit when the occupants were asked to perform various tasks with the controls outside this doctoral research. These tasks involved switching the heating on, changing schedules etc., all of which could be seen in the data file. Due to the second interview visit occurring in late summer the majority of households visited had their heating switched off at that time. By looking at what time the heating was switched on in the data file it was clear to see in six of the nine households visited that the time shown in the data file was one hour behind the manual interaction. In two of the remaining households the system had gone offline and was reactivated during the visit, however the time was still one hour behind. It was therefore assumed that the same issue was happening within all of the twelve households so the data was corrected via Excel by inserting a formula which added 1 hour to the original time.

During the nine months monitoring period the clocks changed twice: the end of British Summer Time (BST) in October and the beginning of BST again in March.

Due to this the clocks moved back an hour at 2am on the 26th of October 2014 and moved forward 1 hour at 1am on the 29th of March 2015. Upon checking the data downloaded from the server it was noticed that the clock changes were opposite to that expected. This meant that there was a 2 hour discrepancy between October 26th and the 29th of March. Therefore the time for this period was corrected in Excel using a formula.

The recorded temperature data were also checked for any erroneous readings. The maximum demand temperature possible with the new heating controls is 30^{o}C therefore anything above this within the following data files was removed:

- set-point temperature;
- advance temperature;
- energy save temperature; and,
- away temperature

Due to the demanded temperatures on the controls always being a whole number any readings within the data files identified above which had decimal values were also removed. The occurrence and number of these errors varied across the sample however only a small number of these errors were found.

However for the recorded room temperatures and thermostat temperature, it was more difficult to identify errors. This was due to these recordings potentially being influenced by various other factors such as secondary heating, direct sunshine and errors within the Halo controls and communication of recordings to the server. Firstly any temperatures recorded which were above 100^{o}C were removed. This included a temperature error noticed in several data files, where a temperature of 3276.7^{o}C was recorded. Secondly the temperatures were listed in descending order therefore a note of all high temperatures could be made. These identified high temperatures were then investigated to eliminate any temperatures that were determined to be erroneous, an example being a recorded temperature was 46^{o}C however both temperatures 5 minutes before and 5 minutes after were 10^{o}C. In instances such as these the inconsistent temperature recording was removed. Where there was an apparent gradual increase in temperature, data were left within the data file as these were deemed to be temperatures gained during active heating periods. Plots were also made of the temperatures recorded for each household to see if there were any unusual peaks within these traces which were then investigated further, similar to when listing the temperatures in rank order. Erroneous temperatures identified varied across the sample in relation to the total percentage of recorded data being identified as errors, however this ranged from 0% (in 4 households) to 2% (P03).

5.3.1.2 Initial exploration of data set

The analysis of the data collected as part of this study can be described as both exploratory and confirmatory. Exploratory data analysis is used as the initial analysis as it explores the data to uncover what results the data shows. Initial exploration of the data set involved plotting the data in various formats and graphs to get a feeling for the data, in particular indoor temperatures, set-points and heating patterns. SPSS was used to produce summaries of the data sets in the form of mean air temperatures, level of variability and monthly comparisons. SPSS also enabled frequency distributions to be produced which quickly gave the frequency of occurrences of things such as the number of times a certain temperature was demanded as the set-point or the frequency of manual interaction with the controls. SPSS also allowed descriptive statistics to be produced on the data sets, often also referred to as summary statistics (Robson, 2011, p423) which can be used to represent the level of distribution and the spread within a sample. To measure the spread within a sample "measures of variability" are used which means that SPSS can calculate the following for a data set:

- standard error;
- standard deviation;
- range;

- variance;
- mean deviation; and,
- inter-quartile range.

To measure the distribution within a sample “measures of central tendency” are used for which SPSS calculates the mean, median and mode for the data set. These measures of central tendency and variability were applied to the temperature data.

Using SPSS, the data could also be plotted to see whether it showed a normal distribution or not which was needed to determine which further statistical tests to carry out. If the data did not fit a normal distribution then non-parametric tests would be needed as these do not use the normal distribution shape assumption. SPSS also allowed for correlation coefficients to be calculated for the heating data achieved and the sample descriptives to uncover any patterns or interesting findings. The correlation coefficients allow the strength and direction of a relationship between two variables to be tested to see how linear they correlate with one another.

5.3.2 Seasonal analysis and heating use ‘switch on’

As reported in the literature review in Chapter 2 shoulder month heating is the months on either side of the winter heating season, however little research has been done into how heating use in homes looks during these shoulder months. Results from this study relating to the heating use are presented in the order of autumn shoulder months, winter months and then spring shoulder months. As a reminder the autumn shoulder months is taken to include the months of August and September, the winter months covers October through to February and the spring shoulder months is taken to include the months of March and April within this work.

The quickest way to determine when people started using their heating again or "switching it on" was by plotting the demanded set-point temperature via the heating data file and looking for when spikes started to appear for each household. July was included in the trace to show those that may use their heating throughout the summer months as well as during the shoulder months. The heating diaries also gave an indication of the start date and use of the heating during this period, discussed in more detail in Chapter 6. The start dates were then analysed looking for the first instance of recorded heating use, the start date of three consecutive days with heating being used and then the start date of seven consecutive days of use.

5.3.3 Set-point temperatures

The recorded set-point in each household was found within the Heating data file. This data file recorded the temperature being demanded by the controls regardless of which mode it was switched to. For instance, 5^{o}C is recorded when the controls are switched OFF due to the frost protection default setting. The demanded set-point by the occupant can be determined from the Energy Saving temperature and the Away temperature. The default settings for the Energy Saving temperature is 10^{o}C, whereas the Away temperature is set to 5^{o}C. By knowing which households changed these settings it is then possible to observe when the heating is left on AUTO or switched OFF.

The set-point temperatures were analysed first using the initial exploration explained earlier, to achieve daily, monthly and seasonal statistics. The number of times that the set-point was changed was also analysed. This amount of changes did not include any changes due to scheduled heating. To understand more about whether these numerous changes to the set-point were being made more regularly during morning or evening periods the data was split to show plots relating to morning and afternoon/evening. Due to the data showing that on occasions, typically at weekends, some households made manual changes to their heating which lasted till around 1am the next morning, the morning data was taken to be any set-points being demanded between 2am and 12pm. The afternoon and evening data was taken to be any set-point temperatures being demanded between midnight and 2am and then 12pm till 11.59pm for each day.

5.3.4 Internal temperatures

The individual temperatures of rooms within the participating households were recorded and then analysed through the initial exploration analysis mentioned, to gain daily, monthly and seasonal results. It was impossible to identify what rooms the sensors came from accurately therefore the room temperatures have been analysed as the labelled sensor number from the server. Due to the locations not being known the majority of the analysis used the average whole dwelling internal air temperature.

For the average whole dwelling temperature the daily individual room sensor temperatures were averaged over the 24 hours of monitoring data to gain a daily whole household average temperature.

5.3.5 Scheduled heating use

The new controls gave homes the opportunity to set heating schedules which could be different for each day allowing households to have 7 different daily heating schedules, or different weekday and weekend heating schedules or the same heating schedule for the full week. With the Halo controls there were three default temperature settings which were possible to track through the data recorded by the controls. When the controls were switched ON data was recorded in both the Advance data set and the Heating file. By removing the manual use of heating (heating use which appeared in the Advance file) it left the remaining heating data to analyse for scheduled heating use. To determine the scheduled use, the set-back temperature could be checked to see what temperature would be recorded in the

Heating data file when the controls were left on AUTO but not during heating periods. By identifying the set-back temperature the remaining data related to the heating schedule set by the occupants. The heating schedules were noted down on a calendar so that they could be analysed daily and any changes to the schedule could be noticed, or if occupants used the option of having different heating schedules for specific days of the week.

5.3.6 Manual heating use

Unlike previous published studies looking at heating use within homes this study was able to separate manual use of the heating controls from scheduled heating. Manual use is taken to be any instance where the occupants manually switch the heating on, override their heating schedule or change the set-point temperature manually. This was possible by analysing the Advance data file which recorded the demanded set-point temperature, however when the controls were switched to "AUTO" this showed in the Advance file as $0^{o}C$. Therefore it is possible to distinguish from the advance data file the percentage of the time the controls were used in "AUTO", when used manually in "ON" mode and when switched "OFF" which showed up as $5^{o}C$ in those households which hadn't changed the frost protection setting. Similar to the heating schedules the author also manually noted down the individual daily totals for manual use of the heating within a calendar for each household, allowing the manual use of heating to be calculated as a percentage of the daily heating use total for each household. This meant that the difference in heating durations across the sample households was taken into consideration and presented the manual use of the controls as a percentage of the individual households heating usage. The manual use totals and percentages were analysed using the initial exploration explained earlier.

5.3.7 Heating durations

From the data recorded during the monitoring period it was possible to identify the exact durations of when the heating was actively switched on, this included the duration of scheduled heating periods and the duration of any manual use of the heating. However it was not possible to identify from the data the exact duration the boiler itself was firing, so although the heating is recorded as being "active" the boiler itself may not be firing if the central thermostat connected to the Halo is recording a temperature above that of the desired set-point temperature. The same initial exploration of the data was carried out on the heating durations recorded and the average daily heating duration was calculated, as well as the cumulative total hours of heating for each month and the maximum and minimum heating hours being demanded by each household.

5.3.8 Putting the results into context

To help put the results into context some additional analysis was carried out on the data. To see if there were any trends present with the heating use in households, correlation analysis was carried out. To investigate the influence various factors may have on heating use within the sample, correlation tests were run on the results comparing the influence on daily hours of heating, the percentage of manual use of heating, the set-point temperatures demanded and internal average whole household temperature. The factors which were included in the analysis were the dwelling type, EPC value, income bands, age of the oldest occupant, total number of occupants, the number of children under 16 years of age, the total floor area of the property, year of construction and the total number of rooms available to be used as bedrooms. To ensure that the results were not skewed due to those households which used their heating throughout the summer only the winter month data was used in the analysis, unless stated otherwise with some of the weather related correlation analysis.

Analysis was also carried out to compare the findings of this study against others within the same area of research, by use of similar analysis methods. Due to the inability to identify the living room and bedrooms sensors within the data it was not possible to compare the average living room and bedroom temperatures to previous findings and assumptions with confidence, however it was possible to still calculate average internal temperatures for the winter months. Previous methods of identifying heating durations and estimating set-points were compared against the recorded values of these within this study.

5.3.9 Categorising heating control user types

The households within this study could be characterised by their use of the heating schedule functions and whether the scheduled settings were changed over the monitoring period and whether separate settings were used for weekday and weekends within the sample households. P09 was not included within the categorisation due to the lack of winter data for that household. By characterising households by their use of the heating controls it was possible to identify if there were any trends with specific household characteristics and how the heating controls were used.

When analysing the heating schedule changes made by households, the heating schedule was noted down for each day of the monitoring period from the data collected and this was then analysed for any changes in demanded set-point temperatures for scheduled heating periods and any changes with the time of scheduled heating periods. For characterising the households by their heating schedules on weekdays and weekends both P10 and P12 were excluded from the characterisation due to their preference to use the heating system manually instead of setting a heating schedule on the controls.

These characterisations were analysed for possible trends in household characteristics/demographics, such as dwelling type, number of rooms, occupancy types and income bands.

5.4 Results

5.4.1 "Switch on" of heating use

The start of heating use in homes was identified by plotting the demanded set-point temperature. Figure 5.18 shows the trace for P01. The first spike appears in mid-August, however this relates to the second interview visit where the occupant was asked to carry out tasks with the controls which included turning the controls to ON from AUTO so was disregarded. Therefore the first use of the heating came on the 6th of September when the occupant switched the heating on for two hours mid-afternoon. The heating then wasn't switched on again until nearer the end of September. This was a similar pattern seen in roughly half of the sample with P03, P04, P07 and P08 all interacting with their heating for the first time from middle to end of September. No shoulder month data was recorded for P05 as various issues with the data collection in this household meant the first recorded data came mid-October.

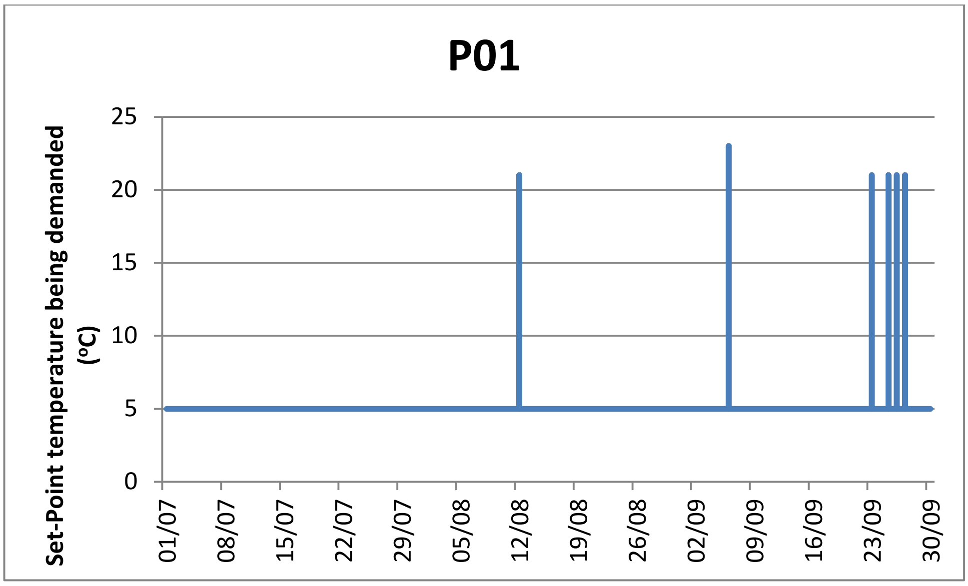


Figure 5.18 Demanded set-point temperature trace for autumn shoulder month season for P01

Six of the sample households used their heating system before middle to end of September, although the degree of this use varied between the households. Figure 5.19 shows the demanded set-point temperature trace for P02 which shows daily use of their heating system in July. P11 also showed regular use of their heating from July, however this was mainly focused at the start of July and the heating was then switched off again till middle of August. P06 showed a similar pattern of use for a week or so in July and then off again until August as did P10. P09 changed their energy saving temperature setting to 20^{o}C therefore their heating showed a demand temperature of 20^{o}C when the controls were left on AUTO with the heating schedule set. They did however still interact with their heating throughout July, demanding various set-point temperatures before being switched off until August.

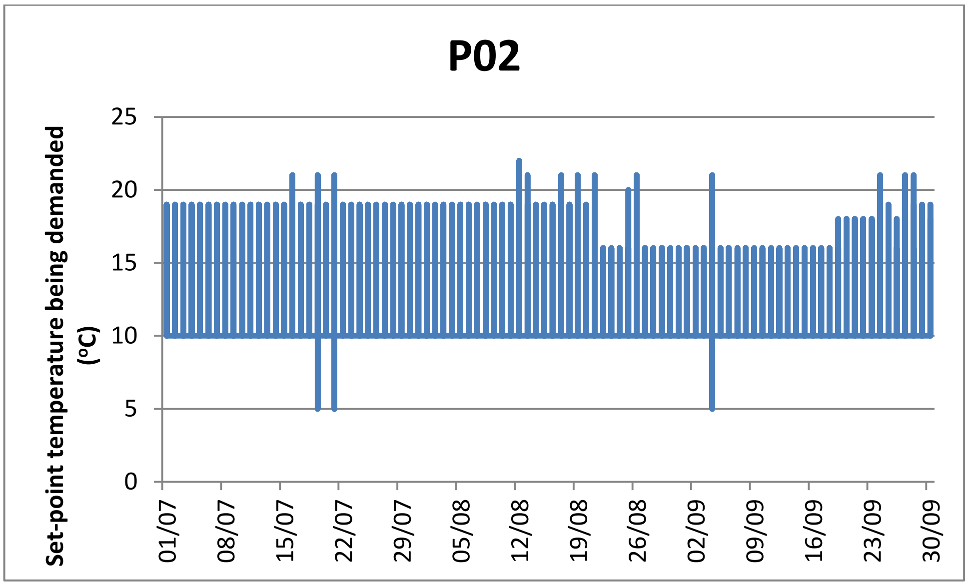


Figure 5.19 Demanded set-point temperature trace for autumn shoulder month season for P02

Table 5.3 summarises the switch on dates for all households, indicating the first instance recorded of using heating since 1st of July 2014, first instance of three consecutive days of heating use and the first week of continuous heating use. P05 did not have any data prior to 18th of October 2014 and therefore may have been using their heating prior to this date.

Table 5.3 Dates of heating use starting across the sample

	First instance of heating use	Start of 3 days of consecutive heating	Start of 1 week of consecutive heating
P01	06/09/14	25/09/14	05/10/14
P02	01/07/14	01/07/14	01/07/14
P03	17/08/14	22/07/14	20/09/14
P04	02/09/14	09/10/14	09/10/14
P05	No data available before 18/10/14	18/10/14	18/10/14
P06	07/07/14	21/08/14	05/10/14
P07	23/09/14	05/10/14	05/10/14
P08	23/09/14	25/09/14	25/09/14
P09	05/07/14	05/07/14	14/08/14
P10	01/07/14	01/07/14	14/08/14
P11	01/07/14	01/07/14	01/07/14
P12	04/07/14	05/10/14	-

Table 5.3 shows that P02, P06, P09, P10, P11 and P12 all recorded use of their heating as early as July. In general from the plots for each household, it was seen that a number of households have numerous interactions with their heating during the shoulder month season. During August and September it was seen that P01, P03, P04, P06 and P12 all used their heating occasionally, and typically the use was clustered which is likely to mean the heating use was in relation to the external weather. Therefore it is more likely that the heating within these households were being used on a needs demand basis. However it is clear to see that all households had started using their heating continuously from the 9th of October (with P05 having missing data until the 18th of October). A total of two households started using their heating within August, two in September and five not having a week of continuous heating use until October.

The spring shoulder month "switch off" was more difficult to analyse due to March and April 2015 still being unseasonably cold. Although there were signs of heating use reducing, there was not such a clear turning point as the autumn shoulder months. However as reported within the literature review, there are known instances of heating still being used during May in the UK due to the unpredictable spring season. The changes in heating use during the spring shoulder months is discussed in more detail in further sections but from the data traces available no clear heating end point was identified, as data was not collected beyond the end of April 2015.

5.4.2 Set-Point temperature

This section presents the results of measured demanded set-point temperatures within a sample of UK households over Autumn, Winter and Spring. The default set-point temperature on the Halo controls is 21°C both when switched manually on and when initially setting up heating schedules in "AUTO". A set-point of 5°C is recorded when the heating is switched 'OFF'.

5.4.2.1 Autumn shoulder months demanded set-points

Table 5.4 shows the mean daily demanded set-point temperature in all sample households for July and the autumn shoulder months. This allows the households which are using their heating to be identified in a quick glance as a set-point of 5°C is demanded when the controls are switched off, therefore those households showing a mean of 5°C are likely to have their heating switched off that month.

Table 5.4 Mean recorded set-point temperature in autumn and spring shoulder months

	Set-Point	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12
July	Mean	5	11.9	5	5	-	5.6	5	5	7.6	7.4	11.9	5.5
Aug	Mean	5	11.9	5.7	5	-	5.6	5	5	12.3	19.1	12.1	-
Sept	Mean	5.3	11.4	7.1	6.9	-	5.5	5.2	6.8	-	21.3	13.5	5.0

Five of the twelve households kept their heating off completely in July with a further four households not using their heating in August either. As can be seen from the table of mean set-point temperatures a further two households had a mean very close to 5°C indicating that these only used their heating a small amount, similarly with the two other households in August. Figure 5.20 shows a trace of the daily mean set-point temperature over August and September. The trace shows that P02, P10 and P11 have a daily mean set-point consistently above 5^{o}C which correlates with their use of the heating more frequently over the autumn shoulder months compared to the other households. The trace also shows the increase in mean set-point within P09 during August before the data stopped.

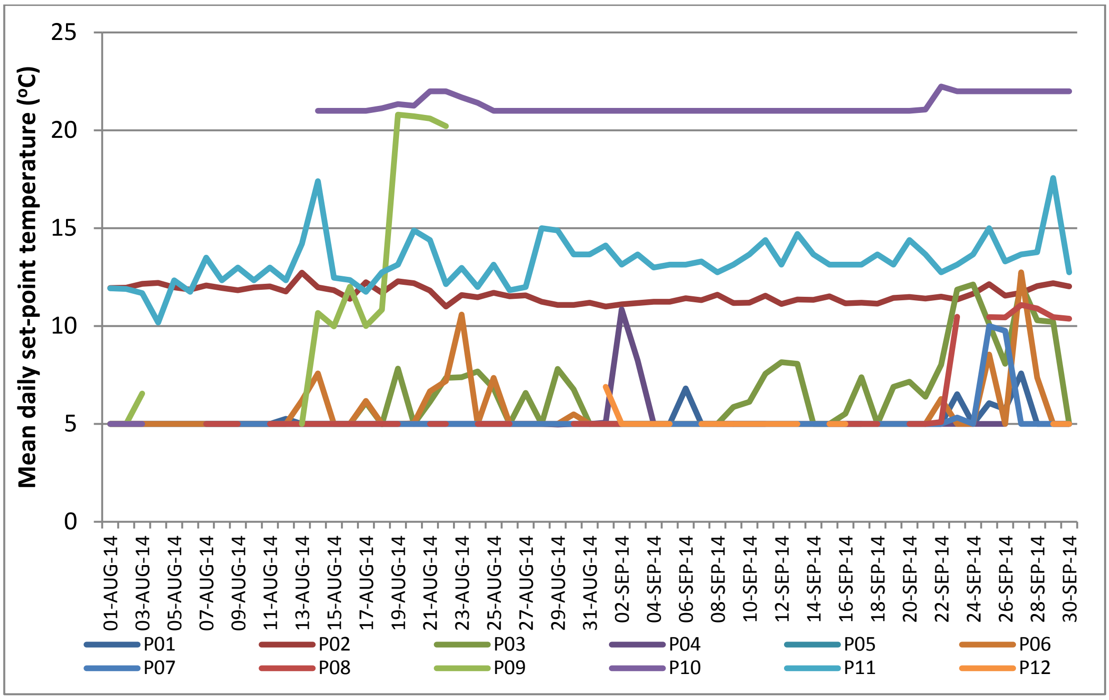


Figure 5.20 Mean daily set-point temperature (over 24 hours) for all households during August and September

The variety in different set-points being demanded within households was examined by analysing the individual monthly set-point data. Table 5.5 shows the monthly difference in set-points recorded for P01 during the shoulder months. When looking at the different set-point temperatures demanded for P01, every month recorded a minimum set-point of 5^{o}C, indicating that during every month of the autumn shoulder months the heating controls were switched to “OFF” at some point and not constantly left on “AUTO” for the duration of each month.

Table 5.5 P01 Set-point temperature variation over shoulder month seasons (Bold temperatures are those from automatic settings such as default thermostat temperature, away or energy saving default temperatures).

	No. of different set-point temperatures selected	Set-point temperatures demanded
July '14	1	**5°C**
Aug '14	1	**5°C**
Sept '14	4	**5°C, 10°C**, 21°C, 23°C

The set-points being demanded varied across the sample, Table 5.6 presents the lowest and highest demanded set-points for each household, not including any set-point for when switched OFF or any baseline set-points for when left on AUTO. Two households demanded the highest temperature possible on the controls, 30°C, over the autumn shoulder months.

Table 5.6 Lowest and highest demanded set-point temperatures across July and autumn shoulder months

Household	July		Aug		Sept	
	Low	High	Low	High	Low	High
P01			21	21	21	23
P02	19	21	11	22	16	21
P03			21	23	16	23
P04					19	21
P05						
P06	21	21	21	21	21	21
P07					18	21
P08					18	18
P09	20	25	20	22		
P10	21	21	21	30	21	23
P11	20	21	20	26	21	24
P12	21	27			22	30

Figure 5.21 presents the number of times the set-point is changed daily over August and September. It is clear to see that the number of changes made by some households is a lot higher than others, however typically the set-point may only be

changed once a day (in addition to any scheduled heating which causes a change in set-point).

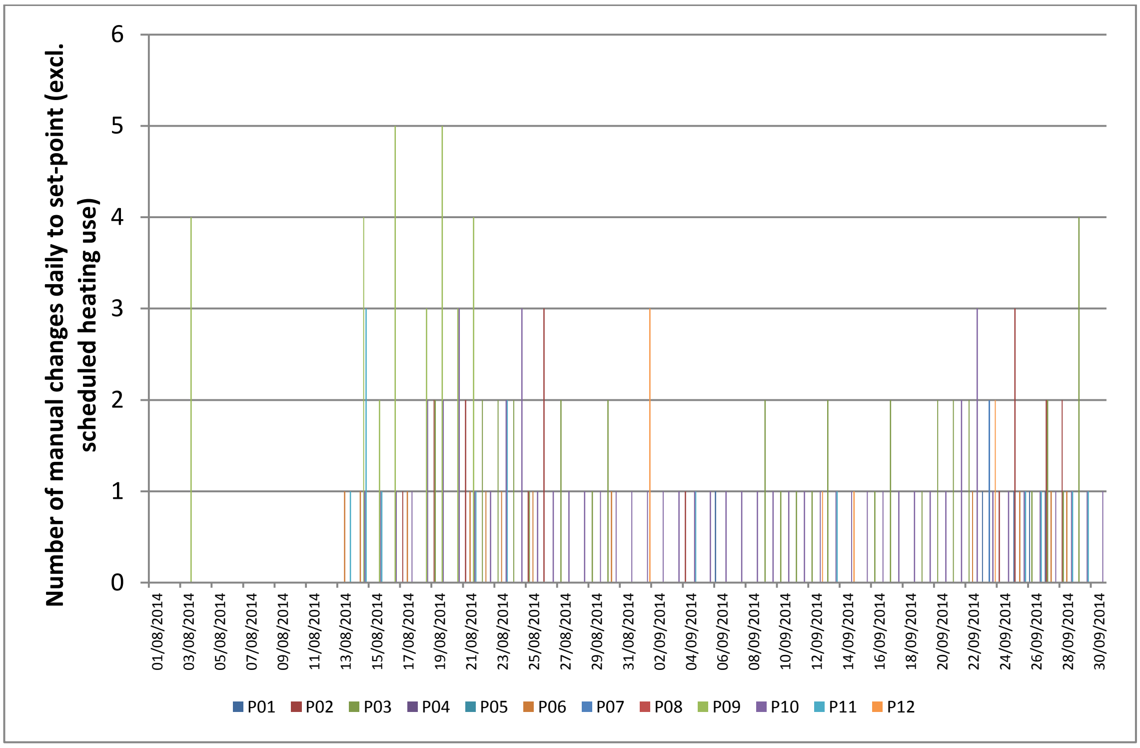


Figure 5.21 Number of changes made to set-point temperatures during August and September

5.4.2.2 Winter months demanded set-points

This section presents results on the demanded set-point temperatures across the winter months (October 2014 – February 2015). Table 5.7 presents the range of set-points recorded across the sample each month during winter. This reports the lowest set-point temperature excluding those default set-points for Energy Saving mode and Away mode (5°C and 10°C). As the Table shows there were four instances where the maximum set-point temperature on the controls was demanded, surprisingly all appearing at the start and end of the winter months not in the middle. Some households within the sample used either the default temperature of 21°C or lower as their highest recorded set-point each month indicating that they follow many assumptions regarding set-point temperatures identified within the literature review. There were other households within the sample that demanded much higher temperatures ranging from 24-28°C. This table only presents the highest and lowest recorded set-point temperatures and so does not take into consideration how many different set-point temperatures were being demanded by the occupants within that range of temperatures.

Table 5.7 Range of set-point temperatures being demanded over the winter period (with mssing data represented by -)

Household	Oct		Nov		Dec		Jan		Feb		Individual household mean	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
P01	15	23	20	23	20	23	20	23	20	21	19	23
P02	17	21	18	21	16	21	16	21	17	21	17	21
P03	19	22	18	24	18	23	18	23	18	22	18	23
P04	17	21	17	21	17	21	18	21	18	21	17	21
P05	18	21	15	21	-	-	-	-	-	-	17	21
P06	21	21	21	21	20	22	21	22	21	22	21	22
P07	18	23	14	21	15	21	15	21	17	21	16	21
P08	18	21	18	23	18	28	18	30	18	30	18	28
P09	-	-	-	-	-	-	-	-	-	-	-	-
P10	20	30	22	22	22	25	21	26	20	22	21	24
P11	21	24	21	24	21	24	15	24	21	24	20	24
P12	26	30	-	-	-	-	-	-	-	-	26	30
Sample mean	19	23	18	22	19	23	18	23	19	23		

Table 5.8 presents all of the set-point temperatures being demanded each month by the households within the sample. A recorded set-point of 5^{o}C indicates the controls being manually switched to OFF. As it can be seen by the sample multiple households recorded switching the heating OFF at some point during December and even January, which may seem highly unusual, however many factors could influence occupants switching the controls off, even by mistake due to the touch screen nature of the controls. The number of different set-point temperatures being demanded by occupants varied across the sample, and varied month by month in each household. This difference in the number of set-points being demanded by the occupants may impact energy model predictions which typically assume one set-point temperature throughout a heating season. However these results show that the majority of households regularly change their set-point temperature and the temperatures being demanded varies across households.

Table 5.8 Demanded set-points recorded across the winter period for all households

	Oct	Nov	Dec	Jan	Feb
P01	5, 10, 15, 20, 21, 23	5, 10, 20, 21, 22, 23	5, 10, 20, 21, 22, 23	10, 20, 21, 22, 23	5, 10, 20, 21
P02	5, 10, 17, 18, 19, 20, 21	5, 10, 18, 19, 20, 21	5, 10, 16, 17, 18, 19, 20, 21	5, 10, 16, 17, 18, 19, 20, 21	5, 10, 17, 18, 19, 20, 21
P03	5, 19, 20, 21, 22	5, 18, 20, 21, 22, 23, 24	18, 19, 20, 21, 22, 23	18, 20, 21, 22, 23	18, 20, 21, 22
P04	5, 17, 18, 19, 20, 21	5, 17, 19, 20, 21	5, 17, 18, 19, 20, 21	5, 18, 19, 20, 21	5, 18, 19, 20, 21
P05	10, 18, 21	10, 15, 16, 18, 21	-	-	-
P06	5, 10, 21	5, 10, 21	5, 10, 20, 21, 22	5, 10, 21, 22	5, 10, 21, 22
P07	5, 10, 18, 19, 20, 21, 23	5, 10, 14, 16, 17, 18, 19, 20, 21	5, 10, 15, 17, 18, 19, 20, 21	5, 10, 15, 17, 18, 19, 20, 21	5, 10, 17, 18, 19, 20, 21
P08	5, 10, 18, 21	5, 10, 18, 19, 20, 21, 23	5, 10, 18, 20, 21, 22, 23, 25, 28	5, 10, 18, 20, 21, 23, 25, 28, 30	5, 10, 18, 20, 21, 23, 24, 25, 30
P09	-	-	-	-	-
P10	20, 22, 24, 30	22	22, 23, 25	5, 10, 21, 22, 23, 24, 26	20, 21, 22
P11	10, 21, 22, 23	10, 21, 23, 24	10, 21, 22, 23, 24	10, 15, 21, 24	10, 21, 24
P12	5, 10, 26, 30	-	-	-	-

To understand the number of changes being made to the set-point Table 5.9 presents the total number of changes made during the week and during the weekend for each month. These numbers of changes exclude any changes in set-point coming from scheduled heating periods and therefore show the level of interaction with occupants demanding different set-point temperatures manually within the sample. To allow for any days with missing data on manual interactions a daily average has been calculated based on the available data for weekdays and weekends within each month.

Table 5.9 Total number and daily average of manual set-point changes each month on weekdays and weekends (excludes automatic changes from programmed heating)(*P12 only had a couple of days of data available in Oct hence the high daily average)

	Oct				Nov				Dec				Jan				Feb			
	Weekday		Weekend		Weekday		Weekend		Weekday		Weekend		Weekday		Weekend		Weekday		Weekend	
	Tot.	Av.	Tot.	Av.	Tot.	Av.	Tot.	Av.	Tot.	Av.	Tot.	Av.	Tot.	Av.	Tot.	Av.	Tot.	Av.	Tot.	Av.
P01	2	0.1	2	0.3	5	0.3	7	0.7	12	0.5	8	1.0	3	0.1	11	1.2	2	0.1	8	1.0
P02	38	1.7	8	1.0	39	2.0	12	1.2	43	1.9	24	3.0	32	1.5	24	2.7	34	1.7	15	1.9
P03	26	1.2	8	1.0	20	1.0	18	1.8	26	2.5	16	2.0	20	1.6	16	1.8	4	0.8	10	1.3
P04	5	0.3	0	0	20	1.0	7	0.7	57	1.1	9	1.1	35	0.9	7	0.9	16	0.7	5	0.7
P05	0	0	0	0	-	-	0	0	-	-	-	-	-	-	-	-	-	-	-	-
P06	17	1.1	7	1.4	32	1.6	15	1.4	27	1.4	14	1.8	12	0.5	10	1.1	2	0.1	9	1.1
P07	11	0.6	6	1.2	21	1.1	11	1.2	37	1.6	14	1.8	24	1.1	17	1.9	21	1.1	7	0.9
P08	17	0.8	6	1.0	33	1.7	11	1.2	64	2.8	14	1.8	66	3.0	20	2.2	37	3.0	18	2.3
P09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P10	28	1.2	12	1.5	20	1.0	10	1.0	25	1.1	8	1.0	29	1.3	15	1.7	20	1.0	12	1.5
P11	8	0.3	2	0.4	14	0.7	2	0.2	8	0.3	5	0.6	4	0.2	1	0.1	7	0.4	0	0
P12	6	2*	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

By looking at the difference between weekday and weekend changes to the set-point it appears that the majority of households make more changes to the set-point temperature during the weekend days rather than the during the week days, on average, however this varies on a month by month basis. Six households had higher daily averages for weekends in at least three of the winter months, with P01 having a higher weekend average during every month. It also shows that some households clearly change the set-point temperature a lot more than others in the sample, P02 and P08 being examples of this. It can also be seen that for many of the households, the number of changes made to the set-point temperature typically increases in winter, however some households such as P01, P06 and P11 can be seen to have similar number of changes made each month throughout the monitoring period.

The frequency of changing the set-point temperatures is seen more clearly in plots of the demanded set-point temperatures across the full monitoring period. Figure 5.22 and 5.23 shows two examples of these plots from P01 and P07 respectively. The remaining plots can be found in Appendix 5-B. From these plots, it is much clearer to see the households who typically demand the same set-point temperature(s) throughout the full monitoring period with the occasional increase in set-point temperature every now and again, mainly during the winter months. In contrast the households which change the set-point temperature on a regular basis can be seen, such as P07 where the most prominently demanded set-point temperature of 18^{o}C is clear to seen however there are plenty of instances where additional set-point temperatures are demanded by the occupant and this occurs throughout the winter months.

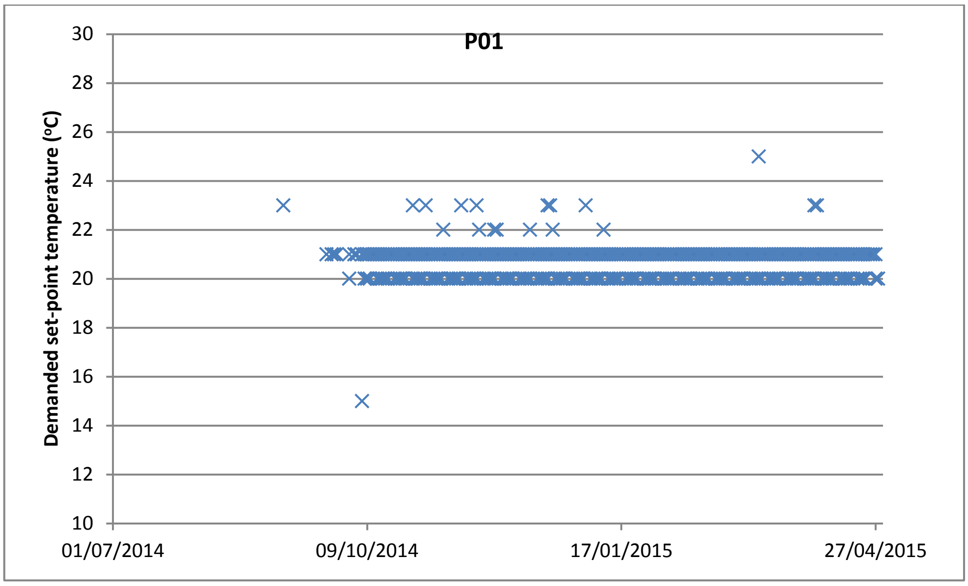


Figure 5.22 Demanded set-point temperatures across the monitoring period by P01

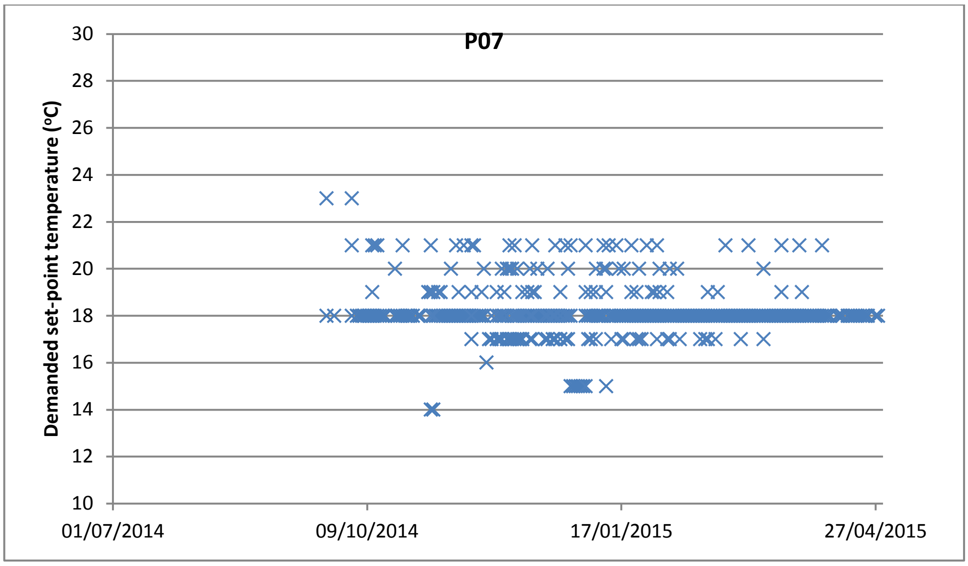


Figure 5.23 Demanded set-point temperatures across the monitoring period by P07

Figure 5.24 presents the morning set-point temperature plot for P07 and Figure 5.25 presents the afternoon/evening results. Morning was taken to be between 2am and 12 noon, afternoon/evening was taken to be midnight till 2am and 12 noon till 11.59pm each day.

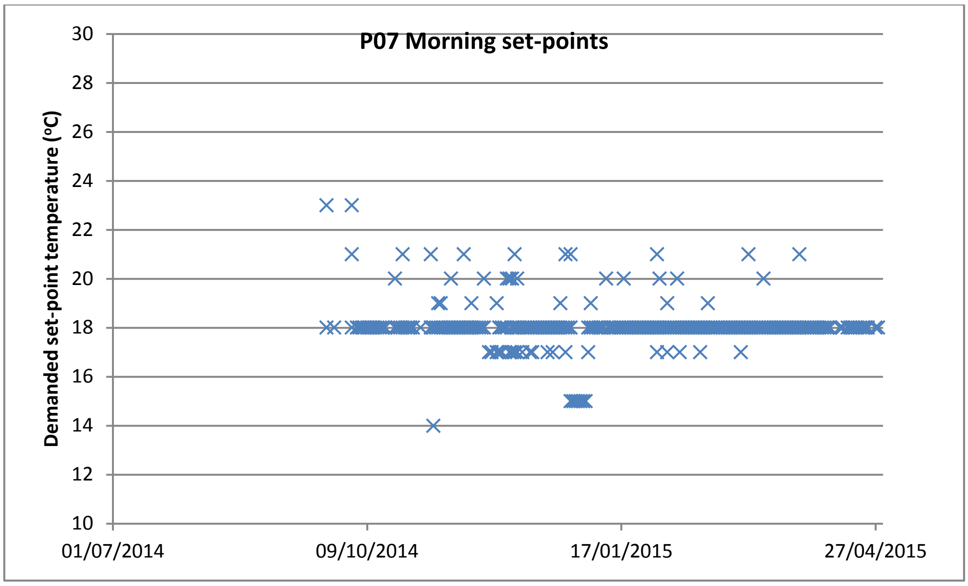


Figure 5.24 Demanded set-point temperatures during morning periods across the monitoring period for P07

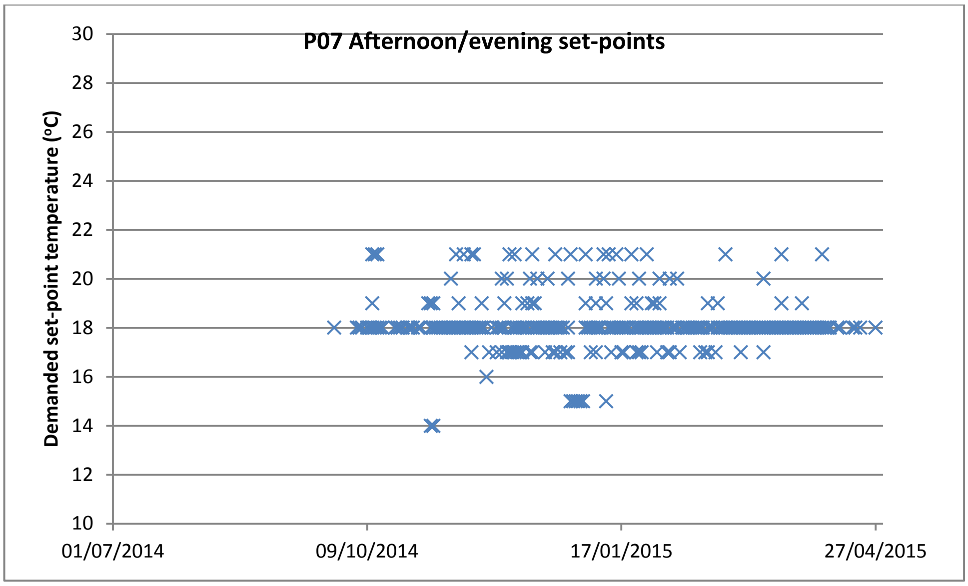


Figure 5.25 Demanded set-point temperatures during afternoon/evening periods across the monitoring period for P07

As it can been seen from these two plots there appears to be more interaction with the set-point temperatures in the afternoon/evening from mid-November onwards over interaction in the mornings, with the biggest difference being during January where a total of 36 set-points were demanded during mornings compared to 55 set-points being demanded in the afternoon/evenings. This may be due to the drop in external temperatures meaning the property was colder in afternoons and evenings and therefore needed additional boosts of heat compared to that in the morning. However it may also be influenced by the occupancy. P07 had most household members leaving the property in the morning and then returning in the afternoon/evenings due to the children going to school and all adults working full-time. However one of the household members occasionally works from home therefore it may cause unpredictable occupancy patterns. In contrast, the morning and afternoon/evening plots for households such as P06 show (Figure 5.26 and 5.27) hardly any difference between the two periods. Again this could be influenced by the occupancy of the household but also the difference in heating schedules set. Whether the occupants liked interacting with the controls could also impact the frequency of how often set-points were changed, especially those who are more hands off with the controls.

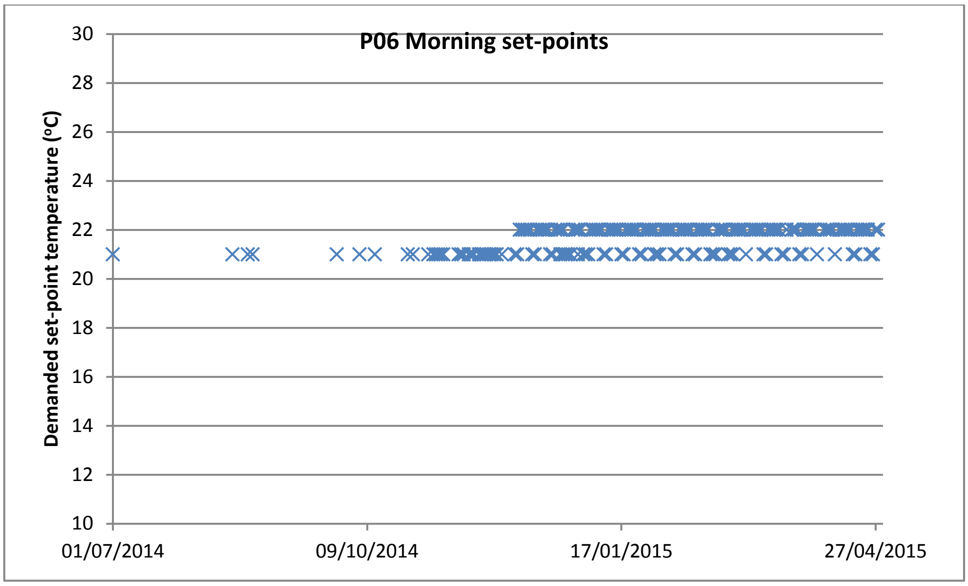


Figure 5.26 Demanded set-point temperatures during morning periods across the monitoring period for P06

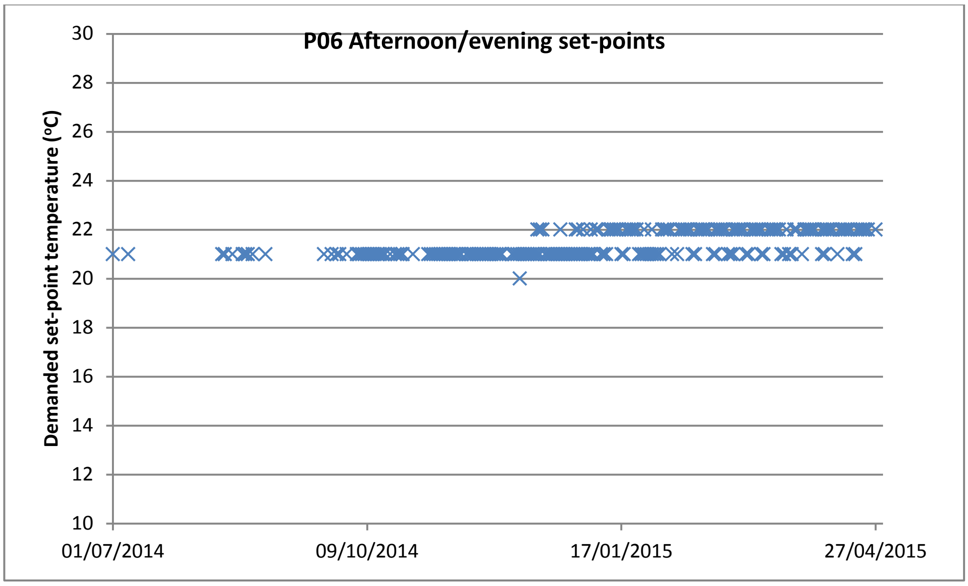


Figure 5.27 Demanded set-point temperatures during afternoon/evening periods across the monitoring period for P06

The differences observed in the recorded set-point temperatures shows that the measured data may be very different from the assumptions of one set-point temperature during the heating season. The variation in set-point temperatures could also impact those studies which try to surmise the demanded set-point temperatures from measured internal temperature data as the methods used to calculate these estimates may be skewed by the constant changes being made to the set-point temperatures meaning differences in internal temperatures on a daily and monthly basis.

5.4.2.3 Spring shoulder months demanded set-points

Table 5.10 shows the recorded set-point temperature in all sample households for the spring shoulder months.

Table 5.10 Mean recorded set-point temperature in autumn and spring shoulder months

	Set-Point	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12
Mar	Mean	13.3	14.8	19.2	11.5	-	13.1	13.0	13.6	-	22.0	13.9	-
April	Mean	13.1	13.9	18.8	8.0	-	12.2	8.8	10.7	-	19.2	13.4	-

The mean set-point temperature gives a better indication of how the duration of heating increases the further into the shoulder months it gets as it was kept at a higher set-point for longer and less likely to have been switched off. The spring shoulder months have much higher mean set-point temperatures compared to the autumn shoulder months, indicating the heating is being used more during these months.

The range in set-points being demanded during the spring shoulder months varied across the sample with Table 5.11 presenting the lowest and highest demanded set-points for each household. This does not include any set-point for when switched OFF or any baseline set-points for when left on AUTO. The range shows that even in spring two households demanded the highest temperature possible on the controls, 30^{o}C, with P10 demanding this temperature over both shoulder month periods.

Table 5.11 Lowest and highest demanded set-point temperatures across spring shoulder months

Household	March		April	
	Low	High	Low	High
P01	20	25	20	23
P02	17	21	18	21
P03	18	22	18	21
P04	19	21	19	30
P05				
P06	21	22	21	22
P07	17	21	18	21
P08	11	21	16	21
P09				
P10	21	22	21	30
P11	21	24	21	24
P12				

It was not just the demanded set-point temperatures that varied between the households within the sample, the amount of times that the set-point was changed also varied on a household to household basis.

When looking at the number of changes made to the demanded set-point temperature over the spring shoulder months, Figure 5.28, it is seen that the number of changes made to the set-points is not only more often but by a higher proportion of the sample households. This is likely due to the colder weather during the spring shoulder months compared to the autumn shoulder months. It can be seen to be declining nearer the end of April also so this could match up to households starting to need the heating less than in previous months.

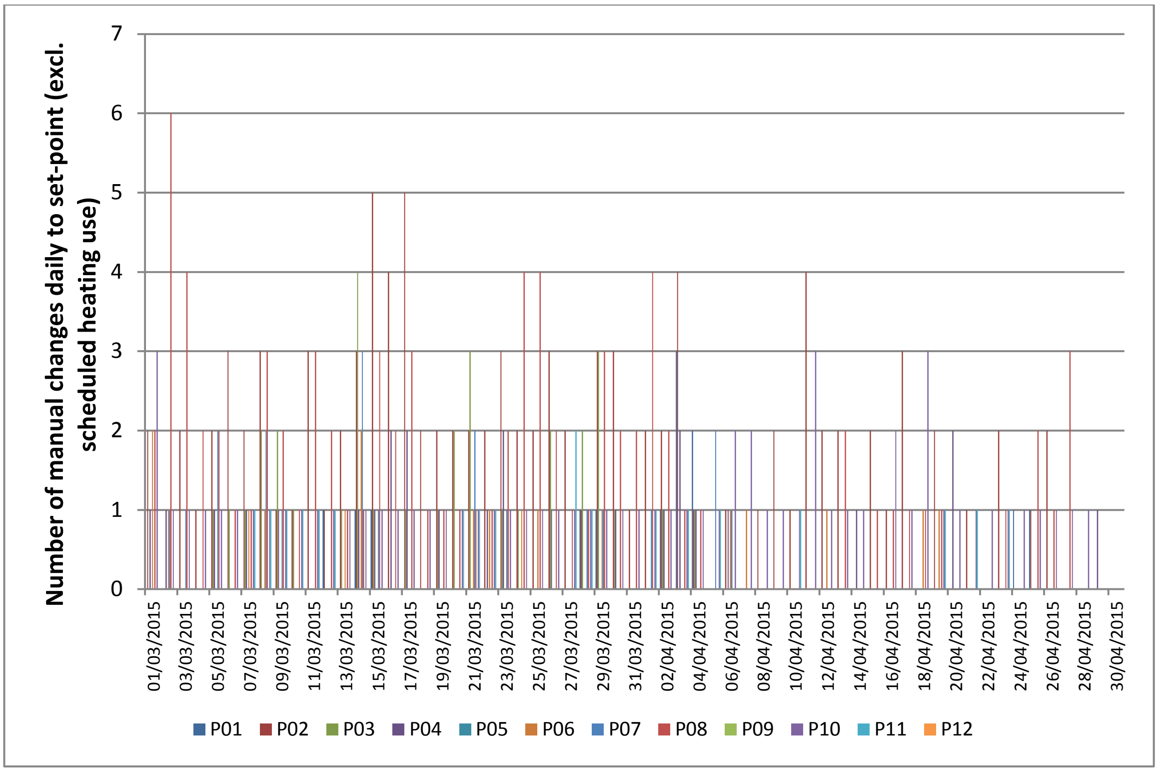


Figure 5.28 Number of changes made to set-point temperatures during March and April

5.4.2.4 Summary of demanded set-points

A variety of different set-point temperatures were recorded as being demanded by householders across all seasons. The maximum set-point of 30°C was demanded within numerous households across each season. Within the winter months highs of 28°C and 30°C were recorded as demanded set-points within households. The lowest demanded set-point over winter was 14°C (P07) which occurred during November. The number of different set-point temperatures varied across the seasons and within the sample. During winter the number of different demanded set-point temperatures varied from one up to nine within just one month. This study found that more changes were made to the set-point at weekends, which is likely to relate to when occupants are in the property longer. The spring shoulder months has higher mean set-points compared to the autumn shoulder months, however it was noted that the use of heating only started more regularly right at the end of September. The number of changes made to set-points on a daily basis peaked during the winter months and decreased again moving from winter to spring.

5.4.3 Internal temperatures

This section presents the findings from analysis of the internal temperatures recorded as part of this study.

5.4.3.1 Autumn shoulder months internal temperatures

Figure 5.29 shows a plot of the average daily internal temperatures for all of the sample households during August and September. It can be seen from the plot that the majority of the sample has very similar internal temperatures during the autumn shoulder months, with P10 and P11 being slightly higher than the other households.

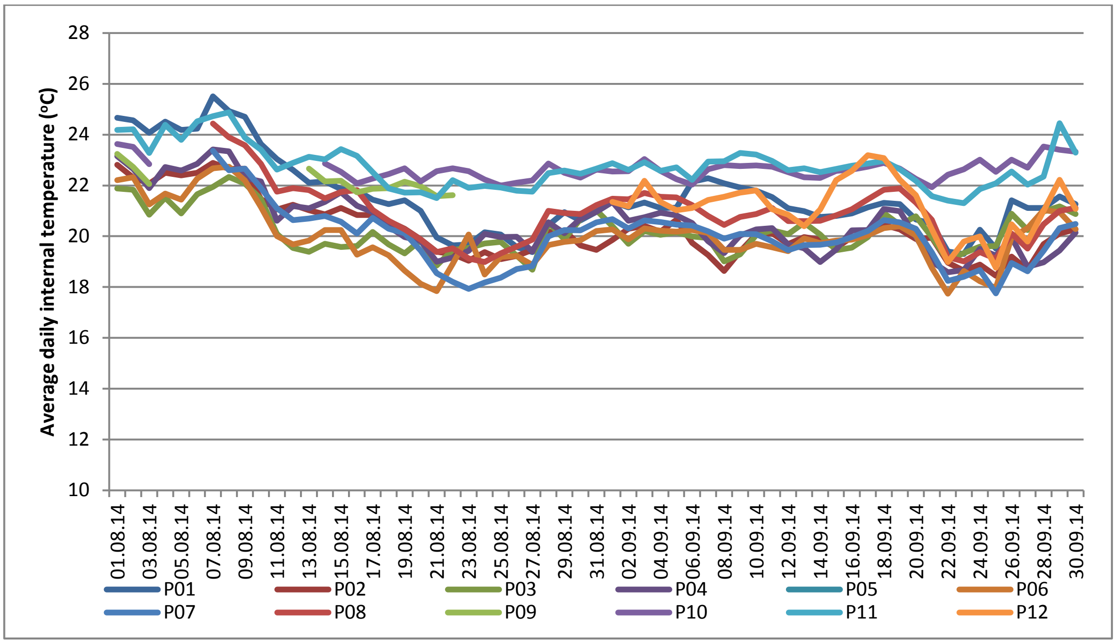


Figure 5.29 Average daily internal temperature across all households during August and September 2014

When the average daily internal temperature is plotted against the external temperature, as shown in Figure 5.30 of P02, it can be seen that the average internal temperature follows closely the pattern of the external temperature during the autumn shoulder months. It can also be seen that the internal temperature starts to level off more during the winter months and not follow the external temperature as closely, indicating a more constant use of heating during the winter months.

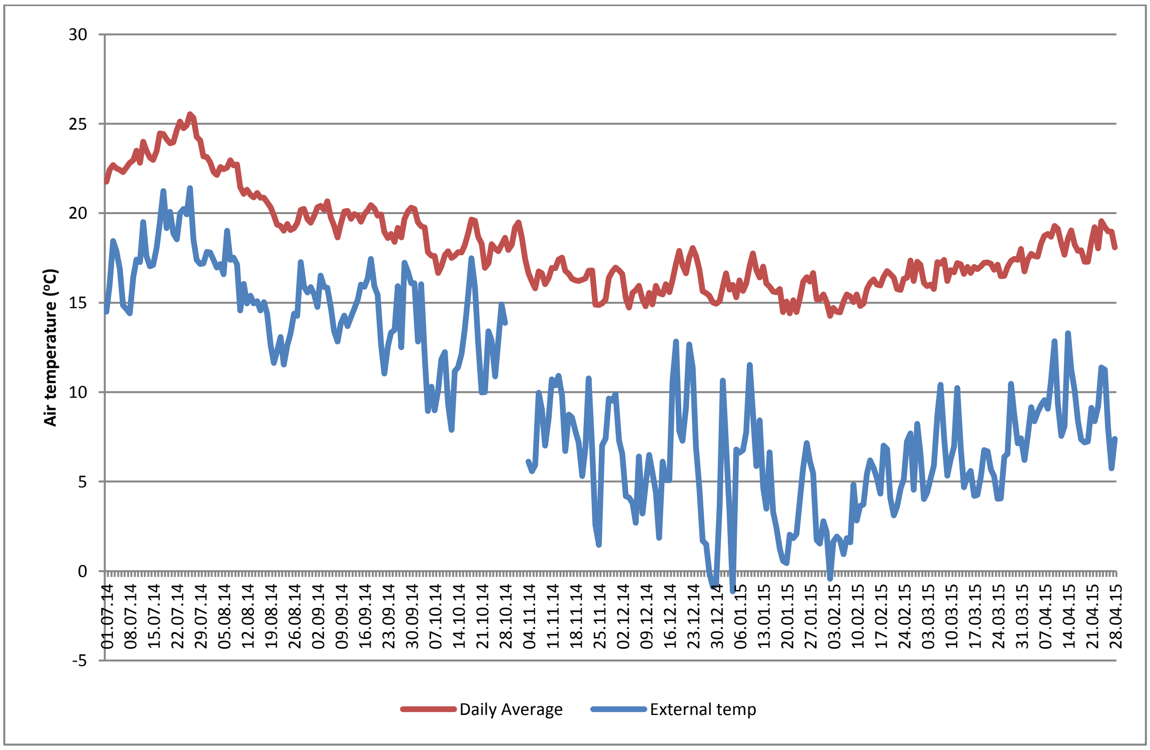


Figure 5.30 Daily internal temperature against daily external temperature recorded over the whole monitoring period for P02

Table 5.12 shows the monthly mean, maximum and minimum temperatures recorded by the thermostat during the autumn shoulder months. As can be seen, mean recorded thermostat temperature for August was 20.9°C and 20.5°C in September indicating that the majority of the sample had very similar internal temperatures during the autumn shoulder months. The mean range between the maximum and minimum recorded temperature were very similar during both August and September, 4.5°C in August and 4.9°C in September.

Table 5.12 Mean, maximum and minimum temperatures recorded by the thermostat during the autumn shoulder months across the whole sample

	August 2014			September 2014		
	Mean	Max	Min	Mean	Max	Min
P01	18.5	18.8	18.3	19.0	19.1	18.8
P02	20.7	23.7	18.0	19.7	21.2	17.8
P03	20.2	23.7	18.0	20.3	22.8	18.4
P04	20.8	23.6	18.4	19.7	21.7	17.4
P05	-	-	-	-	-	-
P06	20.8	23.0	18.2	20.1	22.2	18.1
P07	20.6	23.6	17.7	20.4	21.6	18.4
P08	20.4	24.3	17.6	19.8	21.6	17.7
P09	22.2	23.7	20.7	-	-	-
P10	22.4	24.4	21.3	22.4	24.2	11.1
P11	22.7	25.2	20.3	22.1	25.0	19.8
P12	-	-	-	21.3	24.4	17.6
Mean of sample	20.9	23.4	18.9	20.5	22.4	17.5

However when the range of temperatures (24 hour daily average) within individual rooms are analysed there is an obvious difference. Table 5.13 shows the range in temperatures recorded by each individual box temperature sensor for each month within P01 for the shoulder months. The variations in temperatures internally can be down to numerous factors such as rooms being heated differently to the other rooms within the household due to the use of them or personal preference of the room occupier, the location of the room and whether it has any external walls, drafts, or solar gains or if there is any possible use of secondary heating within the dwelling. These differences such as heating rooms differently or secondary heating will be more obvious during the winter month data as the heating will be on more consistently than the shoulder months.

Table 5.13 Range in temperatures recorded (monthly max-monthly min of daily 24 hour average temperatures) °C within P01

	July	Aug	Sept
Sensor 2	9.0	8.8	8.3
Sensor 3	7.9	8.0	6.6
Sensor 4	-	5.2	5.2
Sensor 5	10.7	10.1	6.0
Sensor 6	6.9	8.1	6.4
Sensor 7	8.5	9.1	4.3
Variation range	3.8	4.9	4.0

5.4.3.2 Winter months internal temperatures

Figure 5.31 presents a plot of all the average internal temperatures (from 24 hour daily averages) from the households within the sample across the winter heating period. The average internal temperature across the sample during winter was 18.6°C, with an average of a 4.9°C difference between the warmest (P10, average of 21.5°C) and coldest (P07, average of 16.6°C) household within the sample across the winter period. The internal temperatures may be seen as relatively cold in relation to the recorded set-point temperatures.

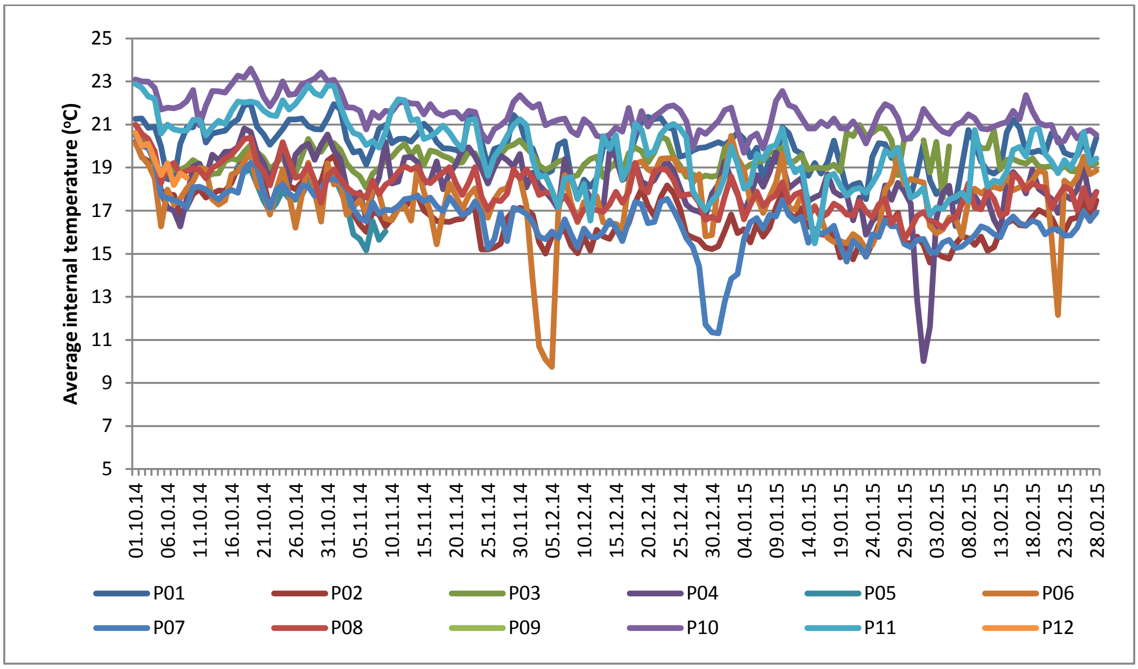


Figure 5.31 Average internal temperatures across the winter months for all sample households

There are instances within the trace where there are obvious dips within the internal temperature of the property. The first of these dips occurs in P06 at the start of December and this related to a change in set-point temperatures during this period indicating that the occupants may have went on holiday and as such adjusted their heating to a lower temperature so to reduce energy wastage whilst away from the property. The remaining dips in internal temperatures out with the normal trace pattern, P07 at the end of December, P04 at the start of February and P06 at the end of February are likely to be for a similar reason (this was confirmed with P07 and P04 during interviews). It can be assumed that the spread of the dip is dictated by how long the occupants are away for, with the shorter the break resulting in the shorter the dip in temperature.

Table 5.14 presents these temperature variations within each household for each month of the winter heating season. These variations in temperatures ranged from 1.5°C - 11°C.

Table 5.14 Average temperature range within households (daily max temp - daily min temp from individual room box temperature sensors), (*based on 9 days of Oct data)

	Oct	Nov	Dec	Jan	Feb
P01	1.7	2.6	3.1	3.1	2.9
P02	3.7	5.7	6.8	6.7	6.9
P03	3.1	3.1	2.6	2.3	2.5
P04	3.0	6.1	7.1	8.0	8.0
P05	1.8	2.3	-	-	-
P06	3.4	5.6	5.6	5.3	6.2
P07	1.6	2.0	2.4	2.5	2.7
P08	3.0	3.3	3.3	3.7	3.9
P09	-	-	-	-	-
P10	7.0	9.5	11.1	7.5	6.5
P11	3.0	3.2	4.7	4.5	4.3
P12	0.6*	-	-	-	-

Table 5.15 lists the average winter temperature for each household based on averaging the individual room sensors and it lists the average temperature recorded by the thermostat itself. By comparing the calculated average temperature from the room sensors with the average temperature being measured by the thermostat it gives an indication as to how varied the temperatures may be within the household. Households with larger differences between the two indicate that the rooms furthest away from the thermostat may in fact be much colder than the area of the dwelling where the thermostat is located. This again is similar to some of the findings within the Phase 1 research, where participants reported areas of their home being vastly different in temperatures, e.g. between upstairs and downstairs or additional rooms such as those build from extensions being of a different thermal environment. Within the sample all but P08 recorded a higher average temperature across winter from the thermostat temperature readings compared to the whole household average from individual room sensors. This could be evidence of P08 using sources of secondary heating in certain rooms which boosts the average temperatures compared to the main heating control sensor.

Table 5.15 Average internal winter temperature for all households (October - February)(*P12 set-point data only includes a week in Oct)

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	Mean
Average winter internal temperature (whole household)	20.0	16.7	19.4	18.3	17.4	17.5	16.6	18.0	-	21.5	19.8	19.3	18.6
Average temperature recorded at thermostat (one location)	20.3	18.0	20.6	18.5	18.2	19.1	17.6	16.9	-	21.9	20.4	19.6	19.2
Average demanded set-point temperature (winter)	21	19	21	20	18	21	18	21	-	22	22	29*	21

5.4.3.3 Spring shoulder months internal temperatures

Figure 5.32 shows a plot of the average daily internal temperatures for all of the sample households during March and April. It can be seen from the plot that the majority of the sample follow similar internal temperatures patterns during the spring shoulder months, with the internal temperatures being between 16-22°C on most occasions. P06 appears to become more unusual within April with higher spikes in internal temperature than in the previous months indicating that P06 may have been changing how they use their heating or secondary heating within the household, or that there may be more influence from external weather and solar gains within the property.

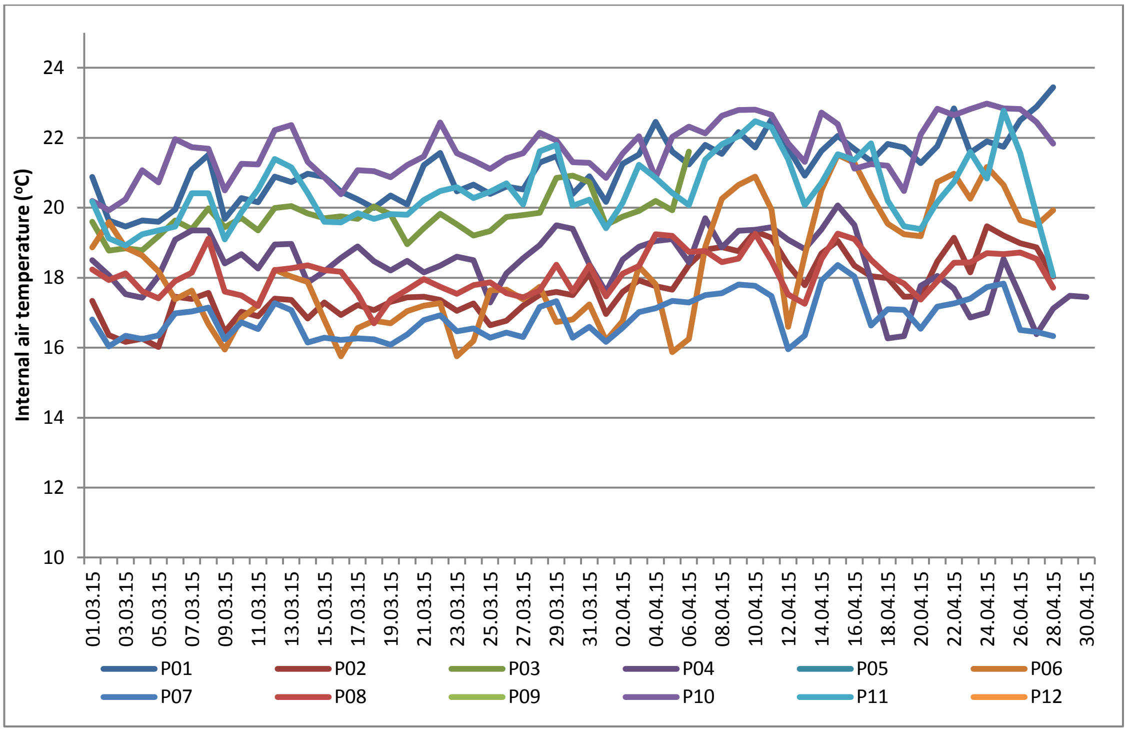


Figure 5.32 Average daily internal temperature across all households during March and April 2015

The influence of external temperatures on the average daily internal temperature is plotted for P06, as shown in Figure 5.33. It can be seen that the average internal temperature follows closely the pattern of the external temperature more from April and that the unusual spikes do match closely to changes in the external temperature. Therefore it is likely that within P06 the internal temperature is influenced from solar gains during the spring shoulder months.

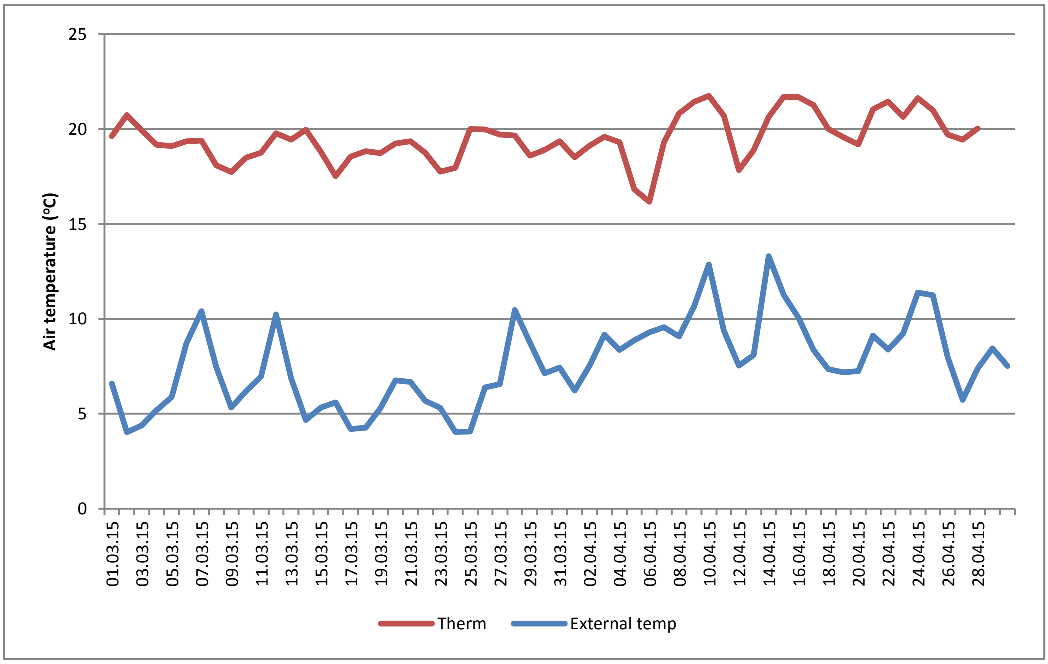


Figure 5.33 Daily internal temperature against daily external temperature recorded over the spring shoulder months for P06

Table 5.16 shows the monthly mean, maximum and minimum temperatures recorded by the thermostat during the spring shoulder months. As can be seen, the mean recorded thermostat temperature for March was 19.5°C and 20.2°C in April indicating that the majority of the sample had very similar mean internal temperatures during the spring shoulder months, with April only being slightly warmer. However the mean thermostat temperatures across the sample varied significantly with P08 having a mean temperature of 16.8°C in March compared to P01 which had a mean temperature of 22°C during the same month. The difference in mean temperatures will be influenced by the temperatures being demanded by the household, the physical properties of the dwelling and the location of the thermostat. The mean internal temperature, for all but two households, was warmer in April than March, which is likely to have been down to the increasing external temperature. The mean range between the maximum and minimum recorded temperature were very similar during both August and September, 5.8°C in March and 5.5°C in April.

Table 5.16 Mean, maximum and minimum temperatures recorded by the thermostat during the spring shoulder months across the whole sample (P03 April results only based on one week of data)*

	March 2015			April 2015		
	Mean	Max	Min	Mean	Max	Min
P01	22.0	22.7	21.7	24.5	27.0	22.7
P02	18.2	20.5	15.6	18.7	20.8	16.6
P03	20.4	22.7	17.6	20.9*	22.6*	19.4*
P04	18.5	21.1	15.7	18.2	21.1	14.5
P05	-	-	-	-	-	-
P06	19.1	22.5	15.8	20.0	23.3	15.6
P07	17.8	20.0	15.8	18.2	20.2	16.2
P08	16.9	21.4	14.4	17.8	21.6	15.3
P09	-	-	-	-	-	-
P10	21.9	22.8	10.7	21.8	24.3	18.3
P11	20.9	24.7	18.2	21.4	24.9	18.3
P12	-	-	-	-	-	-
Mean of sample	19.5	22.0	16.2	20.2	22.9	17.4

5.4.3.4 Summary of internal temperatures

The average internal temperature of households was found to match closely with the external temperatures during the autumn shoulder months and the spring shoulder months. The winter months did follow the external temperature but not as closely as the shoulder month seasons. The average internal temperatures for the sample were 20.9°C and 20.5°C for August and September, 18.6°C for the winter months, 19.5°C for March and 20.2°C for April. This indicated that moving from autumn into winter there was a decrease in the average internal temperature of the sample before slowly starting to increase again during the spring shoulder months. Across all seasons there was a range found between the average internal temperatures of 4-6°C. It was not possible to analyse the variation in temperatures within the sample between individual rooms to see if certain rooms were warmer than others (living room versus rest of the dwelling etc.) due to the exact locations being unknown. However, the study did find that within winter the variations within households ranged between 1.5-11°C.

5.4.4 Scheduled heating use

This section presents results on the heating schedules programmed by households during autumn shoulder months, winter and spring shoulder months. Results are also presented relating to changes made to the default settings of the new controls.

5.4.4.1 Autumn shoulder months programmed schedules

Within the sample it was found that during the autumn shoulder months most households only started using their heating near to the end of September as already reported in Section 5.4.1, however by using the data recorded within the Advance data file it was possible to then match what use was from scheduled heating or manual use. Table 5.17 presents the heating schedules programmed into the controls during the autumn shoulder months for the sample households.

Table 5.17 Autumn shoulder month heating schedules

	Weekday heating periods	Weekend heating periods
P01	No schedule set	No schedule set
P02	19°C 5.30-7.30am/19°C 7-10pm	19°C 5.30-7.30am/19°C 7-10pm
	18°C 5.30-7.30am/18°C 7-10pm	18°C 5.30-7.30am/18°C 7-10pm
	16°C 5.30-7.30am/18°C 7-10pm	16°C 5.30-7.30am/18°C 7-10pm
	18°C 5.30-7.30am/19°C 7-10pm	18°C 5.30-7.30am/19°C 7-10pm
P03	21°C 6.30-8.30am	21°C 6.30-8.30am
	22°C 5-10.30pm	22°C 5-10.30pm
P04	-	-
P05	-	-
P06	No schedule set	No schedule set
P07	18°C 6.45-9am	18°C 6.45-9am
	18°C 4.30-5.30pm	18°C 4.30-5.30pm
P08	18°C 5.45-6.45am	18°C 5.45-8.45am
P09	22°C 5.45-6.45am	22°C 5.45-6.45am
P10	No schedule set	No schedule set
P11	21°C 7.30-8.30am	21°C 7.30-8.30am
	20°C 5-8.30pm	20°C 5-8.30pm
P12	No schedule set	No schedule set

P05 had no recorded data available for this analysis. P06 had no data recorded in the advance data file for these shoulder months however they only used their heating on a total of 12 days during August and September which all seemed to occur at different times therefore it was assumed that they were using it on a demands basis and not left on a schedule at that time. Similarly there was patchy Advance data for P04, P11 and P03, however it was possible to see repetitive heating use occurring at the same time periods over multiple days and therefore these were taken to be scheduled heating use, as it was unlikely occupants would manage to turn their heating on and off at the exact same times over numerous days. P09 also had patchy data during August and September, with data only available up until the end of August when data was lost due to equipment failure. As the Table shows, P02 changed their heating schedule on numerous occasions during the shoulder month season.

5.4.4.2 Winter months programmed schedules

The heating schedules recorded during the winter heating season varied across the entire sample in set-point temperatures, durations of heating and even number of heating periods scheduled. Table 5.18 presents the recorded heating schedules in each of the winter heating season months for the sample households (removing P09 due to lack of winter data). As it can be seen from the results households regularly change their heating schedule even in mid-winter. Although P01 did show this behaviour of setting an initial heating schedule at the start of the winter months and then leaving it, within this small sample P01 looks to be an exception, with the other participants changing the heating schedule throughout the winter months. The results also show that households not only adjust the timings for the heating schedule during the winter but also the set-point temperatures and the duration that the heating is set to be on for. The scheduled heating periods typically were set to be between 18 and 21^{o}C however one household did programme their heating so their evening heating period was 24^{o}C.

Table 5.18 Recorded heating schedules set over the winter heating season for all sample households

	October		November		December		January		February	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
P01	20°C 6-8am 21°C 5-9pm	21°C 6-10am 21°C 5-9pm	20°C 6-8am 21°C 5-9pm	21°C 6-10am 21°C 5-9pm	20°C 6-8am 21°C 5-9pm	21°C 6-10am 21°C 5-9pm	20°C 6-8am 21°C 5-9pm	21°C 6-10am 21°C 5-9pm	20°C 6-8am 21°C 5-9pm	21°C 6-10am 21°C 5-9pm
P02	18°C 5.30-7am 19°C 7-10pm	19°C 6.30-7.30am 19°C 7-10pm	18°C 5.30-7am 19°C 7-10pm	19°C 6.30-7.30am 19°C 7-10pm	19°C 5.30-8.40am/ 5.50-10pm 5.30-7.30am/ 5.30-10pm 5-8am/ 6-10pm	19°C 7-9am 19°C 6-10pm	19°C 5-7.30am/ 5.30-10pm 19°C 5-8am/ 5-10.30pm	19°C 7-9am 19°C 6-10.30pm	19°C 5-8am 19°C 5-10.30pm	19°C 7-9am 19°C 5-10.30pm
P03	20°C 6-8.30am 20°C 2-4pm 21°C 4-10.30pm	20°C 6-8.30am 20°C 2-4pm 21°C 4-10.30pm	20°C 6-8.30am/3-10.40pm 20°C 2-4pm 21°C 4-10.30pm	20°C 6-8.30am/3-10.40pm 20°C 2-4pm 21°C 4-10.30pm	20°C 6-8.50am 21°C 3-10.40pm	20°C 6-8.50am 21°C 3-10.40pm	20°C 6-8.50am 21°C 3-10.40pm	20°C 6-8.50am 21°C 3-10.40pm	20°C 6-8.50am 21°C 3-10.40pm	20°C 6-8.50am 21°C 3-10.40pm
P04	19°C 5.45-8.30am 19°C 4.30-10.30pm	20°C 7-10.55am 20°C 4.30-10pm	19°C 4.30-10.30pm	20°C 7-10.55am 20°C 4.30-10pm	19°C 6-9am 19°C 4.30-10pm	20°C 7-11am 20°C 4.30-9.45pm	19°C 8-9am/4.30-10pm 19°C 6-9am/4.30-10pm	20°C 7-11am 20°C 4.30-9pm	19°C 6-9am 19°C 4.30-10pm	20°C 7-11am 20°C 4.30-9pm
P05	18°C 6-8.20am 18°C 6.15-9.30pm	18°C 6-8.20am 18°C 6.15-9.30pm	18°C 5.50-8.15am 18°C 6-9.30pm	18°C 5.50-8.15am 18°C 6-9.30pm	-		-		-	
P06	No schedule set		No schedule set		22°C 5.05-7.30am 22°C 5.25-10.20pm	21°C 8.30-10.30am	22°C 5.05-7.30am 22°C 5.25-10.20pm	21°C 7.30-10.30am	22°C 5.05-7.30am 22°C 5.25-10.20pm	21°C 7.30-10.30am
P07	18°C 6.45-9am 18°C 4.30-7.45pm		18°C 6.45-9am 18°C 3.30-7.45pm	18°C 6.45-9am 18°C 1.45-7.45pm	18°C 6.30-9am 18°C 3.30-7.30pm	18°C 8-10.15am/4-8pm 15°C 9-11am/ 4-6pm	18°C 6.30-9am 18°C 3-8.15pm	18°C 7.35-11am 18°C 4.15-8.15pm	18°C 6.30-9am 18°C 3-8.15pm	18°C 7.35-11am18°C 4.15-8.15pm
P08	18°C 6-7am	18°C 6-7am	18°C 6-7am 18°C 6-8am	18°C 6-7am 18°C 6-8am	21°C 6-8am	21°C 6-8am	21°C 6-8am	21°C 6-8am	21°C 6-8am	21°C 6-8am
P10	No schedule		No schedule		No schedule		No schedule		No schedule	
P11	21°C 7.30-8.30am 21°C 5-8.30pm 21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 21°C 5-8.30pm 21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm	21°C 7.30-8.30am 24°C 5-8.30pm
P12	No schedule set		-		-		-		-	

Figure 5.34 shows a daily trace from the start of January of three of the households being monitored. As can be seen P01 follows the 'typical' pattern of two daily heating periods, however they have different demanded set-points with the evening heating period being at 21°C compared to the morning set-point of 20°C. P10 disregards the scheduling potential of the new heating controls by instead preferring to leave the heating constantly on at 22°C for the full day. P08 also differs from the 'typical' heating schedule as it uses one heating period during the day, although with a decrease in demanded temperature during this heating period. This figure highlights that not all households follow the same type of heating pattern in the total number of heating periods during the day.

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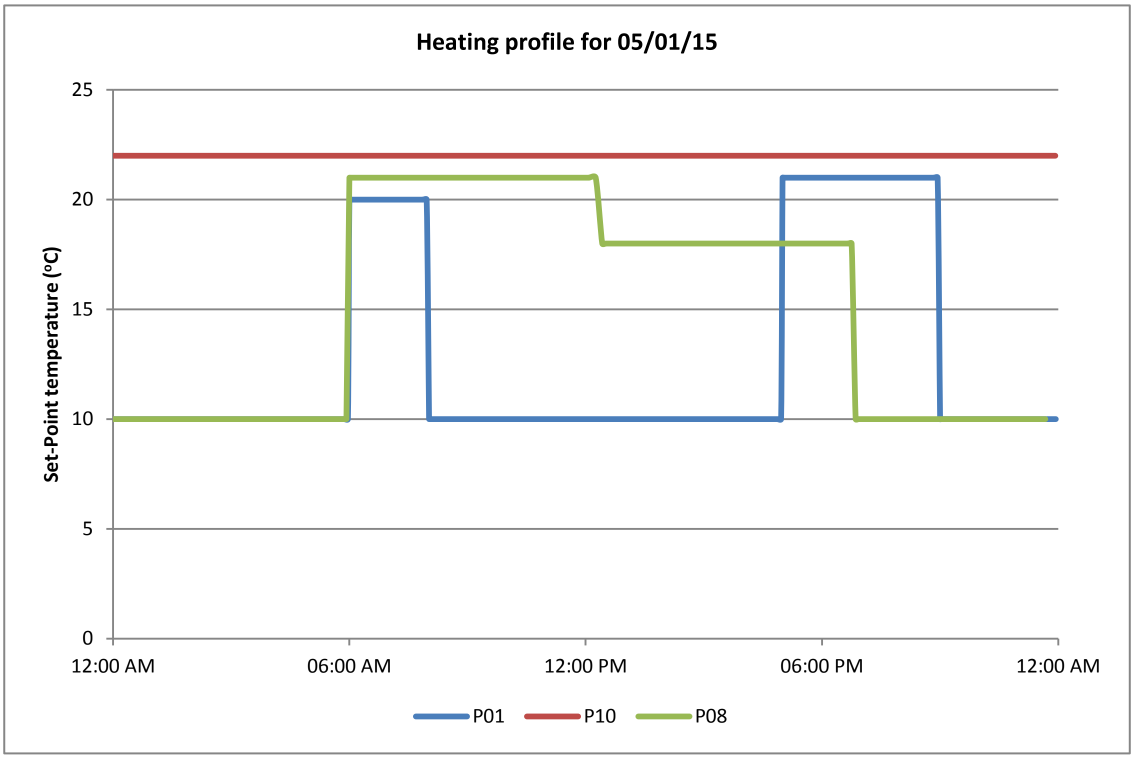


Figure 5.34 Heating profiles for sample households recorded on 5th of January 2015

Although P08 exhibits one heating period for the day (shown in Figure 5.34), upon inspection of the data for programmed heating schedules presented in Table 5.18 it can be that P08 only has a heating schedule programmed for the morning. Therefore, the one heating period is due to the occupant overriding the heating schedule and switching the heating onto manual. This shows that the number of daily heating periods within a household can be influenced by manual use. Therefore, if it is not possible to separate the manual use and scheduled use, like this study has done, a different number of heating periods may be found compared to what is from scheduled settings. Although, as seen in Table 5.18, the majority of the sample did program two heating periods. However, both scheduled and manual use can be combined to analyse the total number of heating periods recorded. Table 5.19 summarises the number of heating periods recorded over the winter months giving the average number of heating periods across the winter months as well as the maximum number of heating periods recorded in any one day over the winter as well as the minimum number recorded.

Table 5.19 Average, maximum and minimum number of separate daily heating periods over winter months (Oct-Feb) for sample households

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12
Average	2	3	2	2	2	2	2	2		1	2	1
Max	22	5	3	4	2	4	3	3		2	4	2
Min	0	2	0	0	1	0	0	0		1	1	0

As the table shows, P02 and P08 show an average number of heating periods higher than the number of programmed heating periods. This indicated that these households regularly use the controls manually to supplement the heating use already programmed. The maximum number of heating periods recorded in any one day for P01 was 22 and this was due to multiple changes made to the controls with the heating regularly switched on and off after less than an hour. This shows that there can be instances where some occupants regularly keep switching their heating on and off throughout a day for short periods of time.

5.4.4.3 Spring shoulder months programmed schedules

When analysing the spring shoulder month data, there was a total of nine households with relevant data however one of those households, P03, was sold and subsequently moved out of at the start of April. Of the nine households with data only one of them was found not to have any schedule set and that was P10 which still chose to leave the controls switched ON constantly. The remaining eight still used schedules which had been altered over the winter, which are summarised in Table 5.20. Unlike the autumn shoulder months and winter months, no changes were made to the programmed heating schedules during the spring shoulder months. Most of the remaining households started switching off their controls during heating periods instead of altering the heating schedule itself, however P11 showed only their morning scheduled use at the end of April, P08 and P02 reduced the temperature which they set the schedule for at the end of April and P07 switched the controls off completely at the end of April.

Table 5.20 Spring shoulder month heating schedules

	Scheduled heating periods	
	Weekdays	Weekends
P01	20°C 6-8am and 21°C 5-9pm	21°C 6-10am and 5-9pm
P02	19°C 5-8am and 5-10.30pm	18°C 7-9am and 5-10.30pm
P03	20°C 6-8.50am and 21°C 3-10.40pm	20°C 6-8.50am and 21°C 3-10.40pm
P04	19°C 6-9am and 4.30-10pm	20°C 7-11am and 3-10.15pm
P05	-	-
P06	22°C 5.05-7.30am and 5.25-10.20pm	21°C 7.30-10.30am
P07	18°C 6.30-9am and 3-8.15pm	18°C 7.35-11am and 4.15-8.15pm
P08	21°C 6-8am	21°C 6-8am
P09	-	-
P10	No schedule	No schedule
P11	21°C 7.30-8.30am and 24°C 5-8.30pm	21°C 7.30-8.30am and 24°C 5-8.30pm
P12	-	-

As shown in the Table typically all households schedule two periods of heating daily, except for P08 who only had one morning heating period scheduled and relied on manual interaction the rest of the day. Five of the households had different weekday and weekend schedules still set during the spring shoulder months often with different temperatures and times for both.

5.4.4.4 Changes made to default settings

However, as previously reported the heating schedules could be impacted due to occupants changing the default settings on the controls, therefore potentially changing the set-back temperature when the controls are left on AUTO or the frost protection temperature when the controls are OFF.

Out of the eleven households with data recorded for the Away heating (P05 had no recorded data for either Away heating or Energy Saving heating due to faults with the data recording for that household), nine of the households left this default setting exactly how it was. Of the two which changed this setting, P11 increased the temperature and P03 changed the settings on numerous occasions. Out of the eleven households with data for the Energy Saving temperature, eight chose to keep the default setting. One household reduced this temperature with another household increasing the temperature and another, P03, changed the temperature settings for the Energy Saving temperature on numerous occasions. Table 5.21 summarises those households which made changes to the default settings and what those changes were.

Table 5.21 Default settings and changes made to these within the sample

Setting	Default temperature	Households with no change	Households with changes made
Away heating	5°C	P01, P02, P04, P06, P07, P08, P09, P10, P12	P11 → increased to 10°C P03 → increased to 13°C, decreased back to 5°C, increased to 10°C
Energy Saving	10°C	P01, P02, P06, P07, P08, P10, P11, P12	P04 → decreased to 5°C P09 → increased to 20°C P03 → increased to 20°C, decreased to 19°C, decreased to 10°C, decreased to 5°C, increased to 18°C

P03 made the most changes to the default settings within the sample, and interestingly set the defaults back to the originals at one point, however this is likely to have been from resetting the controls to their default settings as both settings recorded a change back to the original default at exactly the same time on that date. Interestingly was that both P11, P09 and P04 only made changes to one of the default settings not both like P03.

Although this study only looked at a small sample and therefore cannot be representative of how people may adjust default settings, it does show that given the same controls, the majority chose to leave the default settings as they are. If changes are made to the default setting it seems to typically be to increase the default temperature and therefore this could be detrimental to trying to reduce energy use within domestic heating. Given the majority of the sample did not make any changes to the default settings this highlights the importance for the default settings to be correct for householders, and therefore more research is needed on what the best defaults for heating use are.

5.4.4.5 Summary of scheduled heating use

The study found that during the autumn shoulder months six households had set heating schedules with the new controls. Four of those were for two heating periods a day and the remaining two had just one heating period. Within the autumn shoulder months P02 regularly made changes to their heating schedule. Within the winter months a total of nine households had heating schedules programmed. P08 only had one heating period daily and P06 had two heating periods during the week, but only one during the weekend. It was found that the number of heating periods daily was influenced by manual use of the controls. P02 and P08 had a higher average number of daily heating periods than the number of scheduled heating periods. Within the spring shoulder months no changes were made to any of the existing heating schedules within the sample. A total of eight households were still using heating schedules. The analysis also found that changes were made to the default settings of the controls by a number of households. Two households changed the Away setting, which was the frost protection temperature. Three households changed the Energy Saving setting, which was the set-back temperature for when the controls were left on AUTO.

5.4.5 Manual heating use

This section presents the results relating to manual use of heating during this study. Manual use is taken to be any instance where the occupants manually switch the heating on, override their heating schedule or change the set-point temperature manually.

5.4.5.1 Autumn shoulder months manual use of controls

Table 5.22 presents the manual heating use percentage for each household during the shoulder month period. With two of the households the Advance data file had not been programmed to be included on the server and this was only noticed by the author during November therefore without this data it is not possible to give the percentage of manual use during the autumn shoulder months. A further four households only had Advance data for one of the two autumn shoulder months, so a comparison between August and September was not possible. Therefore the autumn shoulder month manual use analysis only includes six households with data covering the full shoulder months.

Table 5.22 Percentage of heating use which resulted from manual use of the controls during August and September and the change in manual use between those months

	August manual use	September manual use	Change in manual use
P01	0%	100%	+100%
P02	2.9%	6.0%	+3.1%
P03	1.3%	/	/
P04	0%	/	/
P05	/	/	/
P06	7.2%	/	/
P07	0%	13.2%	+13.2%
P08	0%	0%	0
P09	26.5%	0%	-26.5%
P10	100%	100%	0
P11	/	/	/
P12	/	100%	/

As the Table shows, three of the households used their heating manually for all of their heating within September suggesting that some households prefer to use their heating on a demand basis during the shoulder months, however the difference in the total number of hours that manual use is hidden, with P10s 100% use referring to a total of 720 hours but P01s 100% use referred to only 12 hours of use. To show the difference in hours of manual use between the sample, the total monthly hours of manual use are seen in Table 5.23. When not considering P10 and P09 (in August) the sample records low total hours of manual use of heating so although the percentages of manual use may be high, overall the use of heating is still small within the autumn shoulder months.

Table 5.23 Total hours of manual use of heating recorded during August and September in all households

	August total hours of manual use	September total hours of manual use
P01	0	12
P02	4.4	8.2
P03	0.4	-
P04	0	-
P05	-	-
P06	1.9	-
P07	0	0.5
P08	0	0
P09	32.3	-
P10	432	720
P11	-	-
P12	-	3.2

Due to the lack of missing Advance data within the autumn shoulder months it is hard to say if during this season most households did rely on manual use of their heating or whether most set a heating schedule and just left it on AUTO.

5.4.5.2 Winter months manual use of controls

The manual use of heating for all households was recorded for every day of the monitoring period and plotted over the whole monitoring period, as seen in Figure 5.35. The external daily mean air temperature is plotted on the stacked manual use graph to show the influence of external temperatures on the total hours of manual use heating across the full sample. As the plot shows, there is a significant increase in the manual use of heating from mid-November until early January, which coincides with the external average temperatures falling below 10^{o}C. The decrease in manual use due to the increasing external temperature moving into spring can also be seen clearly within the plot, which is likely to be from people just leaving their heating as it is already scheduled or starting to switch it off when not needed, therefore a lower total hours of manual use of heating is recorded.

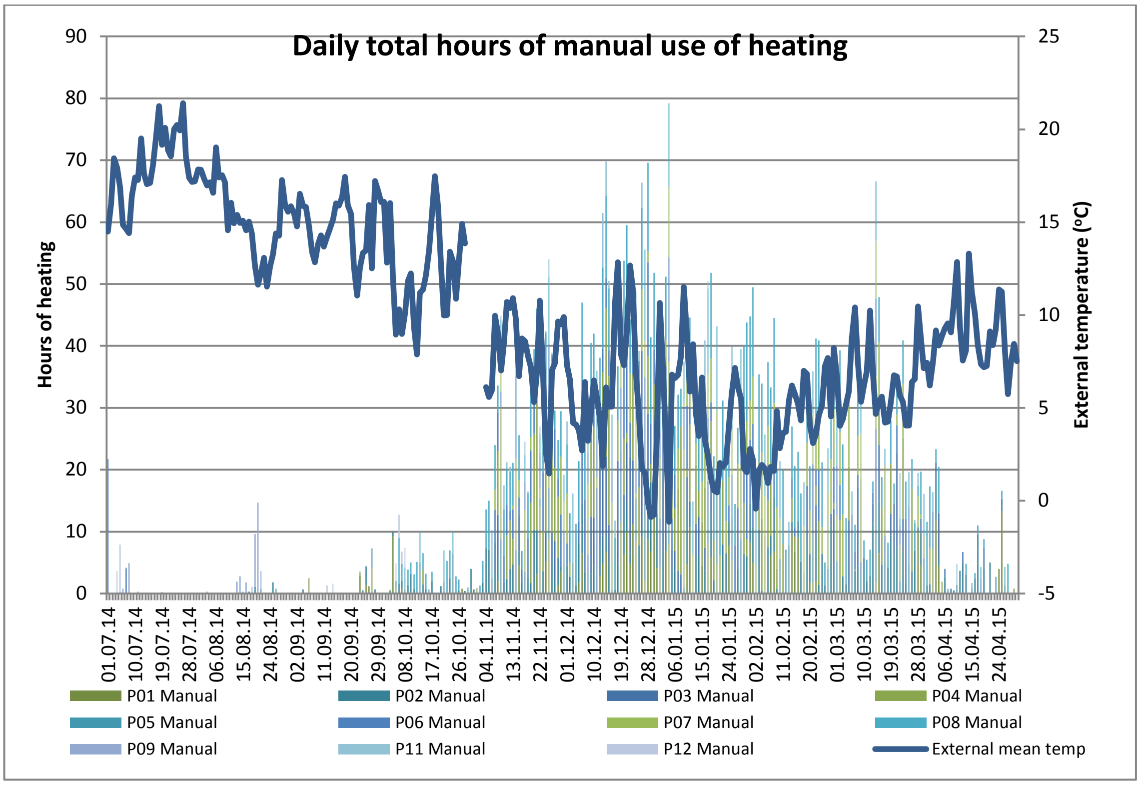


Figure 5.35 Daily total hours from all households manual use of heating across monitoring period

The manual use of heating can be compared on an individual household basis to see how the use changes over the monitoring period. Figure 5.36 shows the plot for total hours of heating use and total daily hours of manual use for P01. The manual use of the heating increases most during the winter months. The analysis of the Advance data file can provide further detail on how manual use varies within the sample and across the winter period.

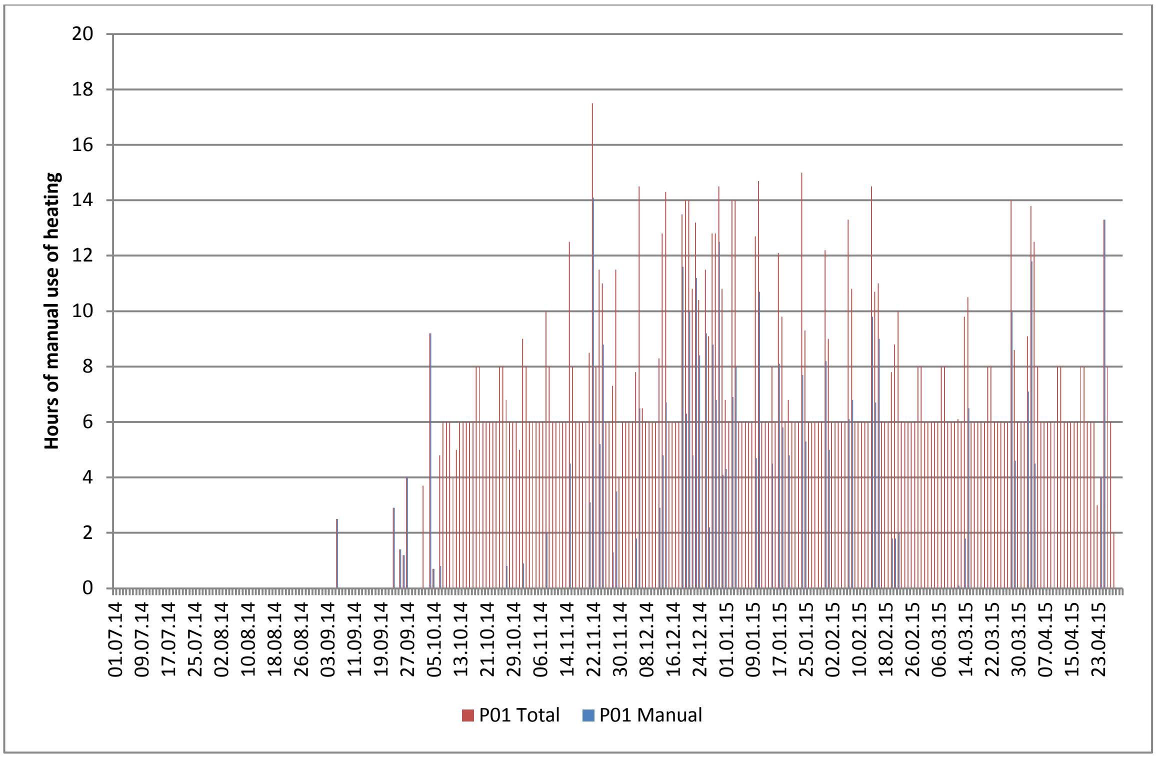


Figure 5.36 Total hours of active heating and hours of manual use for P01 across monitoring period

Table 5.24 and Table 5.25 show an example of the output from analysing the Advance data files for P01 and P06, with all household summary tables included in Appendix 5-C. It can be seen in Table 5.24 P01 used their heating in an "AUTO" mode 61.1% of the recordings with it switched "OFF" 33.4% and then the manual use accounted for 5.5% of the recordings. During this manual use of the heating, the demanded set-point ranged from 21^{o}C to 25^{o}C. However, when looking at Table 5.25 it can be seen that P06 differed in that when the new controls were used in a manual setting, the demanded temperature stayed at only 21^{o}C, which accounted for 13.5% of the recordings. This is similar to the results reported within Section 5.4.2.2 regarding the variation in the amount of set-point temperatures being demanded by households across the sample. The majority of the sample recorded various set-point temperatures being manually demanded, however the percentage of manual use across the sample varied significantly and particularly the manual use on a month by month basis varied within each household and between the sample households.

Table 5.24 Summary of Advance data file for P01

P01 Advance			
Set-Point (^{o}C)	**Total number of recordings**	**Percent of all recordings**	**Cumulative Percentage of recordings**
0	54011	61.1	61.1
5	29514	33.4	94.5
21	4048	4.6	99.1
22	480	.5	99.6
23	355	.4	100.0
24	1	.0	100.0
25	3	.0	100.0
Total	88412	100.0	

Table 5.25 Summary of Advance data file for P06

P06 Advance			
Set-Point (^{o}C)	**Total number of recordings**	**Percentage of all recordings**	**Cumulative Percentage of recordings**
0	30329	47.6	47.6
5	24850	39.0	86.5
21	8588	13.5	100.0
Total	63767	100.0	

By analysing the monthly advance file individually it is possible to compare how the use of the new controls changes through winter. Table 5.26 summarises the monthly data from P01 into the percentage of recordings that were from using the new controls in either “AUTO”, “OFF” or “ON”. Table 5.26 shows that there is a distinct increase in the manual use of the heating controls during mid-winter peaking at 16.8% of the recordings in December before decreasing again when moving towards spring. This shows that this household typically left their controls to AUTO during the winter months, however they manually interacted with the controls most in winter, to manually override them, increase the temperature and duration of use.

Table 5.26 Monthly percentage of heating use via scheduled heating (AUTO), OFF or manual use for P01

P01	AUTO	OFF	ON (Manual use)
July	-	100%	-
August	-	100%	-
September	-	98.4%	1.6%
October	79.8%	18.4%	1.8%
November	92.5%	0.8%	6.7%
December	82.7%	0.5%	16.8%
January	88.6%	0.1%	11.3%
February	92.2%	0.1%	7.7%
March	96.6%	0.1%	3.3%
April	87.8%	5.7%	6.5%

These monthly percentages can be used to plot the monthly manual use for all households in spider diagrams, taking into consideration any months where there may be missing data therefore some use different scales where a month may be missed out. However by plotting the manual percentage use of heating in this way, it gives a clear indication that, within the sample, the manual percentage use of the heating increases during mid-winter. Figure 5.37 shows an example of one of the spider diagram.

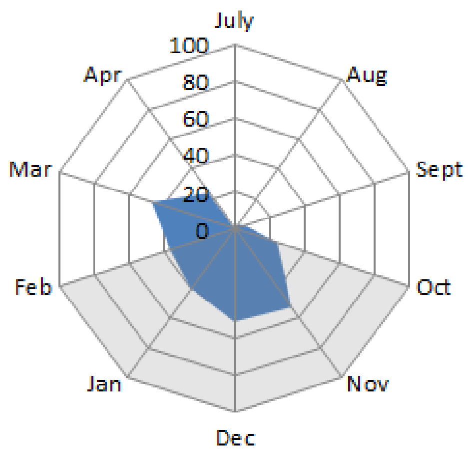


Figure 5.37 Spider diagram plot of monthly manual use percentage of total heating use for P02

Here it can be seen that each point of the diagram refers to a month during the monitoring period (between July 2014 and April 2015). The axis for each of these points goes from 0-100 and represents the percentage of manual use of heating within that month for that household. The percentage goes from 0-100% from the central point of the diagram towards the outer part of the diagram. So, from Figure 5.37, the percentage of the total heating use being manual use in January is seen to be roughly 40%. The greyed out section of the diagram highlights those months which are included in the winter months analysis. Figure 5.38 and Figure 5.39 presents all of the spider diagrams for the sample, missing out P05, P09 and P12 due to the limited data from those households. However, P05 did have data for October and November which showed 0% of the total heating use came from manual use of the controls. It should be noted that were the months are not in order, this is due to missing data and to avoid the assumption that manual use accounted for 0% that month.

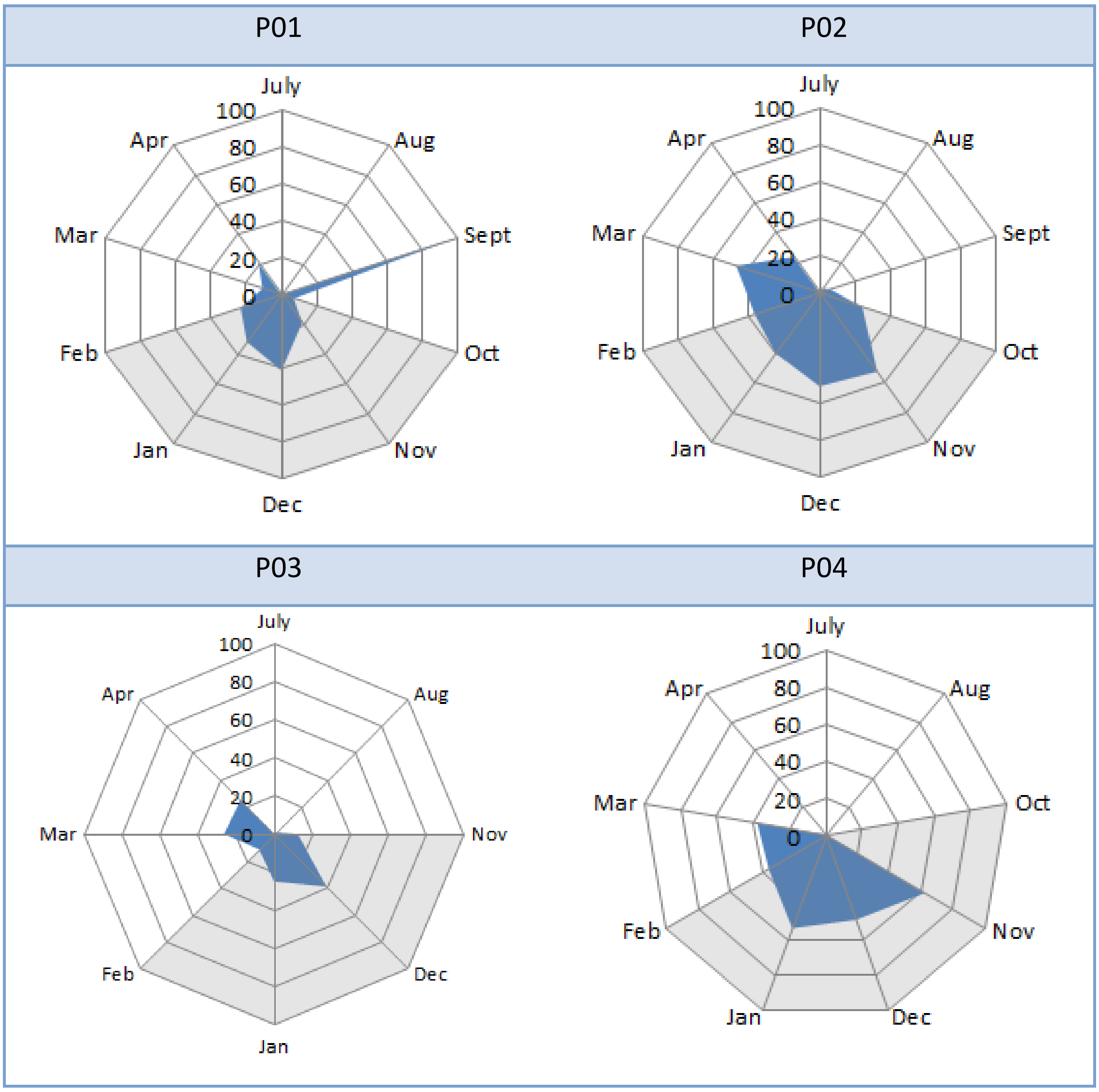


Figure 5.38 Percentage of manual use of heating across the monitoring period for sample households P01-P04. Winter months shaded in grey.

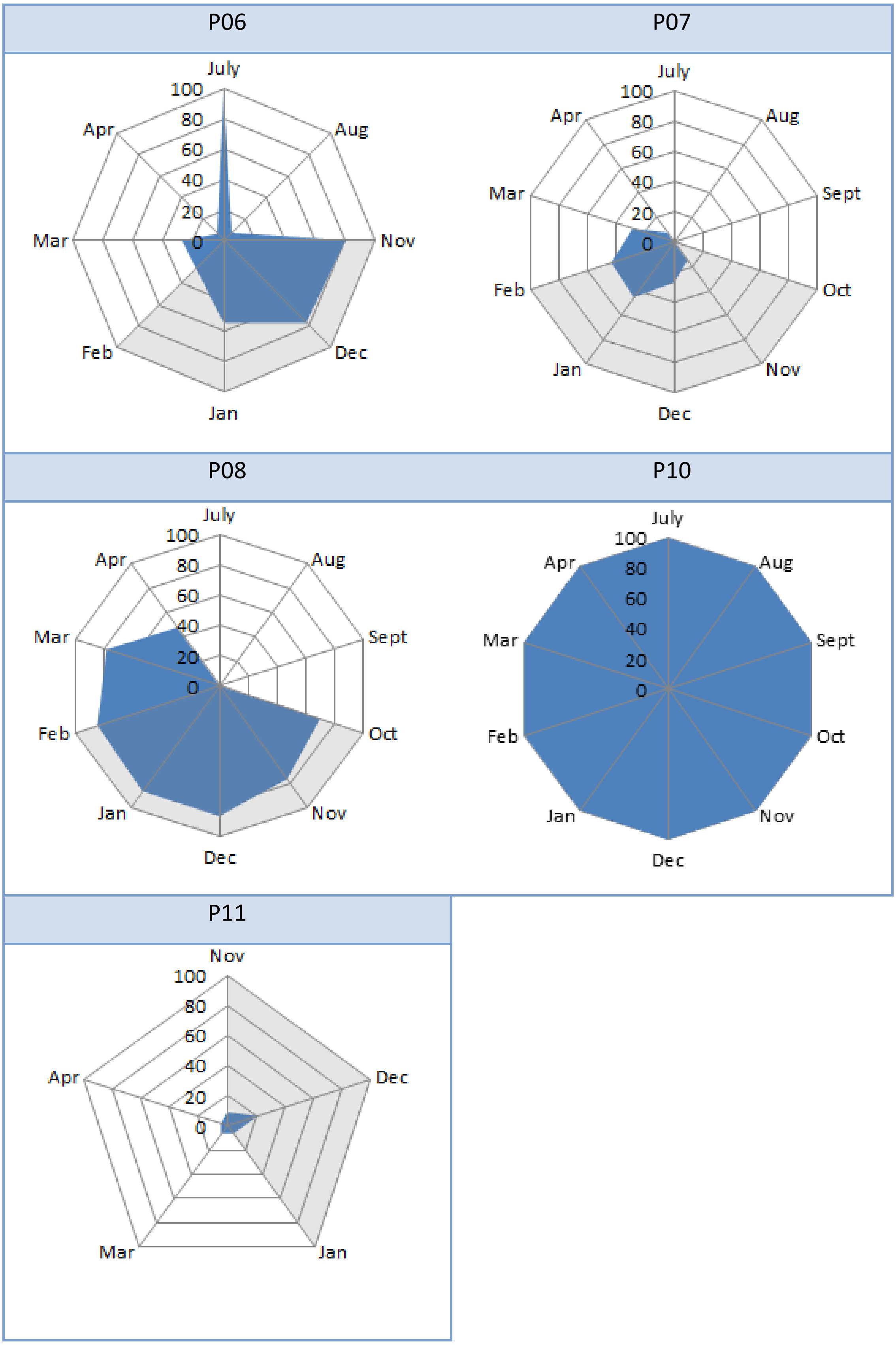


Figure 5.39 Percentage of manual use of heating across the monitoring period for sample households P07, P08, P10 and P11

The spider diagrams make it very easy to spot the households which use their heating controls in a manual mode more often than others. P10, as previously reported, leave their heating switched ON typically over the duration of winter and therefore their spider diagram shows 100% manual use for nearly all of the monitoring months. P08 is another household which used their heating in the manual mode for a high proportion of the active heating recorded, it also shows the slight increase during the start of winter and then slight decrease in manual use near the end of winter and into the spring shoulder month season. However in contrast P02 exhibits the same pattern of gradual increase in manual use going into winter and then decreasing again, although the percentage of manual use is much lower than P08, due to the difference in heating schedules demanded by the households. Therefore it is likely that manual use of heating is influenced on a day to day basis by the heating schedules set by the occupants as well as other influential factors such as thermal comfort and activity level.

5.4.5.3 Spring shoulder months manual use of controls

There was available advance data to calculate the manual use of the heating during the spring shoulder months for nine of the sample households. These results are reported in Table 5.27. It shows that in all but one of the nine, the manual use drops between March and April so this suggests that these households may have reduced how often they were manually overriding or demanding the heating on outside of scheduled heating periods as they moved into spring. This suggests that households reduce their manual interaction level with the new controls following the winter months.

Table 5.27 Percentage of heating use which resulted from manual use of the heating controls during the spring shoulder months and change in use between March and April

	March manual use	April manual use	Change in manual use
P01	10.7%	20.8%	+10.1%
P02	47.3%	23.9%	-23.4%
P03	26.3%	25.1%	-1.2%
P04	37.7%	1.0%	-36.7%
P05	/	/	/
P06	27.8%	6.0%	-21.8%
P07	28.7%	7.8%	-20.9%
P08	78.1%	47.7%	-30.4%
P09	/	/	/
P10	100%	99.9%	-0.1%
P11	6.6%	4.2%	-2.4%
P12	/	/	/

5.4.5.4 Summary of manual heating use

This study found that the manual use of the heating controls increased over autumn to winter before starting to decrease again in spring. The majority of the households all recorded a peak in the percentage of heating use coming from manual interactions during the winter months. However the percentage of total heating use that the manual interactions accounted for varied massively across the sample, with P05 recording 0% in winter compared to P10 recording 100%. The new controls also meant that P08 only set one period of heating with the schedule and resorted to manually using the heating every day to suit their needs in the afternoon/evening. Within the spring shoulder months it was found that all bar one household (P01) decreased their manual interaction with the controls.

5.4.6 Heating durations

This section presents the results of analysis of the daily total active heating durations during the autumn shoulder months, winter months and spring shoulder months.

5.4.6.1 Autumn shoulder months heating durations

Table 5.28 presents the heating duration results found for the autumn shoulder months. There was no data available for P05 for the autumn shoulder months and both P09 and P12 only had one of the shoulder months available.

Table 5.28 Total and daily heating durations during autumn shoulder months

	August					September				
	Av. Daily hours of heating	Cumulative monthly total	% of monthly total	Max daily hours of heating	Min daily hours of heating	Av. Daily hours of heating	Cumulative monthly total	% of monthly total	Max daily hours of heating	Min daily hours of heating
P01	0	0	0%	0	0	0.4	12	1.7%	2.9	0
P02	4.8	149.8	20.1%	5.7	4.4	4.5	135.7	18.3%	5.2	3.7
P03	2.8	84.9	11.4%	9.0	0	1.0	30.1	4.1%	4.1	0
P04	0	0	0%	0	0	0.8	13.1	1.8%	8.3	0
P05	/	/	/	/	/	/	/	/	/	/
P06	0.9	26.5	3.6%	8.7	0	0.6	17.6	2.4%	9.4	0
P07	0	0	0%	0	0	0.1	3.8	0.5%	3.3	0
P08	0	0	0%	0	0	0.5	10.3	1.4%	2.3	0
P09	9.4	121.7	16.4%	24	0	/	/	/	/	/
P10	20.6	432	58.1%	24	0	24	720	100%	24	24
P11	5.0	153.9	20.7%	14	4.5	4.9	145.9	19.7%	14.5	4.5
P12	/	/	/	/	/	0.2	3.2	0.4%	1.6	0
Mean	4.4	96.9	13.0	8.5	0.9	3.7	109.2	15.0	7.6	3.2
Range	20.6	432	58.1	24	4.5	23.9	716.8	99.6	22.4	24

Surprisingly the percentage of the monthly total reduced within four of the households between August and September, it is also worth noting that the average external temperature in August 2014 was 15.2^{o}C compared to 14.8^{o}C in September, so not a massive difference in external temperature between the two months. The monthly total percentage was just the cumulative monthly total of heating hours as a percentage of the available hours in each month. The results show variation in the number of hours the sample households were using their heating during the autumn shoulder months, with four households within the sample showing no use of their heating at all during August. As reported earlier, all households were recorded as using some form of heating come the end of September (except P05 and P09 who had missing data) however it is possible to see which households only started heating their homes right at the end of the shoulder months by the lower daily average heating hours within September.

5.4.6.2 Winter months heating durations

The recorded duration of active heating increased during the winter months for all households, seen clearly in Figure 5.40. P10 was removed from Figure 5.40 due to the household leaving the heating constantly ON which meant a reading of 744 total heating hours was recorded for the months containing 31 days. By removing P10 it ensured a smaller axis could be used allowing the differences across the monitoring period to be observed easier. December and January recorded higher total hours of heating use compared to the other months within the monitoring period.

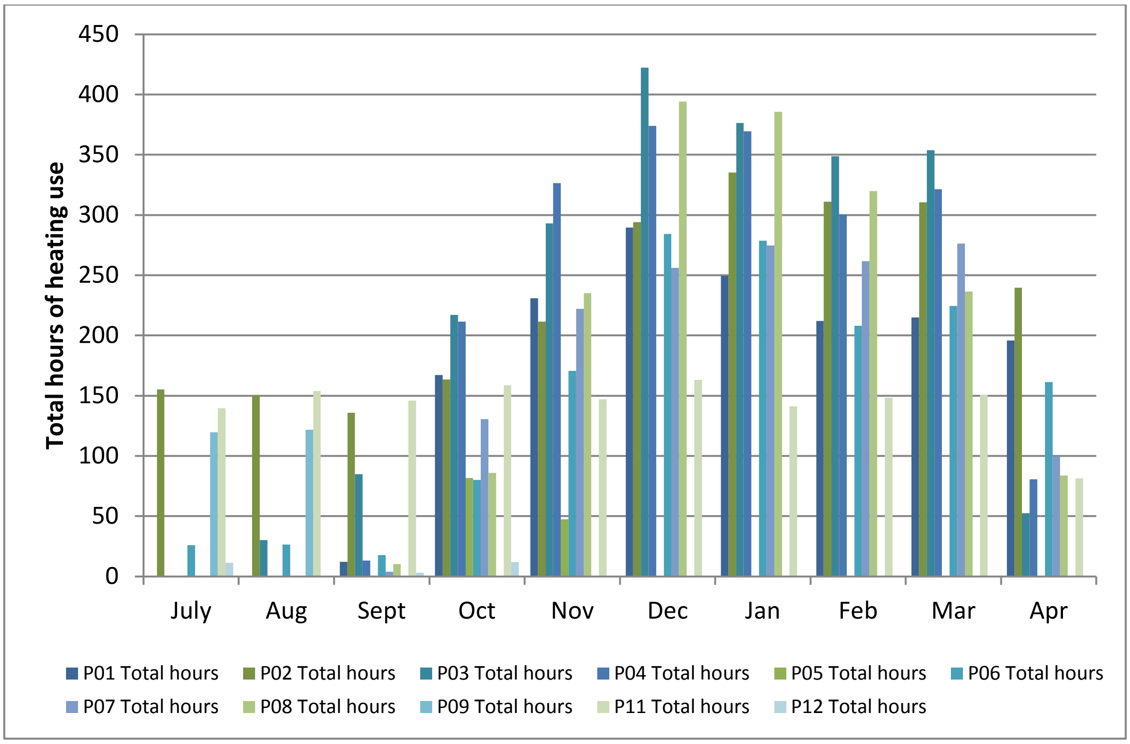


Figure 5.40 Total hours of active heating across the monitoring period for all sample households (excluding P10 due to leaving heating to ON constantly and therefore classed as active heating 24 hours a day (744 hours in total for 31 day months) for the majority of the monitoring period)

Figure 5.40 also shows the variation in amount of heating being used by the different participating households. For example within the month of December, P03, P04 and P08 record using over 350 hours of active heating within their home but P11 only records just over 150 hours of active heating, equivalent to a difference of over eight whole days of constant heating between these households. P06 heated their home differently to other households within the sample, rarely demanding a different set-point to their heating schedule and therefore showing a hands-off approach with regards to their heating use, initially programming a heating schedule and just leaving it to come on and off as set.

The plot of total active heating hours across the monitoring period also shows the gradual increase and decrease in heating hours within the sample during the shoulder month seasons indicating that there is a change in heating use during these months.

5.4.6.3 Spring shoulder months heating durations

Table 5.29 presents the results for the average daily heating duration, the cumulative total hours of heating and the maximum and minimum heating hours being demanded by each household for the months of March and April. No data was available for P12 due to the property being rented out and both P09 and P05 had no data due to equipment faults. It is also worth noting that P03 only had data available up until the 5th of April due to the property being sold, therefore the cumulative monthly total and percentage only takes up until the 5th of April into consideration.

Table 5.29 Total heating durations and daily averages over spring shoulder months

	March					April				
	Av. Daily hours of heating	Cumulative monthly total	% of monthly total	Max daily hours of heating	Min daily hours of heating	Av. Daily hours of heating	Cumulative monthly total	% of monthly total	Max daily hours of heating	Min daily hours of heating
P01	6.9	215	28.9%	14	6	7.0	195.7	27.2%	13.8	2
P02	10.0	310.4	41.7%	14.5	7.5	8.6	239.6	33.3%	15	3
P03	11.4	353.9	47.6%	18.1	4.5	10.5*	52.5*	43.8%*	13.7*	7.3*
P04	10.4	321.5	43.2%	16.4	6	2.7	80.5	11.2%	11.7	0
P05	/	/	/	/	/	/	/	/	/	/
P06	7.2	224.5	30.2%	13	2.1	5.8	161.4	22.4%	8.1	0
P07	8.9	276.2	37.1%	15.8	5.6	3.6	99.8	13.9%	11.1	0
P08	7.6	236.5	31.8%	15	3.7	3.0	83.7	11.6%	12	1.3
P09	/	/	/	/	/	/	/	/	/	/
P10	24	744	100%	24	24	20.5	574.1	79.7%	24	0
P11	5.0	150.8	20.3%	9	1	2.9	81.4	11.3%	13	0
P12	/	/	/	/	/	/	/	/	/	/
Mean	10.2	314.8	42.3	15.5	6.7	7.2	174.3	28.3	13.6	1.5
Range	19	593.2	79.7	15	23	17.8	521.6	68.5	15.9	7.3

The results show that all households with data showed a decline in their heating use from March to April which indicates that households were starting to reduce their heating use with the season shifting into spring and the external temperatures starting to rise again (Average external temperature for March 2015 was 6.4^{o}C and 8.9^{o}C in April 2015). Although most households had quite a dramatic cut in their percentage of heating use between the two months there are some such as P01 who only show a small reduction in the heating duration totals and in fact P01 had a higher daily average of heating use duration. The change in heating use during the spring shoulder months will be influenced by numerous factors including personal preferences however it is also possible that some households may feel that because it was now April they should be using less heating and starting to switch it off due to preconceived ideals rather than their comfort levels dictating the switching off of the heating. The unusual weather during the spring shoulder months will not have helped either as during that year it started to get warm at the start of the shoulder months before turning bitterly cold again half way through and then starting to warm up again. This was seen with a drop in the average external temperature of

5^{o}C between the 10th-12th of April, and then another drop of over 6^{o}C between the 14th-18th of April 2015. This was something that many participants commented on during the final interview visits which were carried out during the spring shoulder months.

5.4.6.4 Summary of heating durations

The durations of "active" heating increased from the autumn shoulder months compared to winter and then decreased moving from winter to spring. Interestingly the average heating duration across the sample during the autumn shoulder months decreased from August (with 4.4 hours) to September (with 3.7 hours). This is likely to have been impacted by the fact that most households did not start actively using their heating continuously until the end of September/beginning of October. The total monthly heating durations varied across the sample with some households recording much lower heating durations than others. Within December, P03, P04, P08 and P10 all recorded above 350 hours of active heating use, yet P06 only recorded just over 150 hours of use.

5.4.7 Putting the results in context

This section presents the results of analysis which looked into influences on heating use and comparisons of this study's findings against previous methods and current assumptions of heating use to put the findings into context.

5.4.7.1 Influence of building characteristics, demographics and weather

Table 5.30 shows the results of the correlation analysis against the dwelling characteristics and heating use findings.

Table 5.30 Correlation analysis of heating use categories against house characteristics (* Correlation is significant at the 0.05 level) (using Pearson correlation)

	Dwelling type			EPC Value			Total Floor Area			Number of bedrooms			Year of Construction		
	Correlation	Sig.	N	Correlation	Sig.	N	Correlation	Sig.	N	Correlation	Sig.	N	Correlation	Sig.	N
Av. daily hours of heating	0.255	0.476	10	0.339	0.411	8	-0.138	0.744	8	0.061	0.866	10	0.080	0.838	9
% manual heating use	0.116	0.750	10	0.275	0.510	8	0.051	0.905	8	0.210	0.560	10	0.252	0.514	9
Av. set-point temp.	0.317	0.373	10	**0.758***	0.029	8	-0.397	0.330	8	-0.400	0.252	10	**0.785***	0.012	9
Av. whole household temp.	0.266	0.458	10	0.646	0.083	8	-0.451	0.262	8	-0.544	0.104	10	0.530	0.142	9

As the results show, there were two statistically significant results found with the analysis of dwelling characteristics, both of which were found to have a strong correlation with the average winter set-point temperature recorded. The two characteristics were the EPC value and the year of construction, which in themselves are likely to be correlated as those properties constructed recently would have to meet higher building regulations regarding energy efficiency and therefore have a better EPC value. However it may be found that properties with significant energy efficiency measures installed could skew this in future or in studies with larger sample sizes. The correlation does mean that within this sample the households which are more energy efficient or newer are in fact households which are demanding the higher set-point temperatures within these properties. This shows that even with these properties having a higher level of insulation etc. the occupants still set the thermostat higher. Although these households may then have the heating for shorter durations as the properties will keep the heat in longer, it does show that those occupants within older, potentially leakier dwellings, seem to be more accepting of living in colder environments and as such do not demand as high set-points as those in newer properties.

A number of demographic factors were identified from the literature that may have an influence on heating use. These included income, age of the oldest occupant, number of total occupants and the number of children within the property. Table 5.31 shows the correlation values calculated for these demographic factors against the heating use findings analysed.

Table 5.31 Correlation analysis of heating use against demographic factors (* Correlation is significant at the 0.05 level)

	Household Income			**Age of oldest occupant**			**Total number of occupants**			**Number of children (under 16s)**		
	Pearson Correlation	Sig.	N	Pearson Correlation	Sig.	N	Pearson Correlation	Sig.	N	Pearson Correlation	Sig.	N
Av. daily hours of heating	**0.698***	0.037	9	0.410	0.239	10	0.251	0.483	10	0.035	0.924	10
% manual heating use	**0.687***	0.041	9	0.372	0.290	10	0.100	0.784	10	0.017	0.963	10
Av. set-point temp	-0.328	0.388	9	0.110	0.762	10	-0.429	0.216	10	-0.452	0.190	10
Av. whole household temp.	-0.583	0.100	9	0.023	0.949	10	-0.260	0.468	10	-0.312	0.380	10

As the results in Table 5.31 show there was statistically significant correlations found with income and the daily hours of heating and manual heating use. This correlation shows that it is more likely that those on a higher income band are also those who heat their homes for longer durations. This may be expected due to those on higher incomes not having to worry as much about being able to afford energy bills and therefore are likely to be less stringent with their heating use. However as shown from the work carried out during the Phase 1 of this doctoral research those who are able to comfortably afford heating their home may be conservative of their heating use for environmental issues. Therefore although this correlation may be expected, a larger study may not find as strong a correlation if the sample also includes more environmentally minded higher earners.

When looking for correlations with heating use and weather, the daily external temperature was used to analyse the impact it had on the daily total of heating hours used and the manual use. Unlike previous correlation analysis this took data from the full monitoring period so that it would take into consideration the gradual increase in heating use as the weather got colder during the shoulder months leading into winter. Table 5.32 shows the results for correlation between the daily external temperatures with heating use for each of the sample households. All bar three households showed statistically significant negative correlation results suggesting heating use increases as external temperature decreases, as expected. However it is worth noting that one household does not follow this negative correlation, P05, which shows a weak positive correlation of 0.185, however there was only limited data available for this household with only monitored data for the end of Oct/start of Nov and therefore the lack of summer data or warmer autumn data skews the correlation direction.

Table 5.32 Correlation analysis of daily external temperature against heating use within sample households (** Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level)

	Daily total hours of heating use		Daily total hours of manual heating use	
	Correlation	Sig.	Correlation	Sig.
P01	-0.718**	0.000	-0.315**	0.000
P02	-0.769**	0.000	-0.647**	0.000
P03	-0.820**	0.000	-0.516**	0.000
P04	-0.653**	0.000	-0.262**	0.001
P05	0.185	0.462	/	/
P06	-0.722**	0.000	-0.340**	0.000
P07	-0.777**	0.000	-0.467**	0.000
P08	-0.847**	0.000	-0.826**	0.000
P09	0.185**	0.001	-0.577*	0.000
P10	-0.530**	0.000	-0.529**	0.000
P11	-0.029	0.622	-0.130	0.157
P12	-0.275	0.082	-0.275	0.082

To investigate how the correlation might differ during the shoulder months and winter months, the daily average of heating hours across the sample was analysed against the external daily temperature for the corresponding months, the results of which are shown in Table 5.33. As it can be seen in the table, the strongest correlation is found for the total hours of heating during the winter months, -0.765**. This shows that as the external temperature drops the average daily heating duration within the sample increases. However it also shows that the correlation between external temperature and the average manual use does not change much across the seasons, which is likely to be due to the variation in manual use within the sample.

Table 5.33 Correlation analysis of seasons against heating use total and manual use (** Correlation is significant at the 0.01 level)

	Daily total hours of heating use		Daily total hours of manual heating use	
	Correlation	Sig.	Correlation	Sig.
Shoulder months (Aug & Sept)	-0.597**	0.000	-0.553**	0.000
Winter (Oct – Feb)	-0.765**	0.000	-0.582**	0.000
Shoulder months (Mar & Apr)	-0.554**	0.000	-0.478**	0.000

As the winter months for 2014/2015 was quite mild in comparison with previous years, as shown in Figure 5.41, the impact of solar radiation was investigated. This was to see if there was an impact of solar gain during the winter months which may have caused a change in the hours of heating used.

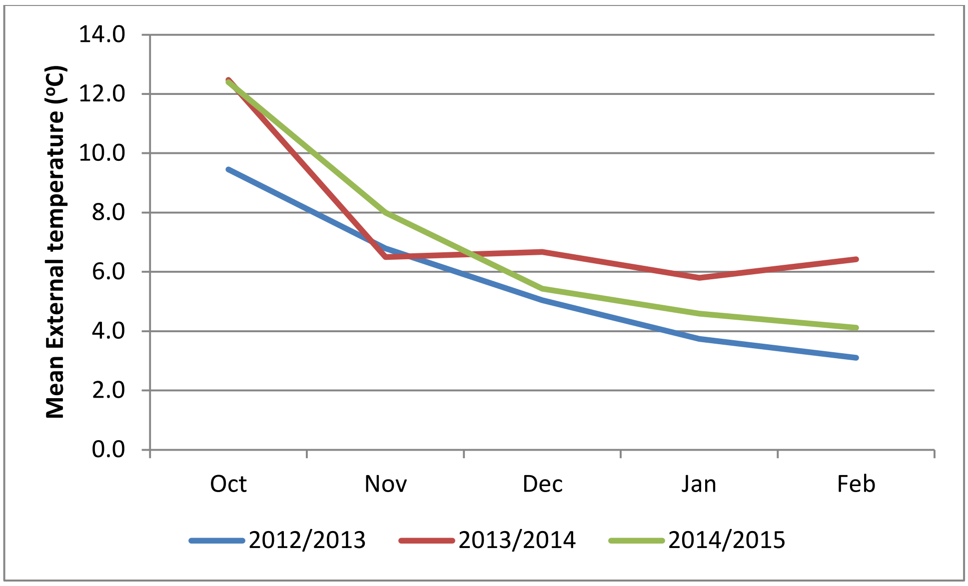


Figure 5.41 Mean external temperature for Leicester area over three past winter months (Oct-Feb)

The change in the daily recorded solar global radiation measurement was plotted against the change in the daily total of heating hours for each household, an example is given in Figure 5.42. By plotting each individual household it would show any dwelling that may get significant solar gains which impact on their heating use. This would be seen by a trend line which took into account an increase along the x-axis but a decrease on the y-axis, accounting for a decrease in heating hours as the solar radiation increased. This can be seen slightly in the Figure for P06 as the trend line moves more into the –y axis as it increases along the x-axis.

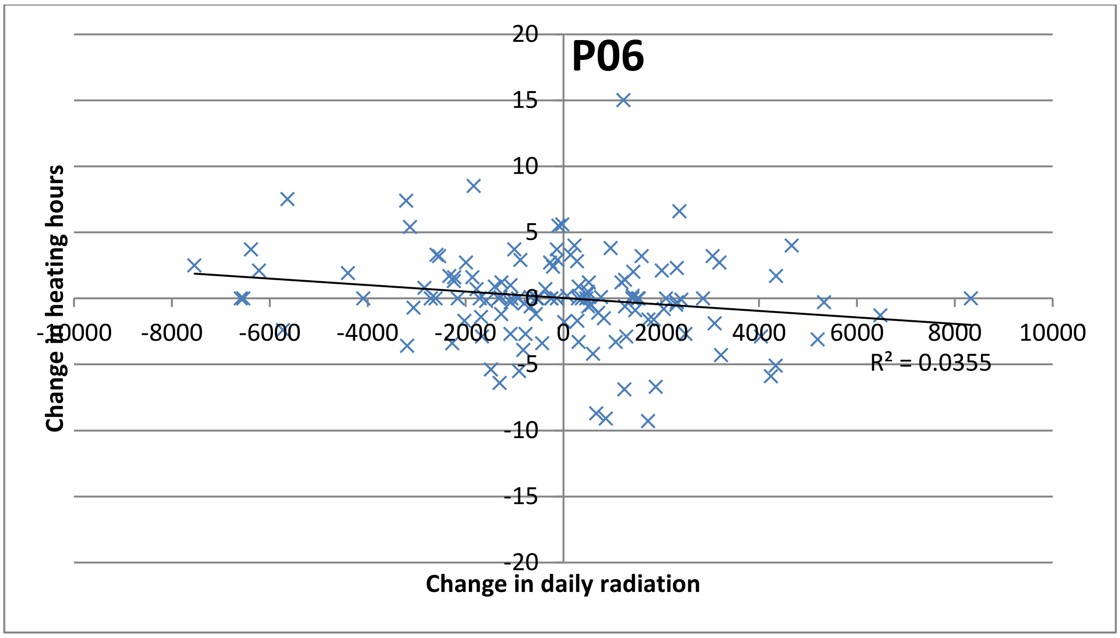


Figure 5.42 Change in daily radiation (x-axis) against change in heating hours (y-axis) during the winter months for P06

However upon plotting all twelve households it was found that the majority looked very similar to that shown in the example by P06, where there was a slight trend with increasing solar radiation and decreasing heating hours, however the trend lines were very close to being perpendicular to the x-axis, and as Table 5.34 of the R^2 values show, the trends found were very weak indicating that it would be too difficult to say there was an obvious influence in heating use with solar gains.

Table 5.34 R^2 values from plotting changes in daily radiation and changes in daily heating hours for all sample households

	R^2 values for change in heating hours with change in solar radiation
P01	0.0007
P02	0.0185
P03	0.0064
P04	0.0193
P05	0.0048
P06	0.0355
P07	0.0005
P08	0.0011
P09	-
P10	0.0022
P11	0.0045
P12	0.915

When the correlation analysis was carried out, all factors were tested against each other and further statistically significant correlations were found within the sample, which are summarised in Table 5.35.

*Table 5.35 Correlations found within demographic categories and household characteristics (*** Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level)

Correlation found between	Correlation	Significance
Total number of adults with Total number of children within household	0.742**	0.006
Year of construction with Total number of children within household	-0.655*	0.029
EPC with dwelling type	0.932**	0.000
Total floor area with Number of bedrooms	0.715*	0.020

5.4.7.2 Current assumptions and methods

As identified within the literature review within Chapter 2, there are assumptions made by certain energy models which are used to depict how heating may be used within homes to help calculate potential energy savings from interventions or improvements to the building fabric or heating system. It was possible to compare how the sample looked against these assumptions by looking at the average results from the sample household. Table 5.36 presents some of the current assumptions made within the literature and how this study's sample compared to them.

Table 5.36 Comparison of sample households recorded heating use with current assumptions

	SAP/BREEDEM	Huebner et al (2013)	Sample households
Demanded temperature for main living area	21	20.6	21.1
Daily total hours of heating on weekdays	9	10	9.8
Daily total hours of heating on weekends	16	10	10.5

The average demanded temperature for the sample households was 21.1^{o}C when including all of those households with winter data (so excludes P09), however P12 only had a short period of winter data and that included manual use where often the maximum 30^{o}C was being demanded by the occupant. If P12 is removed from the winter data an average demand temperature of 20.3^{o}C is calculated for the sample households, so very similar in range of that found by Huebner et al (2013). However it is worth noting that these averages came from a combination of demanded set-point temperatures and therefore this may have had influence over the resulting average demanded temperature for each household as the total counts of demanded set-point temperatures varied on a household by household basis. The Energy Saving Trust states the assumptions they use with the SAP model for calculating potential energy saving values (EST, 2016) and that one of the assumptions is that the heating season lasts over 238 days (68 weekend days and 170 week days) whereas the winter data for this study only considered that of October to February so totalled 151 days. The monitoring period this study covered was August 2014 to April 2015, totalling 273 days, therefore the EST heating season will cover what has been classed as shoulder months in this study, therefore slightly different findings may have been found if only comparing the same dates as the EST heating season.

The comparison of the heating durations with this study's sample and SAP and Huebner et al's (2013) work found that for both weekend and weekday heating durations the average hours of heating recorded in this sample agreed more with Huebner et al's work. This study also showed that the assumption of 9 hours of heating used during the week may only underestimate usage by around one hour. However the assumption of 16 hours of heating for weekends was largely overestimated in comparison with this sample's average of 10.5 hours of heating. The assumption that this weekend heating use is in one block from 7am to 11pm is also disputed by this study's results which showed that most households still schedule two blocks of heating on weekends similar to that of weekdays, as shown in Section 5.4.4. The assumptions made by SAP/BREEDEM regarding the heating schedule of 7am-9am and 4pm-11pm on weekdays was also not seen within this sample as numerous households set their heating to come on at a much earlier time than 7am with some as early as 5.30am but typically most around 6am and finishing earlier than the SAP/BREEDEM end time of 9am. The majority of the sample households also had their heating programmed to stop earlier than 11pm, which would then mean it may be expected that the hours of heating used should be less than the model assumptions, however as reported previously a large amount of manual interaction with heating controls mean that these scheduled heating periods are often overridden or the heating is switched on out with the heating schedule which then results in a larger recorded heating use.

Had the exact room location data been known for this sample then it would have been possible to then compare the measured heating use against other studies which looked at calculation heating demand temperatures and durations by applying the metrics used in previous research such as Kane (2015) to see how different the assumed heating characteristics were from the measured data. However, it was possible to plot the internal air temperatures recorded by the thermostat and from the heating file determine whether the heating was active or not (i.e. switched on via programmed heating settings or manual use) as seen in Figure 5.43 for one household in the study. Previous research (Kane, 2015) has taken the steady increase and decrease in internal temperature to deduce the start and end of heating periods. However this fails to show that the second heating period in this example is entirely due to manually switching the heating on and not from a programmed heating schedule. This means the normal assumption of two programmed heating periods would not represent this household's heating schedule. Whilst a programmed schedule is more likely to be consistent from one day to the next, a manual interaction could be much more variable and so difficult to predict and model.

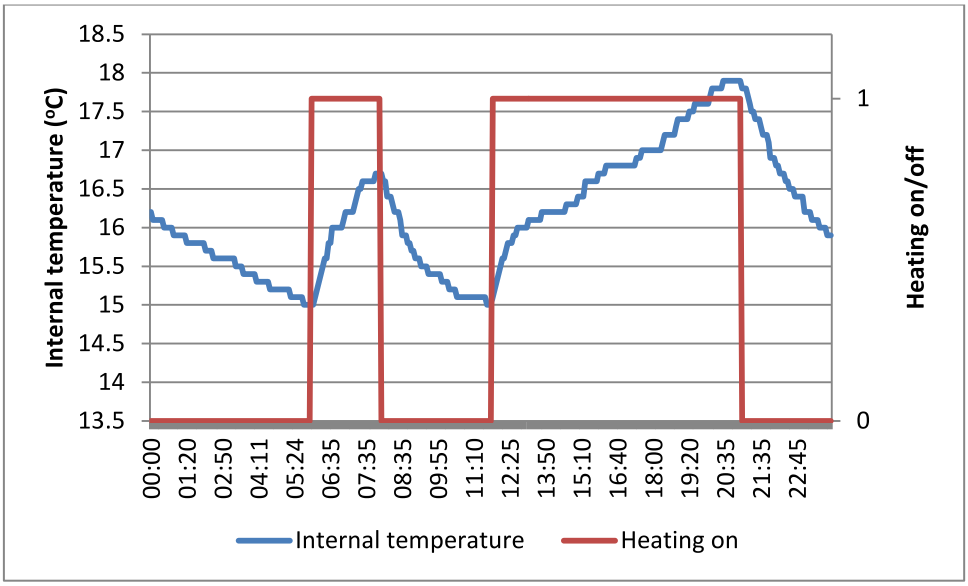


Figure 5.43 Matched internal temperature with heating system status for P08

Previous methods have also taken the maximum temperature recorded as an indication of the demanded set-point temperature. When this method is applied to this example, a set-point of around 18°C might be assumed. However the measured set-point temperatures showed that, during this example, a set-point of 21°C was demanded during the morning heating period and both 21°C and 25°C during the afternoon/evening heating period, as shown in Figure 5.44. As it can be seen from the internal temperature trace during both heating periods, the demanded set-point temperature was not reached. This suggests that previous research may have been underestimating the demanded set-point temperature within homes.

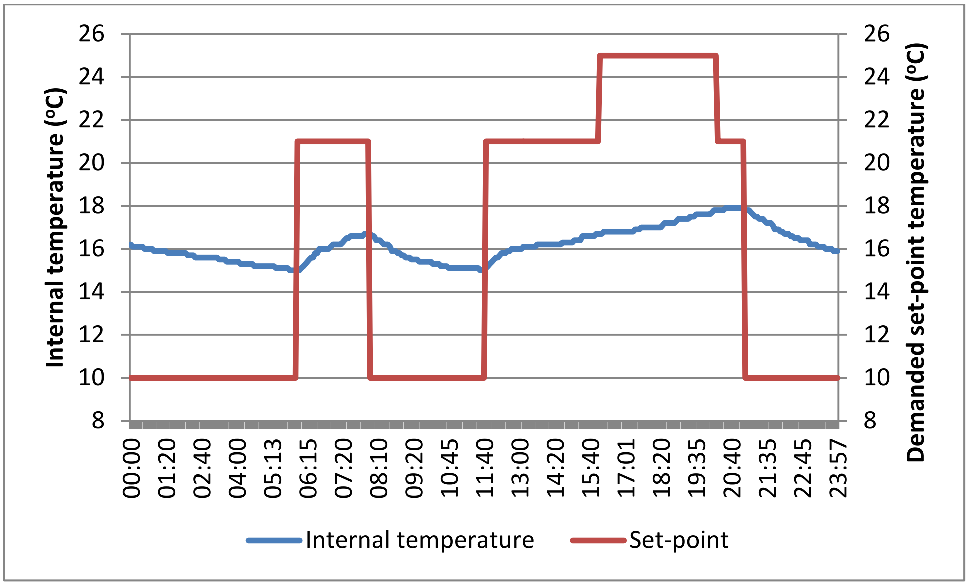


Figure 5.44 Internal temperature against demanded set-point temperature within P08

This comparison of internal temperatures against demanded set-point temperatures were then plotted for nine of the households during the same week in December to see how close the demanded set-points were to the internal temperature maximums, shown in Figure 5.45 and Figure 5.46.

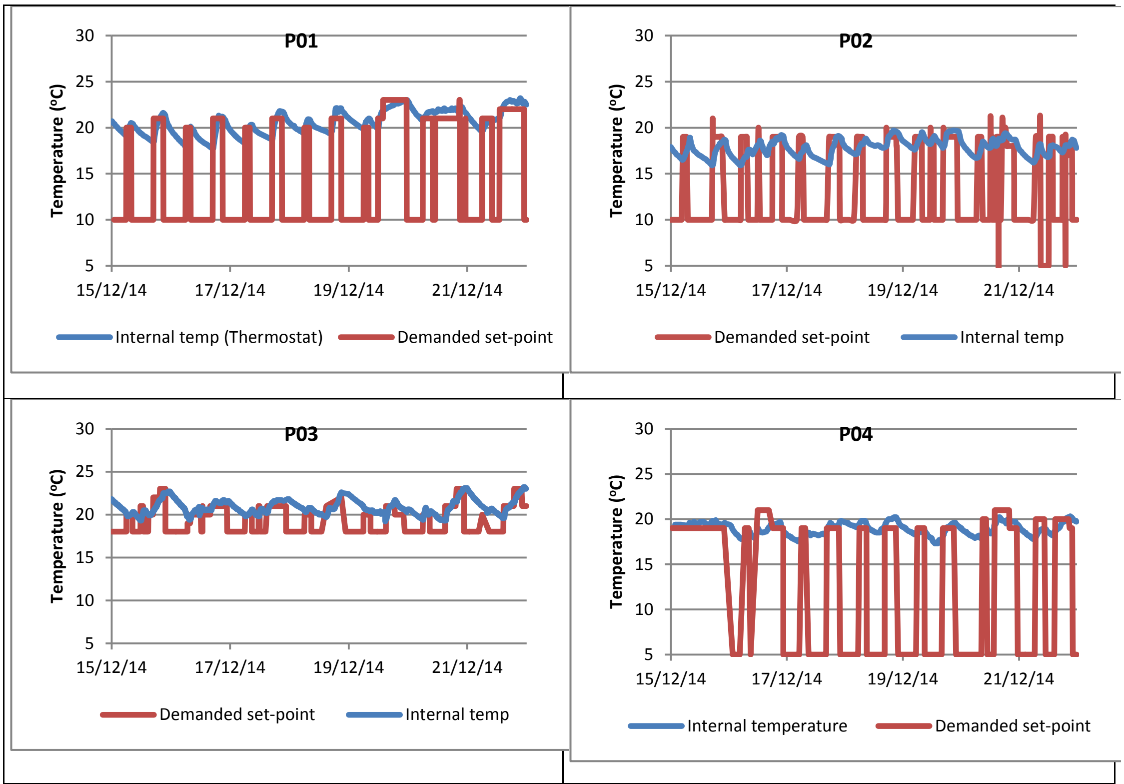


Figure 5.45 Plots of internal temperature against demanded set-point over one week in December (15th-21st) for P01-P04

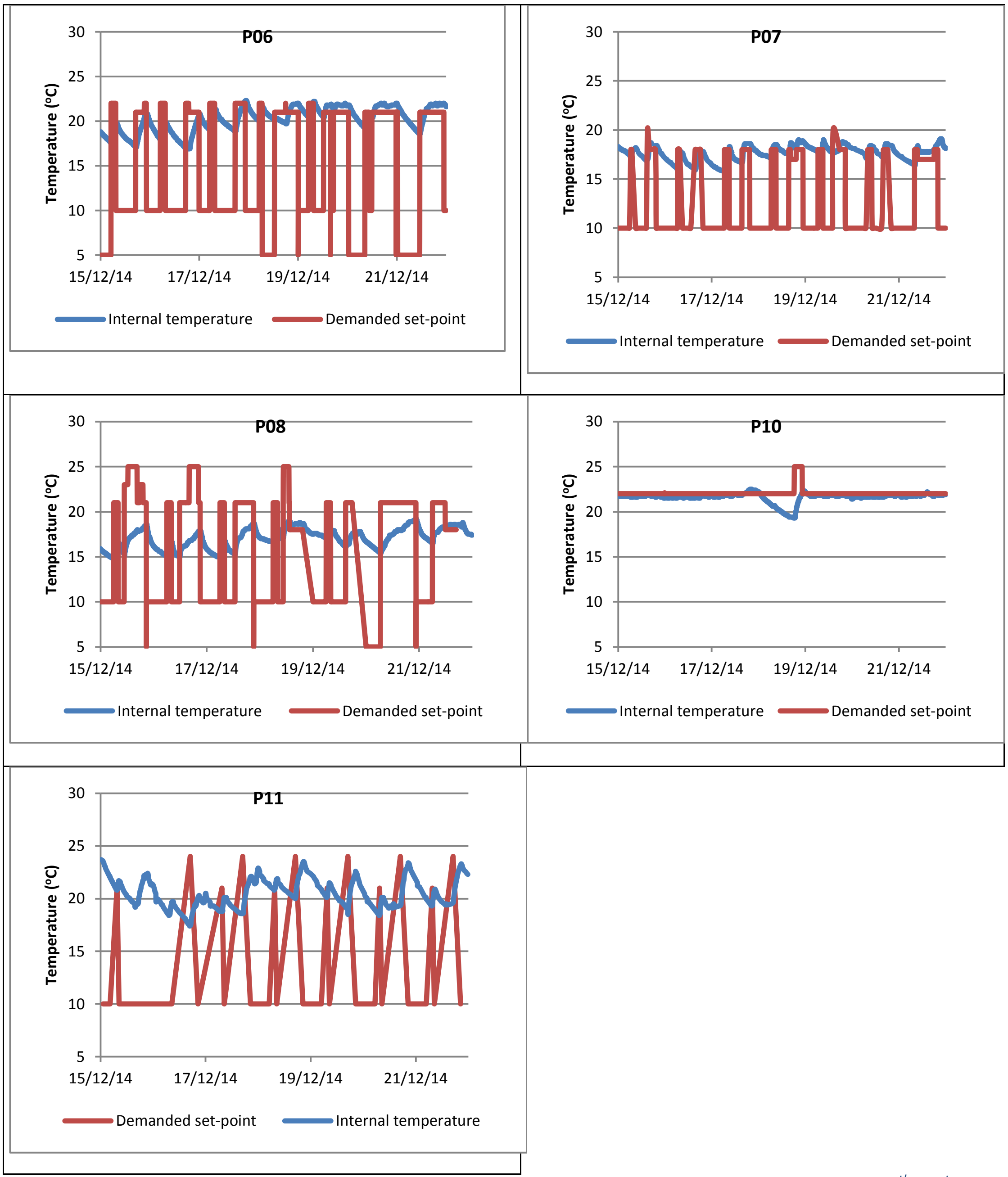


Figure 5.46 Plots of internal temperature against demanded set-point over one week in December (15th-21st) for P06, P07, P08, P10 and P11

The plots show that for most households the plots of internal temperature align to the plot of the demanded set-point, where an increase in internal temperature is seen when an increase in demanded set-point temperature is seen. There were some exceptions for instance P08 as already discussed. P10 had a dip in internal temperature mid-way through the week, however this was confirmed during the household interviews to be due to a broken boiler. P06 showed similar plots in the end of the week which was when they went from using their heating on a demand only basis to a scheduled use. With P11 the demanded set-point is spikey due to the data not recording at the same intervals as the other households during that week, therefore it is difficult to see how close the set-point and internal temperature match compared to the other households. As the internal temperature is from that recorded by the thermostat temperature sensor it would therefore be expected that it closely matched the demanded set-point. It was not possible to compare individual rooms such as the living room or main bedroom against the demanded set-point due to the locations of the individual temperature sensors being unknown. It was also not possible to calculate a whole household average to compare against due to different logging times on each of the temperature sensors. Had it been possible to plot the whole household average temperature against the demanded set-point instead of the temperature recorded at the thermostat, there may have been more variation found within more households, similar to that seen in P08.

Further work can be carried out to investigate further how close demanded set-point temperatures are to those estimated from internal temperature measurements, as well as seeing if there is a link between heating use and those households where the set-point temperature may be underestimated or overestimated from use of only internal temperature measurements.

5.4.8 Categorising heating users

Figure 5.47 shows the sample once characterised for any changes in demanded set-point temperatures or heating time periods made to the heating schedules recorded. Out of the sample it was not possible to include P09 in the characterisation due to no winter data being able for that household.

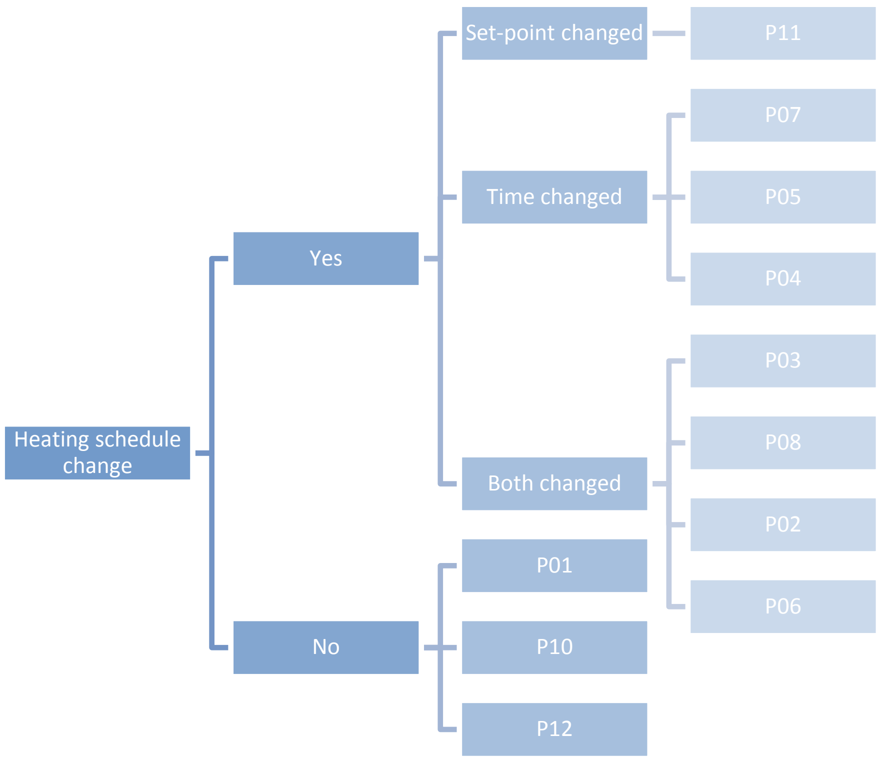


Figure 5.47 Heating schedule change characterisation

From this characterisation it can be seen that three households did not make changes to their heating schedule throughout the monitored period, however it is worth noting that P10 and P12 controlled their heating manually instead of setting up a heating schedule on the heating controls, preferring to control their heating in a simple on/off manner. Therefore P01 was the only household to set up an initial heating schedule and not change this over the course of the monitoring duration. Of the remaining eight households which changed some element of their heating schedule four households changed not only the programmed heating periods but also changed the set-point temperature which they wanted during those heating periods. Three households changed the programmed heating periods only leaving the same demanded set-point temperature throughout whereas only one household changed only the set-point temperature which they wanted during the original programmed heating periods. When analysing this characterisation for possible trends in household characteristics/demographics it was found that the sample size within each category was too small to find any real trends as each category had a range of dwelling types, number of rooms, occupancy types and income bands.

Figure 5.48 shows the characterisation of households by their heating schedules on weekdays and weekends, excluding P09 for lack of winter data and P10/P12 as these households used their heating manually and as such did not set schedules for heating. As it can be seen there were four households which had the same schedule set for both weekdays and weekends, with the remaining five households choosing to schedule different settings for the two. Of those households which chose to have different settings one of them chose just to have the weekend heating schedule to be at different times to that of the weekday schedule but still kept the same thermostat set-point temperature. The remaining four households not only set different heating periods to the weekday settings but also had different set-point temperatures for the weekday and weekend heating schedules. However none of the households chose to only have different set-point temperatures between weekday and weekend settings. Those five households which had different weekend and weekday settings also had different heating period durations, so even those households which had only different time schedules for weekends to weekdays had a different total heating period duration for weekdays compared to weekends. Again due to the small sample size within each category it was impossible to identify whether there was a trend between household characteristics and the category of heating use.

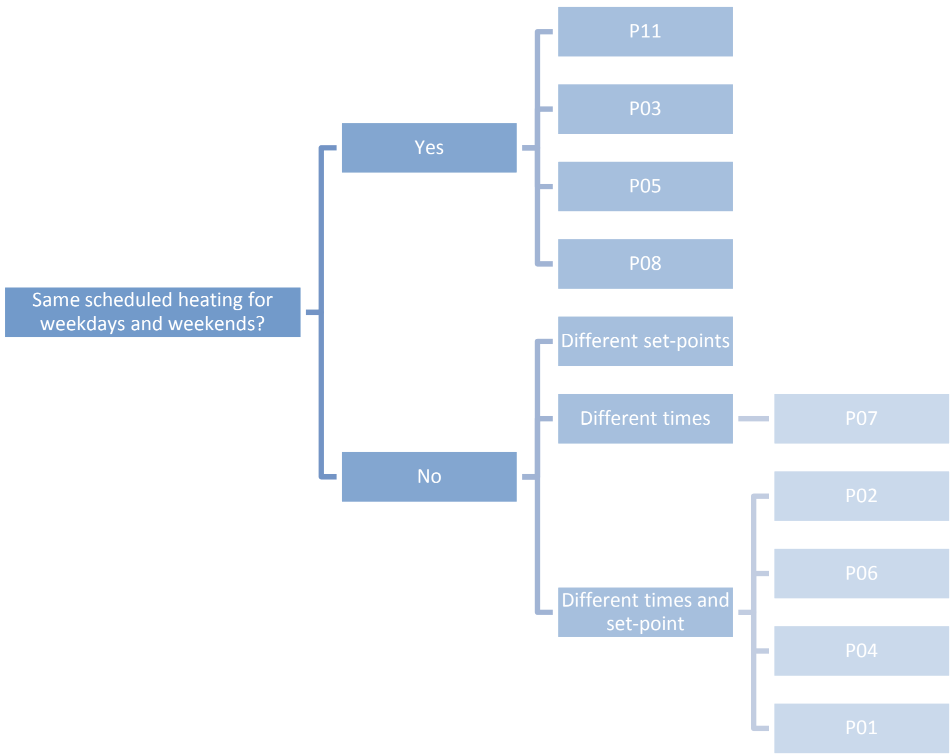


Figure 5.48 Weekday and weekend heating schedule use characterisation of sample

Although the heating use categorisation has been based on a small sample, the findings provide interesting knowledge such as same households keeping the same heating schedules during the week and at weekends, which differs from energy model assumptions, which could impact the energy saving potential of new heating control technologies. The categorisation of households by what settings they change over the course of winter could give indications of heating user types which may respond better to certain new heating controls technologies, such as learning thermostats or zonal heating. Further work on developing these heating user types within a larger sample will help give a better indication on what new heating control technology may best suit which user types.

5.5 Discussion

The aim of this study was to uncover how people heat their homes through measurements of actual heating use, over a ten month period, in 12 households across the East Midlands. This study presented measured set-point temperatures in homes, something which has not been published before. Households typically demanded a set-point between 18-22^{o}C for scheduled heating showing many households have a lower set-point than those who recommended 21^{o}C. The mean winter set-point temperature for the whole sample was 21^{o}C (although this is likely to have been impacted by P12 demanding extremely high set-points as well as the default set-point being 21^{o}C whenever the controls were turned ON). Previous research has estimated average set-point temperatures from internal temperature measurements and reported averages of 20.9^{o}C (Kane, 2015), 20.6^{o}C (Huebner et al, 2013) and 21.2^{o}C (Shipworth et al, 2010), all of which are similar to the average within this study of 21^{o}C. This suggests that the heating behaviour characteristics of this sample may well be similar to those within larger scale studies. This study did however show how often set-points are changed within households and that there is not just one set-point used by a household across the winter period. In fact, multiple set-point temperatures were recorded on an almost daily basis over winter in the majority of the sample households. The variation in set-points used and the number of changes made to them will not only impact energy saving estimates by energy models but could also impact the energy saving potential of new heating controls, in particular those 'learning' controls which may struggle when the set-point is changed often.

The study found that some households set different set-point temperatures for morning and evening heating periods, as well as weekday/weekend heating use. This indicates that the current assumption regarding only one set-point temperature being used could be incorrect. This study also found that some households set their morning set-point temperature lower than the one demanded in the afternoon/evening, and so both desired set-point temperatures may well be achieved in these households, despite short morning heating periods. This means that energy models and previous methods for inferring set-point temperatures may well be overestimating morning set-point temperatures and subsequently the energy used. In one household, the average thermostat temperature was lower than the average whole house temperature, indicated the use of secondary heating to boost the temperature within certain areas of the dwelling. This, combined with the findings of the Phase 1 study, suggests that work is needed on how to measure and monitor the use of secondary heating within homes especially if inferring set-point temperatures from internal air temperatures alone.

The heating schedules set by participants in this study varied, including heating on/off times and durations. Whilst it may have been expected that people adjust their heating during the shoulder months to get the ideal settings and then leave it over winter, this study found participants who regularly changed their heating schedule throughout the heating season, something which is not currently considered by many energy models. Previous research, such as that reported by Kane (2015), Huebner et al., (2013) and Shipworth et al., (2010), has inferred one average heating schedule for households over a winter period but this study found that only one household set up a heating schedule and then made no further changes to it over winter. This means that previous studies may have missed instances where heating schedules have been changed by occupants during a winter season. Meier et al (2011) reported that over 90% of their sample rarely adjusted their thermostat to reflect different settings for weekday and weekends. However, this study found that only 44% of the sample using the programmable features set the same schedule for both weekends and weekdays. This has implications for current energy model assumptions as these tend to assume longer heating durations at weekends, but if occupants keep the same heating schedule for weekdays and weekend then these models may well be over predicting the energy use of these households.

This study was able to measure participants' manual interactions with the heating controls and as such report on the frequency of manual interaction with the controls and the duration of heating use. The level of manual interaction with the controls was far higher than expected. Karjalainen (2009) reported finding that less than 20% of their sample used thermostats weekly and roughly 60% used them less than once a month or not at all, although Meier et al (2011) found that the majority of their households chose to manually control their heating over programmable settings. This study showed that even when households do use programmable features there can still be daily manual interactions on top of that. In the majority of households there was daily interaction with the heating controls, whether to boost the heating, override a schedule, increase/decrease the set-point temperature or simply switch off. During winter, manual interaction with the controls increased, showing that households were not content with the heating programme. During winter, one household manually interacted with their heating to such an extent that 80% of their total heating use duration was the result of manual use (to override heating schedules or simply switch the heating system on again). Therefore this study shows a different picture regarding the level of interaction occupants have with heating controls compared to Karjalainen (2009).

These findings ask whether new controls encourage more interaction from occupants due to their design and functionality, and whether this increased interaction could be detrimental to energy savings. NHBC (2012) reported that manually adjusting temperatures over the use of a programmer or thermostat can lead to higher temperature peaks and increased energy use. This means if new heating control technology actually increases manual interaction compared to previous controls, then higher energy use might be seen instead of energy savings. Due to the nature of some households manually adjusting their heating system on a daily basis it may mean that new technology which is designed to learn from occupants' use of heating may struggle to program ideal settings due to the sheer level of constant change made to the heating system. However, this study found that the level of manual use of heating controls did vary across the sample with a small percentage of the households setting the controls as they wanted and then only on the rare occasion relying on manual interaction. This suggests that some technology may be better suited to certain households, for instance those learning systems would be suited to the occupants who typically leave their settings or regularly interact with their heating around the same time daily. This shows that by better knowing the household and their needs/drivers, technology could be targeted to specific user types to ensure that the best impact from new technologies in energy savings.

This study was able to identify a clear “switch on” for continuous heating use starting at the end of September 2014 for the majority of households, with all households regularly using their heating from the 9th of October 2014. However there was no definite “switch off” point observed during the spring season, suggesting that this “switch off” was stretched out over an extended period. The EST (2016) calculations for potential energy savings are based on a heating season of 238 days (roughly 8 months). Therefore the heating season used by EST will include heating use from shoulder months. This study found regular heating use from September until the end of the monitoring period, which is similar to the EST heating season duration, however heating was still being used at the end of the monitoring period and prior to September in some households, suggesting that the actual heating season could be longer than 238 days. This study found that there were shorter heating use durations and slightly lower set-point temperatures during the shoulder months compared with the winter season, suggesting that there is a shift in heating behaviours during the shoulder months, with householders more likely to rely on the heating schedule alone. Given that this study shows differences between heating use during winter months and heating use during shoulder months, then this could have an impact on the energy saving potential calculations, particularly if the calculation assumes the same heating use behaviour throughout the entire heating season. Previous research reported within the literature review focused on presenting results from winter months and, as such, these studies may not be presenting results which cover the full heating season within homes. Future research needs to include the shoulder months to be able to identify the exact length of the heating season within UK homes and identify how different heating use during the shoulder months may be to the heating use in winter, as without knowing these details energy models may overestimate or underestimate the space heating energy consumed. Although it is recognised that the UK has temperate seasons, clearer comparisons between studies could be carried out if there were specific months being classified as winter, summer, autumn and spring months. The lack of defined heating season dates means that studies present slightly different pictures of heating use due to differences in monitoring periods.

In summary, this study has shown disparities with current energy model assumptions regarding the number of heating periods, heating durations and the level of manual interaction which highlight just how different heating use assumptions may be from reality. By comparing the findings from this study to those found by larger quantitative studies (Kane, 2015; Huebner et al., 2013; Shipworth et al., 2010), similar average set-point temperatures and heating durations have been found, despite the small sample used. Therefore, given the similar results, it could be suggested that the heating behaviours within this sample are not significantly different to the rest of the population. Households may regularly manually interact with their heating, may continue to make changes to their heating schedules over winter, may choose to manually override heating settings on a daily basis and may simply chose not to use the full functionalities of their heating controls. Therefore, samples of all sizes are likely to find extremely varied heating use with regards to set-point temperatures, heating schedules and levels of interaction with heating controls. If energy model assumptions regarding heating use in homes are not reflecting the reality of complex and highly varied use of heating systems then the energy saving predictions from changes to heating use (be that behaviour or technology based) are never going to match reality.

Chapter 6: Understanding the complexity of heating use using a mixed method approach

This chapter explores at the benefits of applying a mixed method approach to this thesis's research area. The chapter discusses how understanding the true complexity of heating use is uncovered by combining different sources of data. The chapter also discusses the complexities in using such an approach and makes suggestions for applying a mixed methods approach within the thesis research area.

6.1 Introduction

In recent years the need for interdisciplinary research, particularly within the energy field, has grown in importance. Yet social science methods and concepts still remain underutilized and underappreciated (Sovacool, 2014). As research strives to understand problems and complexities within “real-world” situations, the need to incorporate more than one discipline to achieve a better picture of complex real world scenarios has taken precedence. This is seen by the increasing expectations to include multidisciplinary and interdisciplinary methods within research grant proposals. The UK Energy Research Council states that researchers need to be aware of the role and value of interdisciplinary research and that “whole systems research involved understanding interrelationships in complex systems – attending to particular problems while also maintaining an evolving appreciation of the whole” (UKERC, 2015). This expanding research focus within the energy field attempts to cover all areas influencing energy use, the building fabric, the heating system and importantly the occupants. However interdisciplinary research of this type is demanding not only on time but also the effort involved to ensure that the combination of different disciplines is done in a way which is successful and beneficial to both discipline areas and creates a holistic outcome.

The occupant influence on energy consumption and use of energy systems or technologies is often underrepresented within the energy research field due to social dimensions being neglected in favour of researching technological innovations or the social dimensions of the research are treated with “disciplinary chauvinism” where the social dimension is treated as being of less importance and often peripheral. Energy research needs to be “intentionally, systematically, and institutionally more problem oriented, interdisciplinary, socially inclusive, and heterogeneous” (Sovacool et al, 2015).

However, currently techno-economic research approaches dominate the energy research field which tends to focus on the house rather than the home (Ellsworth-Krebs et al, 2015). The importance of researching the home and uncovering the social aspects such as comfort, identity, security and privacy, is highlighted by Ellsworth-Krebs et al (2015) as these social expectations or social norms influence occupant's everyday routines which directly influence energy consumption. Research needs to focus more on being of a socio-technical nature as this could help develop better strategies for achieving domestic energy savings.

Mathematician Norbert Weiner once said "Change comes most of all from the unvisited no-man's land between the disciplines" (Yatchew, 2014) which can be applied to the ambition behind this doctoral research. By using an interdisciplinary approach the true complexity behind heating use in homes can be uncovered. It is only once the true complexity of the situation is known that targeted solutions can be applied. As Sovacool (2014) argues, more interdisciplinary inquiry is vital for overcoming the energy problems our society faces which cut across different academic disciplines.

6.2 Aim of study

The aim of this study was to uncover the true complexity of heating use in homes only possible from an interdisciplinary study. To do this triangulation was carried out on qualitative and quantitative data collected as part of the Phase 2 study. The following research questions were used to structure this work:

7. Do new heating controls lead to a reported change in heating use for households?

8. Is how occupants report using their heating different to measured heating use?

9. How does the combination of qualitative and quantitative heating data add to the understanding of heating behaviour?

The answer to these thesis questions then helped to highlight some of the issues encountered by using either qualitative or quantitative methods to measure energy use within homes. Through use of examples from the Phase 2 findings of this doctoral research the benefits of using interdisciplinary research are presented, therefore, completing Objective 6 of this thesis.

Based on the understanding from the Phase 2 explorative study carried out as Objective 4, justify the need for mixed method approaches in relation to heating use within the domestic sector by identifying the true complexity of heating use within homes through combining both measured monitoring data and in-depth interview data

Objective 6

6.3 Methods and Data collection

6.3.1 Overview

The Phase 2 study was carried out in collaboration with the Go Digital pilot study (full details of the author's involvement in the study have been previously presented in Chapter 3, Table 3.3). The Go Digital pilot study involved monitoring energy use and temperatures in a number of homes with new heating controls also being installed shortly after the start of the study. The aim of this study was to bring together the measured/monitored quantitative data from the study (as presented in Chapter 5) with the qualitative data collected to present findings on how heating is used in homes and the reasons behind the use of it, therefore highlighting the benefits of combining both data types together to uncover a clearer picture of heating use in homes.

6.3.2 Sample

This study used the sample recruited as part of the Phase 2 research of this thesis and the Go Digital study. The sample totalled 12 households recruited via a snowballing strategy with a project stakeholder. The participants had to own their property, have gas central heating and a broadband internet connection. The sample covered a range of demographics covering dwelling type and age, age and number of occupants, income bands and occupancy patterns. Full details regarding the sample demographics are presented within Chapter 5 Section 5.2.1.

6.3.3 Quantitative Data Collection

The study comprised of quantitative physical measurements of heating use within the sample homes, including individual room temperatures, electricity and gas usage, set-point temperatures, manual use of heating controls, previous energy usage and the building characteristics of each sample household. Within this study the data on heating use (via the new controls), individual room temperatures, set-point temperatures and manual use of heating controls was analysed. Full details of the monitoring equipment used to collect the quantitative data can be found in Chapter 5, Section 5.2.

6.3.4 Qualitative Data Collection

The qualitative research methods applied within this study provided the social context within the socio-technical approach. This involved a total of three semi-structured interviews over the course of the monitoring period. A heating diary was also used as part of the qualitative methods exercised within this study. The heating diary can be classified as document data, where qualitative data is achieved from published and/or unpublished materials ranging from newspapers and magazine to personal diaries, biographies or even government reports and policy documents. This is due to it being of a personal diary nature, where occupants were asked to record their use of the heating system and reasons behind these interactions over a 4 week period. The heating diary can therefore be defined as "elicited text material" (Charmaz, 2006). It also expanded the areas covered during the face to face interviews and provided a means to get participants to consciously think about their heating on a daily basis over the 4 week period, instead of a general one off question.

Issues are often raised with studies which rely solely on interview data as this often reflects self-reported behaviours/attitudes/views on research areas and, as such, are often used to identify levels of variation, viewpoints or it can be seen as periphery data. This is due to the fact that often it is not possible to validate the reported data as participants may feel they need to represent social norms or want to be seen in a positive light, such as energy efficient or eco-friendly. This study however had the opportunity to validate the reported behaviours of the participants from the heating diary with the measured heating use.

6.3.4.1 Interview Design and Procedure

The first interview was carried out prior to the new heating controls and main monitoring equipment being installed within the households; therefore they were carried out during spring 2014. The first interview was aimed at developing a picture regarding the participants' use of heating within their home and their current heating system and control options. Interview two occurred after the installation of new heating controls and monitoring equipment during autumn 2014 and was aimed at understanding how the installation process went for each household, if any issues had come up, their understanding of heating terminology, what occupants felt about the new controls and whether they could see it changing their heating behaviours. The third interview occurred during spring 2015 and was interested in how occupants interacted with the new controls after the winter months and finding out how the heating system was being used in the home, and whether this now differed to how they used their heating with their previous existing controls. To check if anything had changed with the installation of new heating controls similar wording to questions was used as with that used in the first interview. The interview also referred to the heating user types published by DECC (Rubens and Knowles, 2013) for participants to reflect on their own heating behaviours and how they believed they matched up to the heating user types. The interview scripts for all three interviews can be found in Appendix 6-A, with the questions relevant to this doctoral research highlighted.

All of the household interviews took place in the participant's home and varied in length between 40 minutes up to 1 ½ hours due to the different nature of each of the three interviews. Prior to the start of the interviews participants were informed of the reasons behind the interview and the type of interview questions within it. During the interviews prompts were used occasionally as a means of providing clarity to a question should confusion arise or as a means of expanding participant's answers to delve deeper into areas of interest. Due to the fact that the three interviews occurred across the monitoring period it meant that not all participating households took part in all three interviews, this may have been due to changes in circumstances such as the property being rented out or lack of response from participants to schedule appointments to visit, despite contact via email, telephone and letters. Table 6.1 summarises which interviews were possible for all of the sample households.

Table 6.1 Interviews carried out in each of the sample households and reasons behind reduced sample near end of monitoring period

	Interview 1	Interview 2	Interview 3	Reasons behind interviews not being completed
P01	✓	✓	✓	
P02	✓	✓	✓	
P03	✓	✗	✗	Participant cancelled second interview and never rescheduled before moving out of the property as the third interviews were being arranged
P04	✓	✓	✓	
P05	✓	✓	✓	
P06	✓	✓	✗	Failed to achieve contact with participant to arrange third interview
P07	✓	✓	✓	
P08	✓	✓	✓	
P09	✓	✓	✓	
P10	✓	✓	✓	
P11	✓	✗	✗	Participant stopped responding to all contact made
P12	✓	✗	✗	Property was rented out prior to arranging the second interviews

The first household interview was completed by DEFACTO team members due to conflicting work schedules of the author with Phase 1 of this doctoral research. However the author was involved with the design of the interview questions within the first household interview. This first interview was the initial face to face contact between the participant and team members and therefore focused on securing a good relationship with the participant to maintain their commitment to being a part of the Go Digital study. The interview focused on finding out about the households, their use of the current heating controls within their homes. Notes and photographs were taken of these controls and the heating system within the property and tried to understand more about the participants understanding of how their heating system worked within their home. In addition to the interview questions during all visits additional tasks were also carried out with the participants, some as part of the DEFACTO project and others as part of this study. Such as during the final interviews participants were asked to rank room temperatures in order of warmest to coolest rooms and to identify the type of heating user category they believed they would fit into. During the final interviews the author also presented some of the measured data on heating use, set-points and internal temperatures which provided participants the opportunity to explain any abnormalities within the data or to reflect on their heating use.

6.3.4.2 Heating diary

A heating diary was used to learn more about heating use during the shoulder months leading up to winter and to check what households reported doing. The household's responses were compared with the data on the server showing heating use, and also gave an additional way to check if the timing issue on the server still occurred. There were some basic requirements for the heating diary to ensure the maximum success level and response rate which were identified early on; the diary had to be identifiable as being part of the Go Digital study so needed to match the branding used with all other Go Digital materials previously sent to the participant households, as seen in Figure 6.1, it needed to be clear and easy to understand; it needed to be quick to complete; and it needed to be completed over multiple weeks so as to limit the risk of it being an unusual week for heating use within the household.

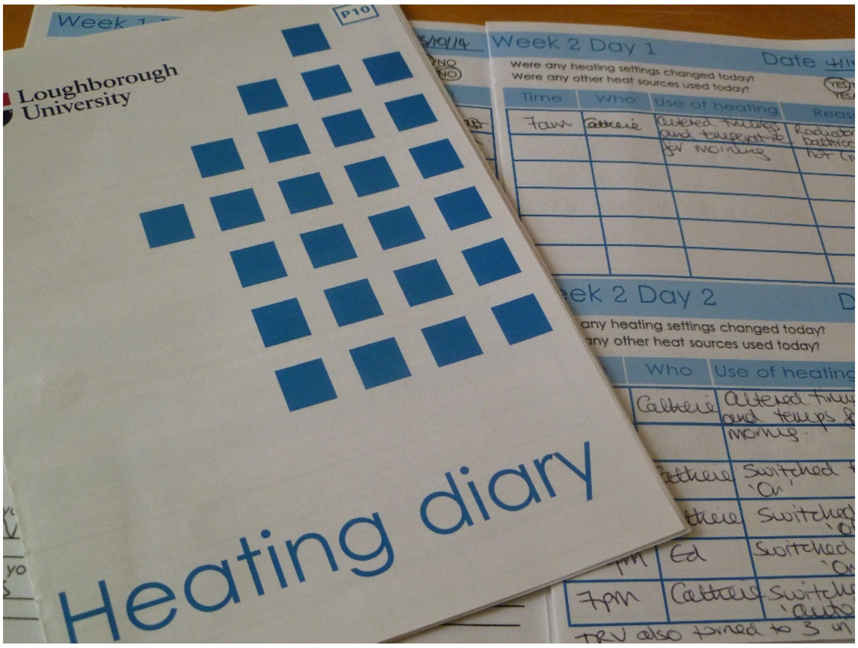


Figure 6.1 Heating diary design using Go Digital branding

Therefore, the heating diary was designed to cover four weeks where each day included a simple yes or no option for whether any heating settings were changed and if any additional heat sources had been used. A table was included where it was possible to fill in any of the changes made to the heating which included the time, use of heating, who interacted with it and the reason behind the change. It was envisaged that this would only take a few minutes to fill in and therefore not be too time consuming for the occupants. The heating diary also included some summary questions at the end of each week which asked the occupants how the Halo controls had been used that week – simple ON/OFF and/or AUTO format, what temperature it had typically been set to, if using AUTO function what schedules had been set, whether there was any issues with the heating and whether the occupants had been warm enough. The last page of the heating diary also included a few additional heating use questions which included whether the heating had been used regularly prior to the heating diary being filled in, whether anything specific had occurred over the past 4 weeks which changed how they would normally use their heating and if who used the heating had changed.

Participants were informed about the heating diary during an interview visit and left a leaflet detailing the requirements of it, but to ensure all households had an equal understanding of what was being requested a cover letter was included (Appendix 6-B) with the heating diary when they were posted out to the participant households at the start of September 2014, where it was envisaged that most of the households had not been using their heating yet. This letter indicated that the households should begin filling in the diary as soon as they first started using their heating again. It also informed participants that they would receive a voucher as a token of thanks for sending the completed diary back in a prepaid envelope. A total of eight completed diaries were returned at the end of October and beginning of November 2014.

6.3.5 Existing heating controls

As part of this study was to look at the impact new heating controls have on heating use in homes it was vital to understand the existing heating controls. Although all households within the sample received the same new heating controls as part of this study, the existing controls prior to installation varied significantly across the households, as can be seen in Appendix 6-C. The heating controls present prior to this study are summarised in Table 6.2.

Table 6.2 Existing heating controls prior to installation of new controls

	Manual thermostat	Digital thermostat	Programmable thermostat	Boiler controls	Timer (separate or on boiler)
P01			✓	✓	
P02			✓	✓	
P03	✓			✓	✓
P04	✓				✓
P05				✓	✓
P06			✓		
P07	✓				✓
P08				✓	✓
P09					✓
P10	✓				✓
P11	✓				✓
P12		✓		✓	✓

The difference in functionality and interfaces between previous controls also varied greatly, with Figure 6.2 showing two of the programmers seen within the sample households prior to the new controls being installed. The differences in the design of the existing controls interface have an influence on the heating use with the household due to: hard to read displays, confusing menus, buttons which are too small and placed too closely together, overly complicated controls with multiple menus to work through to set heating as desired, all of which were found, within the literature review, to be influencing factors. The difference in the designs and functions of existing controls within the sample means that the impact new heating controls have on each household may be different due to their existing heating behaviours based on what control methods they have available to them. Those with only boiler controls may significantly change their heating behaviours with the increased functionality and mobility that the new heating controls will have brought. Similarly those with existing digital programmers may well have adapted to the new heating controls much smoother and as such may not have changed their heating behaviours with the new controls.

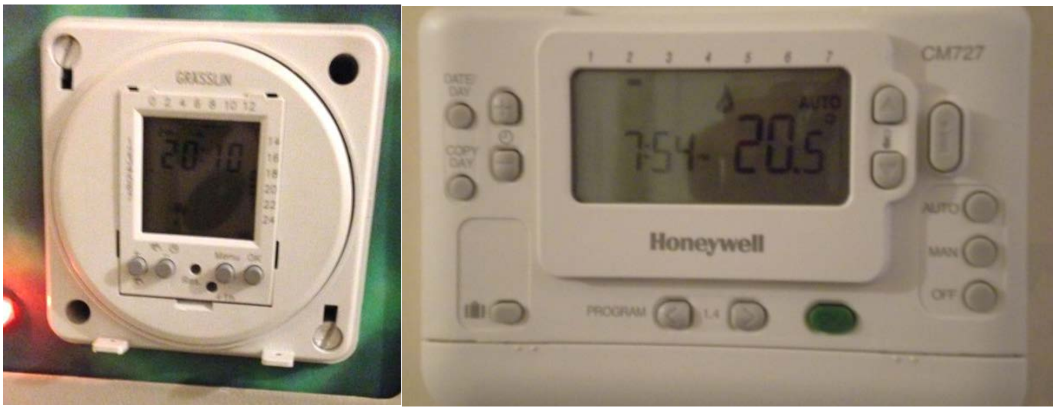


Figure 6.2 Example of aesthetic differences found between existing controls within sample

6.4 Data Analysis

All interviews were transcribed by a third party and the transcriptions were checked for accuracy once the transcriptions were received back to ensure nothing was missed out. On the rare occasion that the transcriber could not determine what was said during the interview this could then be checked against the audio file and interview notes to fill in any blanks. The transcripts were then imported into NVivo 10 to allow formatting and analysis to be carried out. The interviews were analysed to uncover categories regarding the heating use within the participating households and any reasons behind those heating habits. The following categories were identified inductively as being areas for analysis;

- heating use before new controls;
- use of new controls;
- adaptive behaviours;
- drivers for heating use;
- priorities with heating use;
- TRV use;
- secondary heating use;
- interaction with the new controls;
- perception of the new controls;
- household dynamics; and,
- heating term understanding.

After the categories were compiled, nodes were created within NVivo and then the transcriptions were analysed individually and relevant quotes or chunks of text were coded to the corresponding nodes. The coded interview data for each node was then printed so that the researcher could further code/analyse the full sample findings by hand and allowing the author to then compare the findings from the interview data to the measured date presented in Chapter 5. By printing the interview data it allowed easy annotation of any points of interest and allowed key terms to be highlighted which then allowed further exploration of the measured quantitative data.

Each household was taken in turn and both the qualitative and quantitative data were explored to unpick the complexity of heating use within that household. This meant that comparisons could then be made between the sample households to show how similar data traces or interview responses were. By comparing both data sets together it allowed differences to be found between the households, which may have been categorised together had only one data set been used. The combination of data sets allowed for a more complex picture of heating use in homes to be built. Key areas were then identified as being examples where interdisciplinary research provided a more comprehensive picture of heating use within homes, and these are discussed within the Section 6.5 Findings.

The impact the new controls had was analysed from comparing the data from mainly the first and third interview with households. Due to not the fact not all households took part in all of the interviews, it was possible to analyse the impact of the new heating controls on a total of eight households within the sample. The households were assessed based on the analysis of reported heating use in all three of the interviews and from measured data including internal temperatures before and after installation and measured use of the new heating controls.

The impact of the new heating controls on the households' thermal environment was assessed. It was possible to compare internal temperatures before and after the installation of the new heating controls by analysing the temperature data recorded by the stand-alone temperature loggers which were installed into the sample households ahead of the new heating controls being installed. This temperature data pre-controls could then be compared against temperature data recorded with the new controls the following year.

Interview data regarding heating use was also analysed for differences pre and post new controls, and differences between reported heating use and measured heating use. This analysis involved comparing the reported and measured heating schedules and set-point temperatures. By utilising both qualitative and quantitative data in this analysis it allowed to see whether what occupants reported doing was what was being recorded by the physical measurements.

Participating households were asked to report their weekly heating schedules (if using that function on the heating controls) within the heating diaries which were sent out to all households. The heating diaries were analysed for the heating settings reported by the occupants including set-point temperatures, heating schedules and daily use of heating. The diary also allowed for identifying if any problems had occurred within the households which were impacting their use of the heating. It was also possible to compare the reported start date for use of the heating system against the measured use. A total of eight completed heating diaries were returned.

Similar to the research carried out for the Phase 1 study of this doctoral research, the use of a mixed method approach within Phase 2 allowed for drivers behind heating use within the sample to be identified. This information came from all three interviews which participants took part in where any factors which influenced occupants' use of heating were analysed. Similar to the findings of the Phase 1 study key influences were mentioned in multiple households, identifying these influences as being drivers for heating use.

6.5 Findings

6.5.1 Changes in internal air temperatures

A total of seven households had full data for the same corresponding months before and after new controls were installed, these households are summarised in Table 6.3. For these households the average temperature after the new controls were installed was roughly less than 1^{o}C cooler than that of the average temperature before the new controls. The temperature variation between rooms within the households was typically the same for both years, except within P04, P08 and P10 where a much more obvious difference in the variation in temperatures was observed. The temperature results show that based on temperature measurements alone there does not seem to be a large impact on the thermal environment within the sample from the new heating controls being installed.

Table 6.3 Summary of average daily internal temperature and daily inter-room variations before and after installation of new heating controls (taken from the daily 24 hour averages)

		Average daily whole household temperature			Average daily temperature variation between rooms		
		Before controls (2014)	After controls (2015)	Change	Before controls (2014)	After controls (2015)	Change
P01	March	20.6°C	20.5°C	-0.1°C	1.8°C	2.4°C	+0.6°C
	April	21.5°C	21.8°C	+0.3°C	2.0°C	2.3°C	+0.3°C
P02	March	17.2°C	16.9°C	-0.3°C	4.5°C	5.1°C	+0.6°C
	April	18.5°C	18.3°C	-0.2°C	3.5°C	3.4°C	-0.1°C
P03	March	21.1°C	19.1°C	-1.0°C	2.9°C	2.6°C	-0.3°C
P04	March	18.6°C	18.4°C	-0.2°C	5.5°C	7.0°C	+1.5°C
P07	April	18.1°C	17.0°C	-1.1°C	2.9°C	1.9°C	-1.0°C
P08	April	19.6°C	18.5°C	-1.1°C	4.0°C	2.5°C	-1.5°C
P10	April	23.1°C	22.2°C	-0.9°C	7.7°C	4.9°C	-2.8°C
Mean change				-0.5°C			-0.3°C
Range of change				1.4°C			4.3°C

Obviously the weather may have influenced the internal temperatures within certain rooms of households within the sample from solar gains, therefore influencing the variation between rooms, Table 6.4 shows the relevant weather statistics for both 2014 before the new controls and for 2015 after the controls had been installed. It can be seen that the average monthly temperatures in 2014 were warmer than the corresponding months in 2015, indicating that for the months studied the external temperatures were warmer in 2014. This is in agreement with the internal temperatures recorded within the sample as all but one (P01 April comparison) recorded a higher internal temperature average than that recorded in 2015. Due to the small variation observed between the internal temperatures of both years it may be assumed from measurements alone that the heating use within the households remained fairly consistent even with the controls being changed. However, the author acknowledges that in reality various variables could impact measurements of internal temperatures and as such these measurements alone may not reflect the heating use within a home. Therefore, both qualitative and quantitative data is of importance to understand the impact of new controls fully.

Table 6.4 Summary of external weather conditions during relevant monitoring periods being compared

Month	Minimum	Maximum	Mean	Std. Deviation
March 2014	-2.10	17.80	7.50	3.74
April 2014	-0.30	18.10	10.18	3.21
March 2015	-1.90	14.90	6.35	3.13
April 2015	-1.20	19.20	8.93	4.12

6.5.2 Comparison of reported heating use with measured heating use

Although very little change was found overall in internal temperatures with the new controls the data on heating behaviours from reported use shows a slightly different picture. As occupants reported their heating use during winter within the interviews the measured heating use is in relation to the winter months data, taken to be October to February for consistency with other analysis. The comparison between reported heating use before the new controls and that reported and measured after the new controls indicated a change in heating use behaviour if changes were made to the way in which they chose to use/control the heating within their home or if the scheduled use of heating changed in durations or set-point temperatures.

6.5.2.1 Use of heating

Table 6.5 summarises the reported use of heating within the sample both before and after the installation of the new heating controls and compares it with the measured heating use with the new controls. These findings relate to the means in which the occupants chose to control their heating.

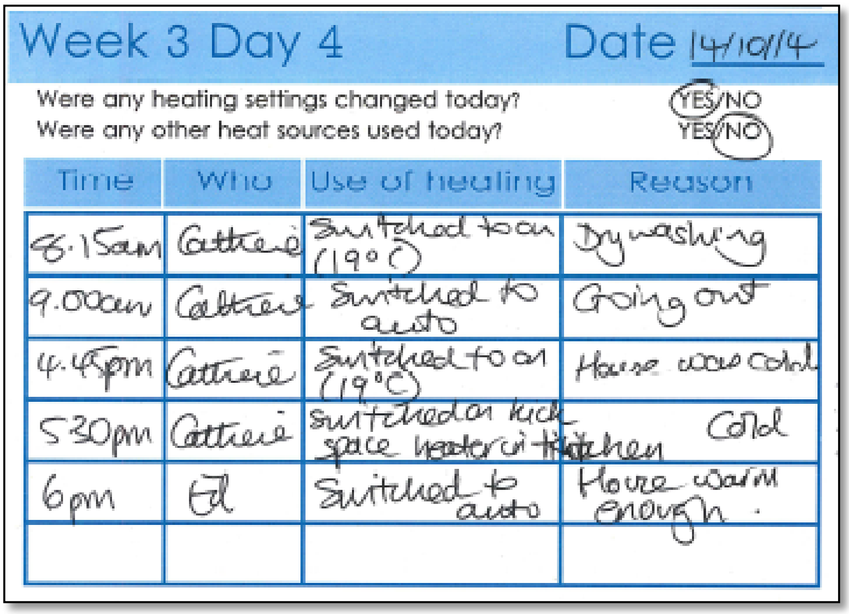
Table 6.5 Summary of reported and measured heating use within homes both before and after new heating controls were installed

	Reported heating use before new controls	Reported heating use with new controls	Measured heating use with new controls
P01	Left on timer with little interaction unless bad weather or need to dry washing then switched to manual for a couple of hours	Uses timer function. Will switch from auto to manual when needed for drying clothes or extra heat if activity level low	Typically left on AUTO majority of the time with manual interaction to increase heating duration and temperatures
P02	Set on timer. Will interact daily with heating system.	Set on timer. Will use manually as needed when at home during the day.	Set on timer with settings changed over winter. Also used controls manually on almost a daily basis on top of scheduled heating.
P03	Thermostat set and left on all day. Will adjust the hall thermostat regularly in the evenings to suit	N/A	Scheduled use with some manual interaction
P04	Set on a timer and typically left. Will use boost function regularly through the week in relation to shift pattern	Timer set. Manual interaction with controls probably daily due to different thermal comfort of occupants	Schedule set and altered over winter. Manual interaction also increased over winter
P05	Use timer	Timer set	Data only available for mid Oct-mid Nov but schedule recorded
P06	Used on a demand basis instead of using timer	Data only from 2nd Interview so pre-winter use. Used only on a demand basis up till then	Schedule only set from December onwards, up till then used on a demands basis. Manual use still occurred with schedule set
P07	Timer used, will use boost function if really cold	Timer set, will switch on and off manually as needed and then left to auto the rest of the time	Schedule set and only changed for holiday. Manual use increased more in Jan and Feb
P08	Set timer but will use as needed when cold or at home longer	Set to AUTO in mornings and then manual interaction in afternoons/evenings	Scheduled use in morning with manual use in the afternoon and evenings.
P09	Timer set but heating often switched on and off as needed, tends to be overridden and left on constant during winter	Timer set and set-back temperature increased	No winter data
P10	Always on	Always on	Always on
P11	Timer set, will use boost function for an hour just before bed in the evening.	N/A	Scheduled use with little manual interaction
P12	Heating set to timer.	N/A	Property rented out shortly after starting to use heating again

A total of four households reported and recorded different heating use with the installation of new controls. P03 went from having their heating left on all the time to setting a schedule and only manually interacting with the controls when needed. P06 similarly went from using their heating system on a demands basis to then setting a heating schedule in December 2015 and only manually interacting with the controls when needed. P08, although still setting a schedule like with their old controls they chose only to set one heating period instead of two like previously and therefore manually interacted with the controls on numerous occasions daily. P09, although only interview data was available, reported using their heating previously on a demands basis, and although set a schedule, resorted to switching the boiler off and on as required. With the new controls P09 reported changing the set-back temperature so that they set a schedule how they wanted and then left the heating as it was, so stopped manually interacting with it as much as with their previous controls. Overall a majority of participants reported very similar heating behaviours to those which they reported having prior to the new heating controls being installed. This indicates that even with new advanced heating control technology being given to them the occupants simply used them in a way which allowed them to have the same heating behaviour as before.

When comparing the reported heating use with the measured heating use, it was found that, with those households that could be compared, all households reported what was measured. The only household that had a slight difference was P06, however they did not partake in the final interview and reported using their heating on a demands only basis. It was not until December that this changed, however the final interviews occurred after this and therefore it was not possible to see if they would have reported still using it on a demands only basis or mention that they had started to use a schedule.

The level of detail regarding heating use reported by householders in the heating diaries varied greatly across the sample, with three households rarely filling in the daily detail section and preferring just to fill in the details regarding the weekly settings. Figure 6.3 however shows an example from one of the participating households which gave a lot of detail about their daily interaction with the heating system.



Week 3 Day 4 Date 14/10/14

Were any heating settings changed today? YES/NO
Were any other heat sources used today? YES/NO

Time	Who	Use of heating	Reason
8.15am	Catherine	Switched to on (19°C)	Dry washing
9.00am	Catherine	Switched to auto	Going out
4.45pm	Catherine	Switched to on (19°C)	House was cold
530pm	Catherine	Switched on kick space heater in kitchen	Cold
6pm	Ed	Switched to auto	House warm enough.

Figure 6.3 Excerpt from completed heating diary showing level of detail in one diary

As it can be seen from this example the diary recorded the heating system being used by both adult members of the household. Across the eight participating households that completed the heating diaries, five recorded interactions from various household members, two recorded the majority of the heating interaction to be from one household member and the remaining participating household diary only had details recorded by one member of the household. This could be due to the fact that one member takes control of the heating within the household or it may have been other members of the household were unaware or not keen on participating with completing the heating diary. This finding however shows the importance of interviewing the most relevant household member(s) if simply relying on interviews to gain more information regarding heating use in homes.

Another factor identified by the heating diaries which may be impact what is reported by participants in interviews was the reasons behind using the heating. Out of the eight completed diaries, the majority of reasons put down for using the heating system was due to feeling too cold and then feeling warm enough. However there were exceptions to this with one household reporting to use the heating on numerous occasions to dry clothes, another reported putting the heating on for their pet hedgehog. One household (P05) reported the change in their use was down to their central heating not working due to a faulty boiler, however this was noted on Day 2 of Week 2 and the fault was repaired the following day with the schedule being reset to as before. One household reported increasing the set-point temperature to "boot up radiators" before lowering the set-point temperature back down again. These "one-off" instances for using the heating may not be remembered by participants unless they are interviewed shortly after the occurrence. Therefore additional details relating to the reasons behind heating use in homes may be lost as participants may forget to report these.

6.5.2.2 Heating schedules

Table 6.6 summarises the reported use of heating within the sample both before and after the installation of the new heating controls and compares it with the measured heating use with the new controls in relation to the heating schedules which were set by the occupants.

Table 6.6 Summary of reported and measured heating use within homes both before and after new heating controls were installed

	Reported heating schedules before new controls	Reported heating schedules with new controls	Measured heating schedules with new controls
P01	6-8am/5-9pm	Weekdays: 6.30-8am/5-9pm Weekends: slightly later in the morning for a few hours/5-10pm	Weekdays: 6-8am/5-9pm Weekends: 6-10am/5-9pm
P02	5.30-7.30am (used to be till 8.30am in winter)/6.30-11pm	Set on timer for morning and evenings with slightly different hours for at weekends.	Weekdays: 5-8am/5-10.30pm Weekends: 7-9am/5-10.30pm
P03	Always on	N/A	6-8.50am/3-10.40pm
P04	6-10am/3pm-10pm and longer at weekends	Weekdays: 6-10am/4-10pm Weekends: similar settings just on later and for longer.	Weekdays: 6-9am/4.30-10pm Weekends: 7-11am/4.30-9pm
P05	6-8am/6.30-9.30pm	6-9am/6-9pm	Data only available for mid Oct-mid Nov 6-8.20am/6-9.30pm
P06	Used on a demand basis instead of using timer	Used only on a demand basis up till then.	Schedule only set from December onwards, Weekdays: 5.05-7.30am/5.25-10.20pm Weekends: 7.30-10.30am
P07	7-10am/3-7/8pm	6.30-9am/3-8pm	Weekdays: 6.30-9am/3-8.15pm Weekends: 7.35-11am/4.15-8.15pm
P08	5.30-8/8.30am/4-6pm	6-8am	6-8am
P09	5.30/6am-10pm	6-8/9am/4-9.30pm.	No winter data
P10	Always on	Always on	Always on
P11	7.30-8.30am/5-8.30pm	N/A	7.30-8.30am/5-8.30pm
P12	6.30-7am/5.30-9pm	N/A	N/A

It was possible to compare the impact of the new heating controls on reported schedules for heating both with previous controls and the new controls in a total of 8 households. Out of these households, three (P01, P06 and P10) households reported very similar heating schedules to those that they had with the previous controls. Out of the remaining five households, one (P08) changed their heating schedule from two periods of heating to just one with the new controls and relied purely on manual interactions in the afternoon/evenings. This could result in energy savings if overall the heating system is being used for fewer hours compared to the old controls. Similarly P09 went from one large heating period with their old controls to programming two periods of heating with the new controls, resulting in the heating being demanded on for a shorter duration in total. P04, P05 and P07 all made changes to the times which their heating was programmed for, but kept roughly the same heating durations.

The reported schedules with the new controls could then be compared with measured data. Some differences between reported values and measured values were found, however these were fairly small differences and all related to the exact start or end time of the heating schedule. For instance, P05 reported their heating was schedules for 6-9am and 6-9pm, however the measured data showed the heating to be scheduled for 6-8.20am and 6-9.30pm. Similarly P07 reported the heating schedule stopped at 8pm but it was 8.15pm according to the measurements, which recorded in 5 minute intervals. These differences may be down to the time gap between when the schedule was set and when they reported the settings, or even that the participant reporting the setting may well have not been the household member who set the schedule on the controls.

P03 and P11 had no reported use of the new controls however had measured data which could be compared to their previous reported heating use with their old controls. P11 recorded the exact same heating schedule as that which they reported with their old controls, indicating that the new controls had not caused a change with their heating use. P03 however reported always leaving their heating on with their old controls but measurements showed with the new controls they had set up a heating schedule. This change could result in energy savings given the heating was on less with the new controls, however the saving potential is determined by the set-points they previously had and now use and also the level of manual interaction with the new controls on top of the programmed schedule.

Heating schedules were also reported in the heating diaries. Table 6.7 shows what each of the completed diaries reported regarding scheduled heating use for the four weeks that the households were asked to fill it in for. Due to being asked to only start completing the diary once using their heating again on a regular basis there was slightly difference in start dates for each household, however there was only a week and a half between the first household starting to complete the diary to the last household starting to complete it.

Table 6.7 Reported heating settings from completed heating diaries sent back

	Start Date	Week 1	Week 2	Week 3	Week 4
P02	27/09/14	5.30am-7am (20˚C) 7pm-10pm (20˚C)	5.30am-7am (19˚C) 7pm-10pm (20˚C)	5.30am-7am (19˚C) 7pm-10pm (20˚C)	5.30am-7am (19˚C) 7pm-10pm (20˚C)
P04	06/10/14	Set to 19˚C	Set to 19˚C	Set to 21˚C	Set to 21˚C
P05	06/10/14	6am-8am (18˚C) 6pm-9.30pm (18˚C)	6am-8am (18˚C) 6pm-9.30pm (18˚C)	6am-8am (18˚C) 6pm-9.30pm (18˚C)	6am-8am (18˚C) 6pm-9.30pm (18˚C)
P06	27/09/14	Set to 21˚C	Set to 21˚C	Set to 21˚C	Set to 21˚C
P07	05/10/14	6.45am-9am (18˚C) 4.30pm-7.45pm (18˚C) Weekend 7.50-9.35 (18˚C)	6.45am-9am (18˚C) 4.30pm-7.45pm (18˚C) Weekend 7.50-9.35 (18˚C)	6.45am-9am (18˚C) 4.30pm-7.45pm (18˚C) Weekend 7.50-9.35 (18˚C)	6.45am-9am (18˚C) 4.30pm-7.45pm (18˚C) Weekend 7.50-9.35 (18˚C)
P08	25/09/14	6am-7am (18˚C)	6am-7am (18˚C)	6am-7am (18˚C)	6am-7am (18˚C)
P09	30/09/14	6am-8.30am (22˚C) 4.30pm-9.30pm (22˚C)	6am-8.30am (22˚C) 4.30pm-9.30pm (22˚C)	6am-9.30am (22˚C) 3pm-9.30pm (22˚C)	6am-9.30am (22˚C) 3pm-9.30pm (22˚C)
P10	25/09/14	Set to 22˚C	Set to 22˚C	Set to 22˚C	Set to 22˚C

Out of the eight households which returned the completed heating diary, three reported only the typical weekly demanded set-point temperature, which was due to some of those households preferring to use the new controls in an "ON/OFF" mode instead of setting up a schedule in the "AUTO" function. Typically, those remaining households that completed their diary reported using the heating with a pattern of two heating periods daily. Only one household reported setting a different heating schedule during the weekend to weekdays. It is also worth noting that during the four week period two of the households changed their heating schedule, either the demanded set-point temperature or the starting time of their heating period. This suggests that during the start the heating season households are likely to change their initial heating settings.

6.5.2.3 Set-point temperatures

Table 6.8 summarises the reported use of heating within the sample both before and after the installation of the new heating controls and compares it with the measured heating use with the new controls in relation to the set-point temperatures being scheduled and does not include the additional manual interaction and increased set-point temperatures being demanded in some households.

Table 6.8 Summary of reported and measured heating use within homes both before and after new heating controls were installed

	Reported heating use before new controls	Reported heating use with new controls	Measured heating use with new controls
P01	22°C	21°C for scheduled use	20°C weekday mornings and 21°C evenings and weekends
P02	18-19°C.	Over winter set to 19°C before reducing down to 18°C. Reported range of temperatures 17-19°C.	19°C for most scheduled use, but also set to 18°C
P03	20°C in hallway and underfloor heating thermostat set to 25°C	N/A	20°C mornings 21°C evenings
P04	About 19°C, however markings on thermostat only ever 5°C	Set to 20°C after some initial experimentation to find comfortable temperature	Weekdays: 19°C Weekends: 20°C
P05	Desire of maintaining a temperature around 18°C.	18°C in morning and evening with 15°C for during the day	Data only available for mid Oct-mid Nov but 18°C mornings/evenings and 15°C set-back
P06	Unaware how to set temperature	N/A	Schedule only set from December onwards Weekdays: 22°C Weekends 21°C
P07	Around 19°C.	18°C mornings and evenings.	18°C mornings and evenings
P08	No temperature gauge on system only scale of 1-10, which will fluctuate between 3-6 over winter.	Set to 21°C	21°C
P09	No temperatures on controls only numbers 1-5	22°C for schedules, set-back 20°C	No winter data
P10	20°C	22°C	22°C
P11	25°C	N/A	21°C mornings and 24°C evenings
P12	Set to 18/19°C	N/A	N/A

When comparing the set-points demanded by participants with their old controls and new controls, three households (P06, P08 and P09) could not give a set-point temperature with their old controls due to the lack of temperature gauges on the system or being unaware of a set-point temperature. Two households (P02 and P05) reported keeping the same set-point temperature with the new controls. P04 reported 20°C with the new controls compared to reporting 19°C with the previous controls, however their previous control was a manual thermostat which only had temperature markings every 5°C intervals therefore it was difficult to say the exact thermostat temperature being demanded. P10 still kept their heating on constantly as before but they demanded a set-point temperature of 22°C compared to their old controls where a set-point of 20°C was demanded. This could be detrimental to any potential for energy savings with the new controls as a higher temperature is now being demanded. P01 and P07 however had set a lower demand set-point with the new controls than previously reported, therefore indicating some energy saving potential from the new controls.

When comparing the reported use of the new controls against the measured use, very similar results were found. P02, P05, P07, P08 and P10 all reported the same set-point temperature as the set-point temperature recorded through the measurements. P01 reported a set-point of 21^{o}C, but had their morning heating period set to 20^{o}C and the evening at 21^{o}C. Similarly P04 reported a set-point of 20^{o}C but had 19^{o}C set as the set-point during the week, with 20^{o}C being the weekend set-point.

It was possible to compare the reported set-point temperature from the old controls with the measured set-point with the new controls for those missing the reported new control set-point temperature. P11 demanded not only a lower set-point than they did with their old controls (going from 25^{o}C), but they also reduced the morning set-point even lower (morning 21^{o}C, evening 24^{o}C). Similarly P03 reported using set-point temperatures of 20^{o}C and 25^{o}C with their old controls, but recorded set-points of 20 and 21^{o}C with the new controls, so kept similar set-point temperatures with the new controls.

6.5.2.4 Occupants' perceptions with new controls

Occupants were asked within the second and final interviews whether they felt the new heating controls would impact how they used their heating within their homes. Most households reported they felt the controls had made an impact. However a number of households stated that they were unaware they had manually interacted with the controls to the level that they had when shown data plots during the final interview. The level of manual interaction with the new controls is likely to have not become obvious to the participants as manual interactions with the controls is often a reaction to feeling cold so participants simply switch them onto manual and do not really acknowledge just how often that may happen.

Both P05 and P08 reported that the new controls gave them a sense of control over the temperature within the property, allowing them to heat their home in a way that fits in with their lifestyle and desired thermal environment. Previous to the new controls these households had no way of knowing what temperature they were demanding of their heating system, instead they had to go by a 1-5 scale. P04 reported that the remote access feature was beneficial in reducing their heating use as with their old system they considered it a hassle to change the settings as it involved going to the garage.

> "So I'll be sitting in the front room, starting to get a bit warm, I'd now just turn the heating off. Whereas before, I just wouldn't. Because I'd have to go all the way to the garage, you know, it's miles away." *[P04, Interview 3]*

The new controls were described as giving more flexibility in heating use in a number of households, with P07 describing that they felt they were now more reactive in the way that they used their heating with the new controls given they were much easier to use.

Occupants were asked about their views of the new heating controls in relation to whether they felt their home was warmer or cooler now with the new controls. Four of the eight households reported that their home definitely felt warmer, one reported it being slightly warmer and one stated they felt the thermal environment was about the same as previous. The remaining two households reported their home being cooler now with the new heating controls with one (P10) stating that they increased the demand temperature because of it, which when then compared against the average internal temperatures reported in Section 6.5.1, their average whole household temperature was cooler with the new controls than previously, even with a higher set-point temperature. The remaining household who believed their home felt cooler with the new controls was P09, who stated that the dwelling was cooler now that they had more control over the thermal environment.

> "I'll tell you why because it wasn't controlling itself, so it was sort of, a case of it'd get warm, then get a bit warmer, I thought, blimey, it's hot now but I can't turn it down." *[P09, Interview 3]*

Interestingly though is the fact that no changes were made to the heating system within the households other than changing the heating controls. So by changing just one part of the heating system the majority of the sample reported feeling warmer than previously, indicating that the households were able to create a warmer environment with the new controls or that there may be a psychological effect on householders. The psychological effect may be where householders believe that just by installing a new part within an existing system it should result in an improved performance, even though the majority of households recorded less than 1^{o}C difference before and after installation. This is why both qualitative and quantitative data is beneficial as it allows triangulation of findings, especially with the similar reported heating settings with the old and new controls in many of the households.

The impact of the new heating controls would also have been influenced by the occupants' perception of the controls and knowledge regarding the use of them. During the second interview occupants were asked about their understanding on the terms used by the new heating controls and what they meant. This uncovered varying levels of understanding across the sample, however at this point most occupants were not regularly using the controls and it had been a few months since they were originally installed and where the installer briefly talked them through the controls. Six of the households had a clear understanding of the AUTO function on the controls, with two not sure exactly as to what it meant the heating system was doing, however they managed to describe the function correctly by talking themselves through it during the interview. During the final interviews occupants were asked whether they had any issues with using the controls and whether they felt there was anything they could not do with them. All eight households stated that they were managing to heat their homes how they would like. However P02 did mention that the connection with the new controls went down a couple of times through the winter and as such were unable to get the app to work for their heating system. Similarly P09 could not get the app to work and had a fault develop with the gateway which stopped the app from being used. Additional faults with boilers were reported within three of the households regarding boiler pressures dropping and leaks within their system but all stated it was no impact from the controls. Although overall most households reported the new controls were easy to use, gave more flexibility to their heating use and overall an improvement on previous controls, the interface of the controls for setting heating schedules was described by one household as not being logical and was overly complicated.

"You have to keep pressing the home button which to me isn't logical, there should be like, a more obvious way of saving it. That's my big bugbear with it. You've got to remember how do I get off this screen, I've got to press the home button every time and that's my annoyance with it. Because then when you press something else, oh God, now I'm going to set more times in it. Well, how do I get out of that? And that is what I find a bit irritating with it. I don't think it's the most user-friendly interface" *[P02, Interview 3]*

This may have had an impact on occupants' use of the programmer functions on the controls, however any household (including P02) that did mention the interface was not ideal also stated that they managed to work out how to program schedules by referring back to the user manual. If occupants have to refer to user manuals to change settings on these advance heating controls, it may mean they are unlikely to change the settings in relation to seasons and simply rely on more manual interaction and a demands basis.

The heating diary also asked participants about whether they had used the remote access function on the heating controls over the course of the four weeks. Only three households reported having used this function. One reported using the app to switch the heating on and off and to change the set-point temperatures. The other participant reported only using the app to change the set-point temperature. Another reported using the app at weekends to switch the heating on/off if too warm when still in bed. However two of the households which reported using the app to interact with their heating system also reported having issues with the app during this time and therefore were not able to use it as much as they may have liked to.

6.5.3 Drivers identified behind heating use

The key drivers identified through this study were the presence of young children or pets, the dynamics within the household, health of occupants and occupants' main priority in relation to heating use, specifically cost and comfort.

6.5.3.1 Presence of children

Three households within the sample stated the use of heating in relation to their children. P05 stated that if it was not for their little girl then they would probably use the heating within their home differently stating that they would use it less if it was just adults within the property. Both P02 and P11 talked about using their heating in specific ways relating to their children. P02 mentioned that when their little boy (aged 2 year old) is home they will put the heating on for the whole dwelling, as he tends to wander around their home so they did not want any areas being too cold for him. However they mentioned that they would heat the specific areas in which their little boy would be, playing or sleeping, and this would be done through the use of adjusting the radiator settings. Children are a key influence on heating use in homes with many parents not wanting their child to get too cold and therefore changing their preferred heating behaviours to suit what is best for the child's needs.

"I'm most concerned about our daughter's bedroom. Evening heating is based on the temperature of her bedroom more than anything, so I think we would have it on less you know, if it wasn't for her" *[P05, Interview 1]*

The average whole household internal temperature over winter was presented within Chapter 5, and this can be compared against the age of the children present within the household, as seen in Table 6.9.

Table 6.9 Whole household average winter temperature with age of children within household

Household	Average winter whole household internal temperature (Oct-Feb)	Age of children in household
P01	20.0	N/A
P02	16.7	2 years
P03	19.4	N/A
P04	18.3	N/A
P05	17.4	2 years
P06	17.5	N/A
P07	16.6	2, 10 years
P08	18.0	3 years
P09	-	15 years
P10	21.5	14 years
P11	19.8	2 years
P12	19.3	N/A

As the average internal temperature show, some of the colder whole household averages are found in households with young children (P08, P05, P02 and P07), which goes against the expectation that the presence of young children results in a warmer dwelling. Therefore this indicates that although children can be a driver in the use of heating within a household it does not necessarily mean higher average temperatures will be found within these households.

6.5.3.2 Presence of pets

Pets were also reported as being influences on heating use within the sample. Both P10 and P12 mentioned that they consider their cats when thinking about their heating use and how they would leave the heating on, even if the occupants' are not there, so that the cats don't get cold.

"It will have to be on for the cats, as silly as it sounds" *[P12, Interview 1]*

"We would probably leave it on because of the cats, the cats stay at home" *[P10, Interview 1 regarding use of heating when away on holiday]*

More unusual within the study was one household with a pet pygmy hedgehog which required a particular ambient temperature.

"[the hedgehog] has to be kept at a constant temperature, between say 22 to about 25^{o}C. Which is a bit of a problem, because if I go out to work in the morning usually I turn the heating off. But we've tended to keep it on for the hedgehog…it's a bit of a pain, really, this hedgehog." *[P09, Interview 1]*

The household reported to leaving the heating on when in normal circumstances they would have switched the heating off. The occupants mentioned trying to use other methods of keeping it warm such as microwavable heat mats, however they were not effective enough. During subsequent interviews the household reported to having a separate electric heater in the room with the hedgehog so to reduce needing the whole household heating on just to keep the hedgehog at the right temperature. This gives an example where secondary heating is being used regularly within a home, not directly for the occupants own comfort.

6.5.3.3 Differences in household members preferences

As seen within the results of the Phase 1 study for this doctoral research, differences in household member's thermal preferences can be a large influence on heating use within homes. Disagreements on use of heating, set-point temperatures and differing levels of personal comfort all impact the heating use within a household. Similar findings were found within this study, with differing thermal comfort levels regularly being reported. Often compromises are made by other household members to compensate for those with lower thermal comfort levels. This was seen within the sample with two households reporting that some members of the household would regularly wear shorts around their home so that the other(s) could feel comfortable at a warmer temperature. In P10 it was reported that the daughter regularly felt cold and would often turn the thermostat to its maximum temperature to get warm, however the husband would always feel too hot and therefore be adjusting it down regularly so often disagreements occurred. The daughter was even told off by the parents for always putting it to the maximum setting. There was an example of thermal comfort being influenced by previous experiences in P12 with the occupant reporting that her boyfriend always liked it warmer in the flat, around 25^{o}C, because he was from the Caribbean and therefore felt comfortable in warmer temperatures, even though he moved away from the Caribbean when he was 5 years old.

"He's not got the sense of putting a blanket on. Like I'm sitting with like full pyjamas, full blanket, dressing gown, everything, and he'll sit there in a t-shirt and shorts and put it up to thirty, and I'm like "Are you for real?" But he literally lives just next door, so if it gets to that stage I'm like, "No, you can go home now!"." *[P12, Interview 1]*

However there were some households which reported those with lower thermal comfort levels simply using blankets or jumpers instead of increasing the temperature which may cause other household members' to become uncomfortably warm. Within the sample, two households admitted leaving the control of the heating up to certain members. In P05, the wife controlled the heating to suit when she was at home with their young child. Similarly in P08, the wife was often home a lot during the day with their young child so she mainly controlled the heating to suit them both and to reflect when they were in or out. The husband just left it to them, even though he reported not liking it to be too warm and as such would often be in shorts.

"I personally don't like it too warm anyway, but my wife does so it's always a battle. I'm sitting in there in shorts…I probably wouldn't have it on at all if it was just me" *[P08, Interview 1]*

Some household dynamics changed with the new heating controls because it meant those who tended to interact with heating controls previously changed with the new controls. This often meant that the heating settings were getting changed more frequently and sometimes behind other household members' backs. An example of this was seen in P04 where typically the heating was left up to the husband to control and he believed there may have been issues with the system as he regularly checked the status of it on the app, however he didn't realise his wife had worked out how to use the new controls.

"It seemed like it kept changing its mind and going from sort of on to off, from off to automatic and…but my wife found out how to use it, so I think that's what was happening. I didn't realise she knew how to do it, but I think she was nipping into the garage and changing it" *[P04, Interview 3]*

6.5.3.4 Priorities towards heating use

Due to the longitudinal aspect of this research it was possible to see that within some households that there was a change in occupants' inherent priorities when it came to heating use. During both the first and last interviews occupants were asked to rank their priorities to heating between cost, comfort and health. The results found in both interviews are summarised in Table 6.10. It can be seen from these results that out of the eight households which took part in both interviews, only two of the households reported the same order of priority in relation to heating use: P05 and P10. Three of the households reported a change in their main priority when it came to heating use, P01 ranked cost as their main priority before the new controls but this changed the following year to comfort being the main priority. Similarly P02 reported cost becoming an equal priority with comfort during the latter interview. P09 showed a difference of opinion between occupants during the first interview where the couple couldn't come to an agreement as to whether cost or comfort was more of a priority for their use of heating within their home. This highlights that the main driver behind heating use in homes can differ dependant on which household occupant is being interviewed, which is likely to be reflective of how aware occupants are to their energy bills and knowledge of energy consumed from heating use. It is also worth noting that both the first interview and the last interview took place in late spring 2014 and early spring 2015 so occupants may well have been basing their answers in relation to the winter months which had just ended and therefore there may have been potential influences from the severity of the winter months.

Table 6.10 Priority rankings in relation to heating use within sample both before and after new heating controls being installed

	1st, 2nd, 3rd priority towards heating (before controls)			1st, 2nd, 3rd priority towards heating (after new controls)		
	Cost	Comfort	Health	Cost	Comfort	Health
P01	1	3	2	2	1	3
P02	3	1	2	1	1	2
P02 (before baby)	2	1	3			
P03	2	1	3			
P04	2	1	3	3	1	2
P05	2	3	1	2	3	1
P06	1	1	2			
P07	3	1	2	2	1	3
P08	3	2	1	2	1	3
P09 (M)	1	2	3	2	1	3
P09 (F)	2	1	3	2	1	3
P10	2	1	3	2	1	3
P11	3	1	2			
P12	1	2	3			
Total of 1st priority	4	9	2	1	8	1
% of 1st priority	27%	60%	13%	10%	80%	10%

It can also be seen from Table 6.10 that 60% of answers in 2014 stated that comfort was the top priority with 27% stating cost and the remaining 13% reporting health. This changed within 2015 with a higher percentage of the answers being in favour of comfort as the top priority, with 80%. Cost and health were both seen as top priorities in 10% of the answers. There were two instances where participants rated two factors as being their main priority with regards to heating, P06 reporting cost and comfort before the new controls and P02 reporting cost and comfort equal priorities with the new controls.

6.5.3.5 Health of occupants

Although the findings typically showed health to be ranked the least important priority to householders, it was found that it can impact heating use within homes significantly. One household, P08, reported during the final set of interviews that they had been quite ill for a few weeks where they could not get warm at all, and this then resulted on the occupant demanding a set-point temperature of 30^{o}C on multiple occasions. This shows that the health of occupants is likely to impact heating use within homes with it most likely resulting in higher demanded temperatures and longer use of heating. Although this may only last for a week or two, without the qualitative knowledge of the driver behind this change in heating use monitored data may be analysed and assumptions may be made that those behaviours are the occupants' normal actions, especially if the monitoring is short term.

6.5.3.6 Changes in priorities/drivers of heating use

This evidence of changes in priorities (seen in Table 6.10) relating to heating use highlights some key issues when using qualitative research methods such as interviews as these are typically discovering a "snap-shot" in the occupant's behaviour, views and attitudes at that moment in time. This is a potential issue for longitudinal studies which rely on both qualitative and quantitative measurements as the time periods when the qualitative research is carried out are important to the hypothesis being made from measured monitoring data. Just because an occupant reports having certain views and attitudes at the start of a study does not guarantee that those are the same views and attitudes that they have at the end. Therefore it is important to determine when "snap-shots", particularly of behaviour, are needed to be taken. The difference in reported behaviours and heating use across this study can explain unusual changes in heating use.

6.5.4 Heating behaviours and use of heating

By using an interdisciplinary approach to this doctoral research, evidence found from qualitative data collected could be combined with the results from quantitative data to further enhance the knowledge uncovered from the research. This included the additional information gained during the interviews on the use of TRVs and secondary heating. The interviews also meant that information regarding occupants' adaptive behavioural traits could be compared to measured results such as those presented in Chapter 5. This section explores these heating use behaviour areas further and presents findings from both the qualitative and quantitative data collected.

6.5.4.1 TRV and radiator use

The use of manual radiator valves and thermostatic radiator valves is very difficult to infer from temperature measurements alone. This is due to the individual room temperatures being affected not only by the size and use of the room but also from the orientation of the room, presence of windows, size of radiators and whether or not the room is typically shut off from the rest of the dwelling.

Occupants were asked about their use of manual radiator valves and TRVs during both the first and final interviews. The use of radiators to control the thermal environment within homes varied across the sample. Those that did report adjusting them typically mentioned it in reference to bedrooms within the household. Some households reported to leaving the radiators set as they were when installed or once a comfortable setting was achieved.

"No we've not kind of touched it since. Basically when they came to fit them, they already set it. They said to us, which room do you use the most, so we'll keep that on high. The rooms we don't use, we'll keep them on low" *[P11, Interview 1]*

One household reported never using them in winter as they never think about using them as a way to alter the environment of different rooms, even though they stated that they would adjust them in the summer so that the radiators upstairs stay on in case the temperature drops overnight.

"I would probably adjust them more in the summer, but it's not something I would tend to do in the winter, I wouldn't have thought" *[P01, Interview 3]*

When the interview findings were compared against the average variation between room temperatures across winter (October – February), as shown in Table 6.11, a link between those reporting changing radiator valve settings on a more regular basis and those with higher temperature variation across rooms was found. Six of the ten households with winter data showed a temperature variation on average between 2-4^{o}C between rooms across the household; however one household showed an average variation of 8.4^{o}C between rooms over the winter period, over double that of the majority of the sample.

Table 6.11 Average winter temperature variations between rooms within a household

	Average temperature variation between rooms across winter	Regularly TRV use	Occasional TRV use	Rarely uses TRVs	Details
P01	2.7°C			✓	Never thought about altering TRVs
P02	5.9°C	✓			Daily routine to alter bedroom TRVs
P03	2.8°C		✓		Son occasionally adjusts bedroom TRV but rest left as they are
P04	6.4°C	✓			Wife regularly alters TRVs
P05	2.0°C (mid Oct-mid Nov data)			✓	Only got one TRV in front room but hardly ever use it
P06	5.2°C	✓			Regularly uses TRVs to control heating
P07	2.2°C			✓	Used to adjust regularly but now tends to leave them how they are
P08	3.4°C			✓	Rarely uses them
P09	No winter data		✓		TRVs in bedrooms altered occasionally
P10	8.4°C	✓			Adjusts those in bedrooms
P11	3.9°C			✓	Leaves TRVs to how they were set when installed
P12	No winter data before rented out		✓		Occasionally in rooms not being used

Those identified as having the largest average inter-room variations were P02, P04, P06 and P10. These households also all reported using the radiator valves (manual or TRVs) as a means of controlling individual room thermal environments.

"Yes, rooms we don't use we've got the TRVs turned right down" and "The one in our bedroom goes up and down all the time because we try and whack as much heat in there as we can, you know, in the evenings, so its warm when we're going to bed. But then we turn it right down because otherwise we both end up with stinking headaches if we wake up in the morning and the heat is on. So that's always being altered" *[P02, Interview 1 and Interview 3]*

"I quite often do [interact with the radiators], well I do both the thermostat and radiators" *[P04, Interview 1]*

"If I am like in my bedroom and a bit hot I just turn it down, and then turn it up again if I get cold" and "The kids do, in their rooms, but the rest of them just more or less stay on the same…if they feel hot or cold, they just turn them up or down"

[P10, Interview 1 and Interview 3]

P06 reported within the first interview that they regularly adjusted radiator valves as that was the only means they felt they had of controlling the individual rooms as they did not have a thermostat at that point. A final interview was not possible with P06 therefore it was not possible to see if giving that household new controls and a means of setting a precise temperature changed their heating habits in relation to changing the radiator valves. It can be hypothesised that they may have continued interacting with the radiator valves to control individual rooms by the fact they still had a relatively large temperature variation between rooms with the new heating controls.

Interestingly with P04 the husband within the household reported that he would never touch the radiator valves after recently having them all upgraded shortly before the first interview for this study. However it was his wife who then admitted that she regularly interacted with the radiator valves stating that if it was a cold day or she felt cold within a room then she would turn the radiator up further. This shows some of the complexity behind multiple occupants within households and how by interviewing only one occupant you may not get the whole picture, especially if they do not know how other occupants use the heating, therefore dependant on who is interviewed it may impact the conclusions taken from the data.

6.5.4.2 Adaptive behaviours

Adaptive behaviours in relation to heating use within homes typically relates to occupants' actions to improve their thermal comfort which does not involve switching the heating on. Within the sample, six households stated to regularly using adaptive behaviours as a first resort before turning their heating on. This was mentioned in reference to use of blankets or additional layers of clothing to increase thermal comfort.

"Put a jumper on, I can't cope with knowing I've got the heating on constant all day. That just seems a really stupid thing to do" *[P02, Interview 1]*

"I would probably put on an extra jumper or sit with a blanket wrapped around me for a certain amount of time, but if it got too much then I would switch the heating on, I think." *[P01, Interview 1]*

"She sits in that front room so she feels the cold, so she's got a blanket down here" *[P09, Interview 3]*

Two of the five households mentioned their previous thermal experience as a reason behind their use of adaptive measures now.

"I've been brought up by parents that live in a freezing cold house, and huddle round the fire" *[P02, Interview 1]*

"There was ice on the window when I was little, so you know, we're all too soft now" *[P07, Interview 1]*

It may be hypothesised then that households with adaptive measures may demand lower set-point temperatures due to this past experience of colder thermal environments. The set-points demanded by the households during the winter months are summarised in Table 6.12. When an independent t-test was carried out on the set-points demanded as part of scheduled heating it was found that a significance of 0.029 (two tailed) was achieved. A 95% confidence interval showed that there was a difference in set-point temperatures between 0.2^{o}C and 3.6^{o}C higher in those households not reporting adaptive behaviours.

Table 6.12 Set-points demanded by households within sample across winter months (Oct-Feb)(bold temperatures refer to scheduled temperatures)

		Set-points demanded by households across winter (Oct-Feb)
Households reporting use of adaptive behaviours	P01	15, **20**, **21**, 22, 23
	P02	16, 17, **18**, **19**, 20, 21
	P04	17, 18, **19**, **20**, 21
	P05	16, **18** (data from mid Oct-mid Nov)
	P07	14, **15**, 16, 17, **18**, 19, 20, 21, 23
	P09	No winter data
	Mean scheduled set-point	19^{o}C
Households not reporting adaptive behaviours	P03	18, 19, **20**, **21**, 22, 23
	P06	20, **21, 22**
	P08	**18**, 20, **21**, 22, 23, 25, 28, 30
	P10	20, 21, 22, 23, 24, 25, 26, 30
	P11	15, **21**, 22, 23, 24
	P12	26, 30 (data only for start of Oct)
	Mean scheduled set-point	21^{o}C

The set-points demanded from set heating schedules are identified by being in bold, with the remaining set-points being those that were manually demanded on top of scheduled heating. When the set-points demanded for programmed heating schedules were analysed it was found that four of the six households who used adaptive measures set lower set-points for their heating schedules compared to the rest of the sample, P02, P04, P05 and P07. However P08 also similarly had a low set-point temperature of 18^{o}C like many of these households but they did not report using adaptive measures as much as other households. Similarly P01 mentioned using adaptive measures regularly however the lowest set-point they demanded was 20^{o}C so slightly higher than other households using adaptive measures.

No connection could be seen between those using adaptive measures and the number of different set-points being demanded across the winter months, with P07 demanding nine different set-point temperatures across winter even though they had the lowest recorded set-point demanded as part of a heating schedule. The small size of the sample will have hindered uncovering whether a strong link between set-point temperatures and those using adaptive behaviours is present within households.

No link was found between the average number of hours of heating or the average internal temperature within the sample and those reporting adaptive measures, except for the two households which reported previous thermal experiences of colder environments impacting their heating use now (PO2 and P07) having the lowest average internal temperature within the sample. However, adaptive behaviours also related to occupants' use of secondary heating instead or in addition to the main heating system use.

6.5.4.3 Secondary heating

Within the sample, only two households mentioned no source of secondary heating within their home. A range of secondary heating sources were reported ranging from gas fires to underfloor heating. The sources of secondary heating within each household are summarised in Table 6.13.

Table 6.13 Sources of secondary heating present within sample households

	Secondary heating sources within households		
P01	Gas fire		
P02	Log burner	Portable oil heater	Fan heater
P03	Log burner	Underfloor heating	
P04	Gas fire		
P05	Gas fire		
P06	Gas fire		
P07	Wood burning stove	Electric fan heater	
P08	Electric panel heater	Electric heater	Gas fire
P09	Electric heaters	Electric fire	
P10	Gas fire		
P11	No secondary heating		
P12	No secondary heating		

Secondary heating use within homes is similar to TRV and radiator use, it can be very specific to one room. Therefore, although possible to infer from internal temperature measurements that it may be getting used, it can also be influenced by solar gains within rooms. This means that it can be extremely difficult to identify with confidence from temperature measurements alone. It was reported in Chapter 5 that secondary heating use was suspected within one of the households on a regular basis due to the internal whole household temperature being higher than the average temperature being recorded by the thermostat itself, however this could also be down to the placement of the thermostat itself. Therefore it is often hard to base assumptions from measurements alone, particularly when some households have secondary heating sources but never or very rarely use them, as reported within Phase 1 of this doctoral research (Chapter 4).

Within the heating diary householders were asked in particular to include any details of secondary heating sources used over the course of the four weeks. Out of the eight diaries completed four reported the use of secondary heating within their homes. One household reported using a separate electric heater every night within their young child's bedroom. Another reported to using their log burner on a particularly chilly evening. The household with the pet hedgehog also reported the use of an electric heater on multiple occasions for the hedgehog so that they did not have to put the heating on in the whole dwelling at the same time. Another household reported using an electric fire on quite a few occasions when feeling cold in the afternoons, again instead of switching the full heating system on.

Households were asked about their use of secondary heating within all three of the interviews to ensure any changes in secondary heating sources was recorded and to see if there was a change in the use of them with the new heating controls. Within the ten households with secondary heating sources, 50% reported only rarely or never using the additional heat sources. Reasons behind not using them included being too noisy, not being connected up or only being seen as an emergency heating source should the main heating system break. The use of secondary heating within the remaining five households varied in type of secondary heating used and the occurrence of use. As previously mentioned, one household used an electric heater in order to keep a pygmy hedgehog warm and not in fact for additional comfort of the occupants. One household, P03, mentioned the use of underfloor heating to provide additional warmth, which had its own thermostatic control and could be used independently to the main central heating system. This household also had a log burner but the occupant reported using it less since the underfloor heating was installed. It was not possible to see if this use changed with the addition of the new heating controls as it was not possible for the household to take part in the final interviews. However it was found within P02 that they used their fan heater regularly when interviewed for the final interview, this was different from the first interview where the occupants reported not using it due to the noise, although it is unclear if this was a new fan heater or if they were simply dealing with the noise now. P08 reported using an electric heater within their kitchen and living room on a daily basis over winter, as there were no radiators from the central heating system within those rooms. P07 reported using a wood burning stove regularly in the evenings over winter, stating use roughly three times a week.

The use of secondary heating can often be hard to determine from internal temperature data alone due to the variation in use and durations of use. Within this study it was possible to look at the internal temperature measurements and the recorded temperatures at the thermostat for the households which reported using secondary heating on a regular basis. By plotting these recorded temperatures as shown in Figure 6.4, obvious peaks above the average thermostat temperature could be taken to be signs of secondary heating use, especially when the average individual room temperatures typically fell below that of the temperature measured by the thermostat.

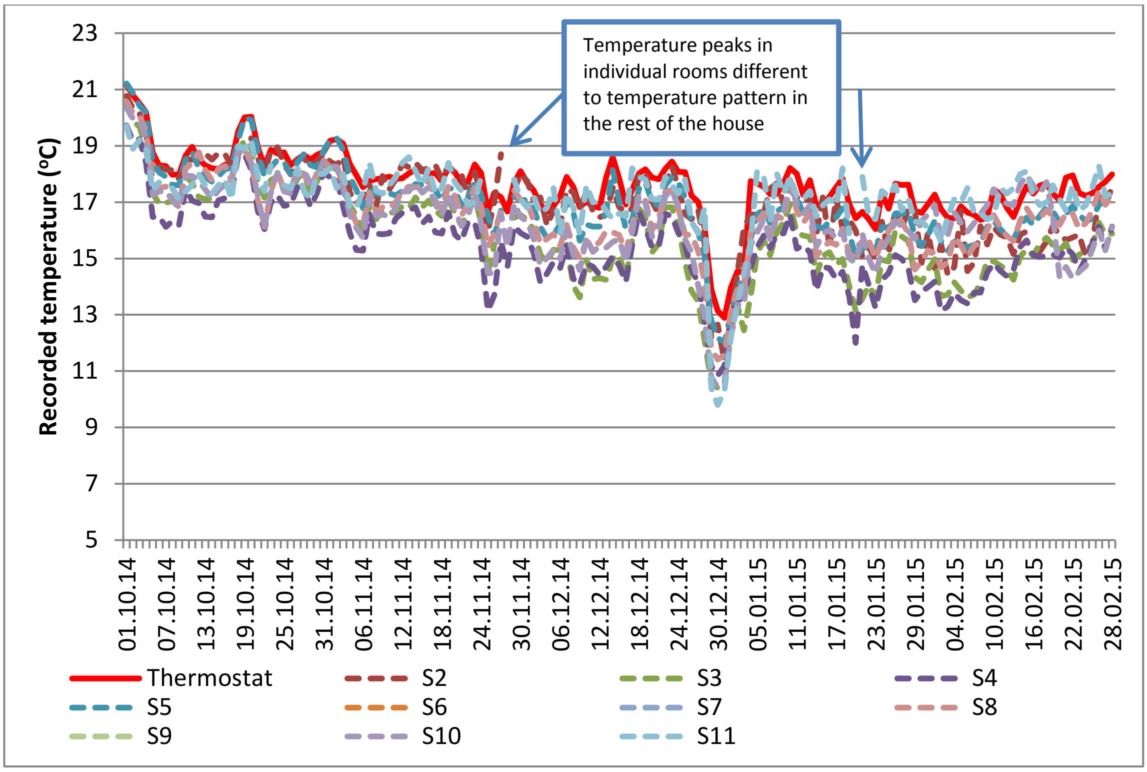


Figure 6.4 Internal temperature trace for P07 indicating peaks in rooms above the average thermostat temperature indicating use of secondary heating

However not all cases are as easy to identify as shown by Figure 6.5 where the plot for P08 shows that the majority of the individual room temperature averages is above that of the thermostat temperature. Evidence of secondary heating can be found within this trace where individual room temperature plots do not match up with the thermostat temperature plot. However these examples are hard to identify unless analysing each individual day separately which can be time consuming in a longitudinal study given the wealth of data, therefore knowing details regarding the level of use of secondary heating sources within homes is beneficial in studies looking at heating use within homes. There is still the added complication of not being able to separate TRV use accurately enough with just internal temperature measurements as differences could be assumed to be secondary heating instead.

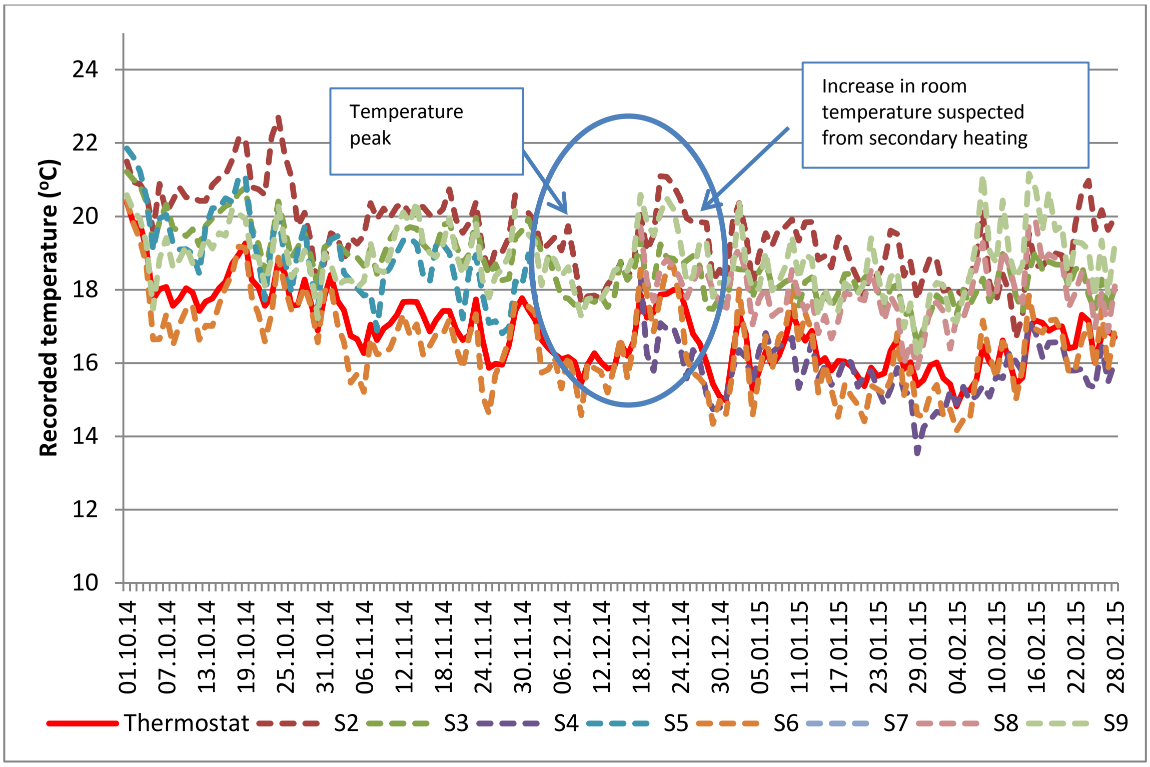


Figure 6.5 Internal temperature trace for individual rooms and thermostat for P08, indicating evidence of peaks within rooms hinting use of secondary heating

6.5.5 Heating user types

During the interviews, occupants were also asked to complete tasks involving the use of the DECC heating user types (Rubens and Knowles, 2013) which were introduced within the literature review chapter and then developed upon within the Phase 1 study of this doctoral research, where occupants' were asked to identify with a heating user type.

The use of the DECC heating user types was a way of understanding more about how the occupants perceived the way in which they used their heating. This was to uncover whether the beliefs occupants had regarding their heating use was different to the measurements recorded. Occupants were shown the five heating user types (Rubens and Knowles, 2013) as character drawings as shown in Figure 6.6 as well as the name given to the user type. Occupants identified which character suited them best before the descriptions of the characters were given and then occupants' had the opportunity to change their mind if they felt a different character suited them better based on the description.

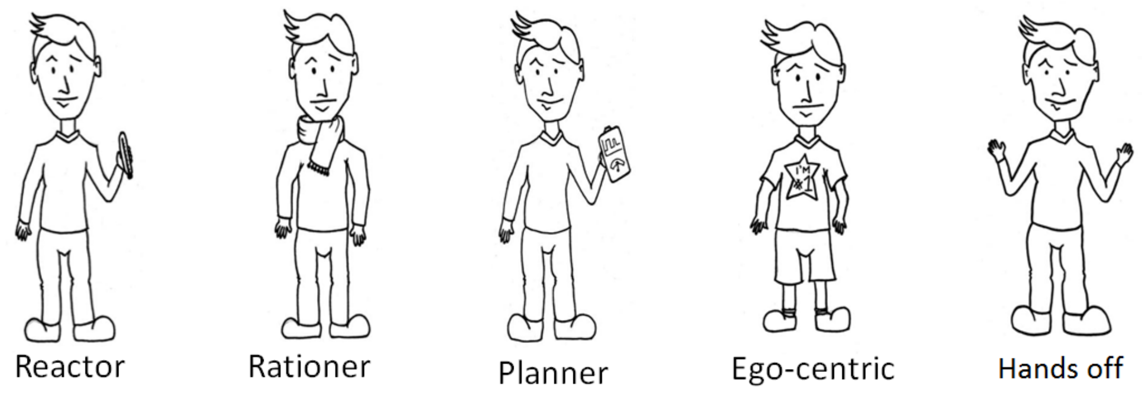


Figure 6.6 Heating user characters presented to households to identify their own user type from

The characters which occupants believed to best suit them once full descriptions of each character were given are summarised within Table 6.14.

Table 6.14 Heating user characters occupants identified themselves to be most like with descriptions given (a double tick represents the main character they identify as being most like them with single ticks representing touches of other characters they think they may be similar to)

	Reactor	Rationer	Planner	Ego-centric	Hands off
P01	✓		✓✓	✓	
P02	✓✓	✓	✓		
P04	✓✓		✓		
P05		✓	✓✓		
P07	✓✓	✓			
P08	✓✓			✓	
P09 M			✓✓		✓✓
P09 F	✓✓				
P10	✓✓				

Out of the eight households only two identified themselves to be best suited to one character (P10, and the wife in P09), the remaining households (and the husband in P09) all identified traits in multiple heating characters which matched their heating behaviours. Seven of the households thought themselves to have qualities of the reactor character, which matches well with the measured heating use of this study, with most households recording various manual interactions with their heating systems on top of scheduled use. By households identifying themselves to have multiple heating character traits it suggests that heating behaviours may be influenced by different situations which may mean one heating character traits are stronger than another and vice versa in a different situation.

Within the sample four of the eight households (P01, P07, P08 and P10) changed their initial impression of which character type related to them once the full descriptions were given. P07 initially saw themselves as being a reactor, however when the descriptions were given they identified themselves as having a touch of a rationer on top of being a reactor. This is similar to the findings found in Phase 1 where participants have characteristics belonging to more than one character or user type. This may be down to priorities changing through seasons and perhaps participants become more comfort driven or even cost driven during the winter season, yet are more relaxed during summer and therefore relate stronger to specific characters depending on the season/situation. However it could also depend on the participants' perception of what the heating use may be like just from the name of the character/user type. Similarly P01 decided that they had elements of other characters as well as their original choice once the descriptions were given. Both P08 and P10 changed their choice of heating character once the descriptions were given. P08 stated themselves to be a planner yet changed to a reactor and ego-centric once they heard the description, which matched the measurements of their heating use within the study.

Interestingly P10 described themselves firstly as a planner as "I just set it and leave it" but changed their choice to a reactor with the description, however based on the descriptions with the user types those who set their heating as desired and then leave it alone would be classified as being hands off. This shows that often occupant's perception of their use of heating doesn't necessarily match up with measurements. Often occupants have the desire to be seen as using energy in a specific way and therefore may have based their initial choice purely on what they felt was the best named user type. It was agreed by many of the households that the names of the user types were misleading, in particular none of them felt comfortable calling themselves an ego-centric person. However the author acknowledges that the character names would most likely not have been presented to the participants within the original research by Rubens and Knowles (2013) and therefore may show participants' desire to be perceived a certain way rather than showing the heating use behaviour without any bias. It does however show that results may vary depending on how much information a participant receives about heating use, drivers and expectations that they are to then try and match their own use with, after all heating use can be very specific to an individual.

6.5.6 Use of combined methods within study

A benefit uncovered within this study from using a mixed method approach was the use of data traces during the final household interviews. Occupants were shown traces from the monitoring data in the form of internal temperatures, set-point temperatures and when the heating was shown to be on. Not only did this give the occupants a sense of receiving some information regarding the temperatures within their homes but it also prompted the occupants to disclose further information. Often during the process of talking occupants through the data traces and overall patterns seen within their homes, they would further divulge reasons behind any unusual spikes within temperature traces or periods of different heating patterns to the rest of the monitoring period. On most occurrences occupants confirmed the researcher's belief that periods of change within temperature patterns related to holidays and as such occupants changing the heating settings for when away from the property. However one household, P10, reported the drop in temperatures to being a fault with their boiler when shown the internal temperature trace for the monitoring period. This fault was due to the boiler breaking and a leak being found however it was only noticeable within the temperature traces. The heating controls themselves did not show any difference as it was still recording the heating controls to be on all the time, as no changes had been made to the controls even though the boiler was not working properly. It was only when the boiler was being fixed, over a week later that the data received from the controls showed a change within the heating use as the plumber switched them off when fixing the boiler. This shows the benefits of having multiple data sources within a study which covers both a quantitative and qualitative nature and the importance of not relying solely on one method of data collection.

By comparing both qualitative and quantitative data sources within this study it could be seen that on the majority of occasions the reported heating behaviours matched up with the measured data. Any differences noticed within the heating diary and measured data was down to manual interactions not being recorded, however this may be due to occupants being unaware of their actions as often adjustments to heating settings can be instinctive or the heating diary may have been kept in a location that meant participants may forget to note down every interaction.

6.6 Discussion

The aim of this study was to uncover a rich insight into measured heating use in homes by collecting qualitative data on heating use, to understand why occupants use their heating system a specific way. The main drivers behind heating use in homes identified from the interview data were individual comfort desires, young children, pets, the household dynamics and health; these agree with those reported by Rathouse & Young (2004) and Wei et al. (2014). This longitudinal study uncovered that occupants' priorities in relation to heating use can change over time. At the start of the study, 60% of households identified comfort as the main priority towards heating use, with 27% of households stating cost. At the final interview, comfort as the main priority had increased to 80% of the sample, with cost decreasing to 10% of the sample. Although health was ranked the lowest priority overall, the findings of this study highlighted the impact poor health can have on heating use. One participant reported being ill for a few weeks over the winter period and at the time could not get warm, therefore demanded a set-point temperature of 30^{o}C on multiple occasions and left their heating on for long durations. Ill health can significantly impact heating use over a few weeks and so it is important to understand the reasons behind household heating use to explain periods of more unusual heating use, and confirm that it is not the normal heating use behaviour of that household. Consideration also needs to be taken as to when investigations into occupant heating behaviours are undertaken as part of a longitudinal study; a single snapshot in a small sample may over or under-represent particular conditions.

The change in inherent priorities within some households may have an influence on the energy saving potential claimed for new technology. For instance when new heating controls are installed, changes in heating use may be attributed to the new technology but may actually relate to changes in household priorities. A household may reduce their energy use due to the change in circumstances, not due to the new controls. The energy use reduction may get linked to the impact of the new heating controls if the change in priorities is not known, which would only be uncovered using a mixed-method approach.

This study found that installing new heating controls led some householders to change their heating use through higher or lower demanded set-point temperatures, different durations of heating periods or in some cases, different methods of controlling their heating use. One of the households changed their heating use behaviour by going from a demand-only use to scheduled use of the heating with the new controls. Although no other studies, that the author is aware of, have previously studied the impact on heating use from installing new heating controls, many have inferred heating use patterns from internal temperature measurements (Kane, 2015, Huebner et al, 2013) However, if this study looked at the impact of new heating controls based on temperature measurements alone, then the new controls may be seen as having no impact on the heating use within homes, as internal temperatures before and after the new controls remained similar. However, the qualitative data collected by this study found that many households had changed their heating use behaviour following the new controls, including changes to how they controlled their heating with the additional remote access, changes to the set-point temperature being demanded and changes to the heating schedules programmed with the new controls. Therefore the use of both qualitative and quantitative measurements within this study has shown that the new controls have impacted heating use behaviours, if not average temperatures. This suggests that previous studies which have looked at heating use patterns based on internal temperature measurements alone may have missed some of the finer changes in heating use, and the reasons for these changes, as the achieved average comfortable temperature within the home may remain the same.

This study found lower demanded set-point temperatures for heating schedules within households who reported using adaptive methods (similar to those reported by Karjalainen, 2009) actively within their home, such as additional clothing layers or use of blankets rather than switching the heating on. This study found a difference in set-point temperatures of between 0.2-3.6^{o}C higher in households not reporting use of adaptive behaviours, indicating that, not only do some participants adjust clothing or use windows to achieve comfort instead of adjusting the heating, they are also likely to set their heating set-point temperature lower. For two households, a link was found between their adaptive behaviours due to previous thermal experiences and having the lowest internal temperature averages. However, further investigation of a wider sample is needed to determine if there is a trend within households with adaptive measures and lower demand set-point temperatures. These findings do give an indication that to reduce energy use within the domestic sector, higher energy savings may be yielded if those not reporting adaptive behaviours are targeted, as those households are likely to be demanding higher set-point temperatures and more prone to switching their heating on whenever they get cold. Introducing ‘learning’ thermostats into these non-adaptive households may mean that energy savings are found, as long as the occupants do not manually override the learning controls.

This study managed to uncover previously unreported findings. It was found that households with children, which are often identified as a driving factor towards heating use, had lower average internal whole house temperatures. This was an unexpected finding. This study also found households which reported using TRVs and manual radiator valves to control the thermal environment of separate spaces had measurements of higher variation between individual room temperatures, which would be expected. The study has observed that there are complications relating to how use of manual radiator valves and TRVs can be measured accurately within longitudinal heating use studies, due to intermittent use and identifying the best interval periods for measurements that would identify any changes in use. There is also the added complexity that the room temperatures will be influenced by the size and efficiency of the radiator in relation to floor area of the room, as well as valve use. It is recognised that in such a small sample these findings may well be idiosyncratic of this particular sample and so further investigation on a larger scale is needed.

Understanding an accurate representation of heating use in homes can be complicated by problems with monitoring heating use and occupants' reporting of their heating use. Although occupants may want to be seen as being energy efficient and want to conform to certain social norms, heating use is often an everyday action and something which could be habitual. As such, occupants may be unaware of how often they are interacting with the controls. The use of the controls, especially to improve thermal comfort, is often in response to physical sensations or their activity levels (such as sitting at a computer for a long period of time) and, as such, occupants may not realise their level of interaction with the controls. This was seen in this study by some participants reporting being surprised (once presented with data traces) at just how often they manually interacted with the heating controls. However, besides the manual interactions with the controls, this study did find that the reported use of heating regarding the set-point temperatures they demanded and heating schedules they programmed well mirrored the measured heating use.

Two households in the sample decided to sell their properties before the end of the study and a further participant rented out their property shortly after the start of the winter monitoring season. Maintaining cohorts in longitudinal studies can involve difficulties, due to people moving, change of surnames, divorce or separation and many other everyday life events. Lee et al (2000) suggests various methods to avoid losing participants by ensuring updated contact details are kept with participants, use of secondary contacts, newsletters, media coverage and reminders to ensure that participants remember they are part of the study and giving email addresses and contact numbers to participants to use should they need to notify the study of any changes, and many of these things were done in this study. It must also be taken into consideration that the occupancy of households may change over any monitoring period; this study had two households where one or more of the occupants moved out during the monitoring period, and another household which had a baby during the study. Another major consideration in a longitudinal study is that any qualitative measurements can be seen as essentially providing only a “snap-shot” of attitudes, beliefs and actions at that point in time and, as shown within this study, occupants can have a change in priorities over the course of a study. Therefore the timing of these measurements needs to be considered within the project planning stage and adjusted to suit individual circumstances. Therefore, as shown with this study, when a longitudinal focus is taken it is worth considering some of these additional complexities by allowing more time to carry out additional data collection if needed.

The combination of qualitative and quantitative data in this study has added to the understanding of the complexities of heating use behaviour. The additional understanding regarding changes in priorities relating to heating use, occupants' understanding and perception of their own heating use, use of hard to measure heating actions such as TRV use, secondary heating use or adaptive measures, and the impact that new heating controls have on heating use behaviours has been presented. The combination of methods can often back up each other when one measurement fails to capture issues such as faults or lack of awareness of occupants' own everyday actions. This additional understanding highlights the complexity of heating use but also the benefit of combined research methods to understand heating behaviour.

Chapter 7: Conclusions, Implications and Future work

This chapter summarises the key findings from both phases of the research in the context of the aims and objectives introduced in Chapter 1. The chapter also discusses the implications of the research findings in a wider context and what they may mean. The limitations of the research and its approach are detailed before presenting recommendations for future work.

7.1 Thesis aim and objectives

The overall aim of this doctoral research was:

To examine household space heating use and to identify the reasons behind heating use in UK homes.

To achieve the aim, seven research objectives were identified (Chapter 1, Section 1.3). Objective 1 was addressed by conducting an in-depth literature review, presented in Chapter 2. Objective 2 was achieved by the Phase 1 study, a qualitative-focused exploratory study on how people use their heating in homes and the reasons for it, presented in Chapter 4. Objective 3 was to develop a taxonomy of heating use characteristics, presented in Chapter 4, Section 4.6. Objective 4 was achieved by the Phase 2 study, presented in Chapter 5, an explorative study, using both qualitative and quantitative methods, to gain in-depth understanding of heating use in a small sample of homes. Chapter 5 also presented the analysis of the seasonal evolution of heating use, meeting Objective 5. Chapter 6 presented the benefits of using mixed methods in relation to heating use within the domestic sector, addressing Objective 6. This chapter is designed to meet Objective 7, evaluating the outcomes and implications of the research findings.

7.2 Thesis methodology and limitations

This thesis has described two separate studies investigating heating use in two samples of UK homes. The first study involved qualitative interviews with 30 households to gain insights into how occupants use their heating, what they use to heat their homes and the reasons behind why they heat their homes a specific way. The second study involved quantitative measurements of heating use within a sample of 12 households with new heating controls over a period of ten months. The measurements were enriched by combining them with qualitative interview data and a heating use diary, to uncover how people use their heating and provided understanding of the reasons behind the heating use, further developing the understanding from the Phase 1 findings.

As with all research, there are limitations to what can be achieved due to factors such as cost, time and resources. The major limitation within this doctoral research was the sample size and location for both studies, meaning the results are not representative to the wider UK population. Therefore the findings of this research may be specific to the sample or the area studied.

Within each phase of this doctoral research, an honest critique of the methods used was given within the relevant chapters. The majority of the qualitative data collected came from interviews so it meant the author was reliant on self-reported behaviour. The interviews also represented the householder but perhaps not the household. This means a detailed picture of different household members' interactions with heating controls may not have been achieved. Phase 1 was based on one interview per household and therefore was a "snap-shot" of heating use and drivers and may be subject to change such as the shift in heating use priorities shown by Phase 2. The Phase 2 research involved carrying out measurements in homes and was therefore subject to equipment faults, battery lifespans, changes in occupants' circumstances and difficulties maintaining a cohort. Although some of these factors were unforeseen, they still needed to be taken into consideration when analysing the data and therefore some analysis had to be carried out using a subset of the sample.

7.3 Key Outcomes and Contribution to Knowledge

Conclusions on the outcomes from this research are outlined within this section by highlighting the key findings and, as such, contributions to knowledge in the area of heating use within homes. The main contributions are summarised below:

- development of a new heating use taxonomy which considered the drivers influencing heating use and heating use characteristics, resulting in ten heating characters which identify how different influences impact heating use in homes. These heating characters provide a framework to understand more about different heating use behaviours and how specific heating use technologies or policies could be targeted to those heating characters most relevant;
- heating use in homes is not always down to occupant preference as some homes are restricted in their use due to the usability/accessibility of controls and some have to rely on workaround solutions if the whole or part of the heating system is broken. This may stop these occupants from being able to achieve a comfortable environment and they may also be unable to carry out any energy saving advice such as reducing their set-point temperature by one degree or setting a heating schedule to control heating use, which means reducing energy used on space heating in these homes may be more difficult;
- even when households are not restricted in their use of heating controls and even with the same heating control, heating use varies in relation to heating schedules, set-point temperatures, level of manual interaction and the use of the heating controls. This shows we cannot rely on assumptions which presume heating use is consistent across households, in particular if trying to estimate energy use or potential savings from technologies or policies;
- heating use priorities can change over time due to changes in household circumstances which could impact the energy used by a household. This raises concerns over whether the impact of a new technology or policy can be based on simply the energy used before and after installation, as there may be subtle changes within a household which also impact on the household’s use of energy due to changes in their heating use priorities;
- the level of manual interaction with controls (to boost heating, override schedules, increase/decrease set-point temperature or to turn off) varied massively across households, however in the majority of households the level of manual interaction increased during winter months showing that

occupants interact with heating controls a lot more than previously expected and that they tend to override heating schedules almost on a daily basis which has an impact on energy model assumptions, previous research and new technologies that assume predominant scheduled heating patterns;

- lower set-point temperatures were demanded in households using adaptive measures, indicating that some households are unlikely to make energy savings from new controls if they are already utilising adaptive measures instead of additional heating use. This suggests that targeting specific heating user characteristics (and building on the heating taxonomy framework) may result in a better potential for energy savings as advice and/or technology is targeted to those who will be most responsive to it.

7.4 Implications of research findings

The findings from this doctoral research have provided insight into heating use in homes with emphasis on what it is that people do, how people heat their homes and why they use their heating in specific ways. The findings have shown that heating use in homes is extremely complex, with insights presented which may have been missed by other studies. The outcomes highlighted in Section 7.3 have implications on the wider research area and include potential impacts to government policy for heating and energy use within the domestic sector, potential impact to control manufacturers and heating control installers and, finally, impact on academic research in this area.

7.4.1 Implications for government policy

Two key findings of this research could have implications for government policy on heating/energy use in homes: firstly, the heating patterns found in this research and how they compare with current energy model assumptions used by, for example, SAP to generate EPCs; and secondly, the restrictions to heating systems that limited households in their use of heating. The findings from both studies showed heating use in households to be extremely varied with regards to the set-point temperatures and heating schedules. Energy model assumptions, in particular the UK government's SAP model, includes one set-point temperature for all heating periods, two periods of heating a day and different heating schedules for weekends and weekdays. This research showed that set-point temperatures were changed frequently over the winter season. It also found different set-points being used for morning and evening heating periods, as well as some households keeping the same heating schedule for weekdays and weekends, going against the current assumptions. The differences observed in this research to the current energy model assumptions will have an impact on the predicted energy calculations from the models, with the potential for overestimating or underestimating the energy savings from different space heating interventions. This could impact the reported savings from rollouts of specific energy saving technologies or retrofit options, as a large difference between expected energy use and actual use following the intervention may be found. The addition of heating controls options into households is currently rewarded in SAP calculations, with more controls (boiler controls, thermostat, TRVs etc.) resulting in a reduced energy consumption estimate and therefore a better EPC rating. However, as shown by this research even when households do have multiple control options they may chose not to use all of them or not use them as designed. For instance although householders may have the option to programme their heating to come on/off at specific times, they may prefer to use it as they need to and not set any heating schedule, which may result in longer heating periods and higher energy consumption. As this research found, often households who have a "full" set of heating controls could be restricted in their use of all heating control options due to accessibility and usability problems. The way occupants use the heating control options available to them could mean that space heating energy could be much higher or lower compared to the modelled assumptions and therefore a house which uses their heating system wastefully could still have a higher EPC score just because all heating control options are present in the household, and therefore would have a larger gap between predicted energy use and actual energy use. Given this research also showed that when households are all given the same controls, they can still have vastly different heating use characteristics, it begs the question of whether just adding heating controls to a household should result in a better SAP score as it does not guarantee the household will use them in the way they are expected to be used.

Energy performance certificates and energy saving calculations are also based on an assumption that the existing heating system is working correctly to begin with. The research findings identified that a number of householders were dealing with heating systems that did not work appropriately and often occupants have adapted to using workarounds in response to this. This will have an impact on the expected energy savings from any energy improvement measure carried out within that property. Some participants reported that fixing parts of their heating system was expensive and they would rather wait until they have no choice but to pay once it breaks completely. Given the fact that there are people currently living with broken heating systems, it does raise the question of why there is no funding available to fix these problems given there are numerous funding sources for installing energy efficiency measures. In particular it raises the question of whether new policies which can provide financial support towards achieving a working heating system are needed, especially given that occupants often believe that repairing part-working systems is too costly and therefore prefer to use workaround solutions until the full system breaks. Therefore, policy on heating use within homes should focus on fixing the existing problems. Without fixing these problems surely we are simply wasting money by installing new controls when the heating system is not working correctly. By fixing problems, not only would this result in more homes being warmer, reduce issues with damp in some homes, it could also reduce energy bills for those relying on secondary heating sources.

7.4.2 Implications for heating control manufacturers and installers

A number of problems were identified from this research relating to use of heating controls which could have implications on control manufacturers and heating control installers. Some households reported current controls being inaccessible to them or that the use of the controls themselves were overly complicated or difficult to use due to poor design. The design of heating control interfaces is extremely varied and, as such, this adds further complications to occupants being able to understand new controls. Participants with the new heating controls in this research reported that changing settings on the controls was not always clear, due to a confusing clock design, multiple menu screens to change a heating schedule and a lack of confirmation that changes had been saved. Control manufacturers may want to consider shortcuts for occupants to use for changing heating settings, given that often occupants struggle with multiple menu options and numerous screens to get to the setting they want to change. This impacts the likelihood of occupants changing these settings again. Occupants may be more likely to manually override heating schedules if the process to change the programmed heating schedule is time consuming or too complicated to remember. Ultimately, occupants want to be able to control their heating in a quick and straightforward way. The heating use taxonomy developed as part of this research could be used to aid the design of new heating controls so that controls could be tailored to suit the needs of different heating characters. Many people may be impressed by the latest fancy controller that has in-built functions to meet every possible action on a heating system; however in reality occupants may only use it on a demands basis. New heating control technology may be designed not only to provide comfort but also to be used in a specific way which achieves energy savings. However if these new controls are installed in a home where the occupants are unaware of their designed use or choose to use them differently, then the controls are never going to have the potential impact on energy savings. Therefore control manufacturers need to consider how they engage the consumer so that firstly they realise all of the capabilities of this new technology and how to use it, but secondly they can relate to how these capabilities can fit with individual lifestyles, so that there is an increase in the uptake of these new technologies. Given that this research found that occupants often did not realise how often they were interacting with the controls on a daily basis, control manufacturers could design helpful tips or suggestions which pop up on the screen after a certain number of manual interactions which gives feedback on the level of manual changes making occupants aware of how often they are interacting with their heating system which could result in them making changes to the heating settings to reduce the number of manual interactions needed.

Control manufacturers and installers need to consider that the location of heating controls can have a direct impact on whether occupants use that control as a method for controlling the heating system. This research found that many heating controls were either located somewhere occupants felt was not ideal, such as hallways or close to large radiators or they were installed in an inaccessible location. Installers should take into consideration occupants' needs and lifestyle when considering the location of heating controls, and should not simply resort to the 'norm'. The correct location of controls could help save energy used on space heating by reflecting the true temperature of the house (or most commonly used space) and therefore may not signal for the boiler to fire as often. It may also encourage occupants to change the settings on their heating controls in a way which could reduce their energy use. However, what happens when someone else moves into that house and the control locations do not meet the new occupants' heating use needs? This could mean that the controls may not get used as designed if a new owner feels the location is inconvenient. The development of wireless thermostats and remote access options may help overcome a lot of these problems. However, portable thermostats typically need to be charged via a mains connected base and, as such, occupants may have to put them close to a power source and not where they would ideally want them. Additionally some may want the controls to be wall mounted so control manufacturers may need to start catering for the needs of both, with a control that could be wall mounted and portable, therefore ensuring that they meet the needs of the range of users.

7.4.3 Implications for academia

This doctoral research also has implications for academia, as it has shown that, to fully appreciate the complexities of heating use in homes, there is a need for interdisciplinary methods. Understanding the 'how, what and why' in relation to the heating use helps to uncover the true picture of why heating is being used a specific way and what the implication may be on energy savings due to the reasons behind occupants' heating behaviours. There is added value in measuring heating use directly rather than inferring actions/patterns from other measurements. This was shown by the level of changes made to set-point temperatures and heating schedules over winter by the majority of the sample, previously unreported. By simply inferring patterns of use from internal temperature measurements, this level of detail and understanding of actual heating use is lost. Studies need to directly measure occupants' use and move away from use of proxies or assumptions on behaviour and patterns of use. Interacting with heating controls can be an everyday action and often habitual and therefore measuring this interaction may be the only way to truly discover the extent of the interaction with heating controls. However, this has implications on interdisciplinary academic research, as the time, possible limitations or complications involved with measuring, additional resources, maintaining participants, and the cost of gaining this level of detail, all need to be taken into account in planning, budgeting and execution of such projects.

7.4.4 Summary of implications

The research presented in this thesis has shown that heating use in homes is extremely varied with regards to how the heating system is used within a home, what occupants use to provide heat within their home and the reasons behind why people heat their home a specific way. Even when households are unrestricted in their use of heating and even with the same heating controls present, heating use patterns are still highly varied. Understanding more about the occupant and their heating use drivers is vital to determine how the heating is used in homes and to identify effective ways to reduce the energy used for space heating. The heating use taxonomy shows that heating use can be categorised by influential factors. The heating use behaviour likely to be expected by these characters can then be identified allowing policies, advice or technology to be targeted to those best suited. New technology and improved controls will only have the impact expected if heating systems are working effectively and if occupants are aware of how to use them efficiently and choose to do so. Therefore, more needs to be done to ensure that people have working heating systems within their home and that clear consistent information regarding efficient use of heating systems/controls is given to households. Ultimately, dwellings vary significantly, heating systems are extremely varied and people have very different expectations of heating systems which means that the task of reducing energy used on space heating is extremely complex. By better understanding occupants' needs and their preferential heating behaviours, we can start to move away from a 'one solution fits all' philosophy and begin to target specific heating use behaviours in order to reduce energy used for space heating.

7.5 Future work

Suggestions for further work, to build on this research and enhance the knowledge within this area, include:

- further development and testing of the heating characters developed within the taxonomy on a larger sample and in different locations in the UK, and combine with use of measured data to determine heating use behaviours likely for each heating character;
- comparison of a wider sample of households with similar controls/heating systems to determine whether use of specific controls/heating systems are driven more by the occupant or the technology.
- further investigation of the extent and nature of restricted heating systems;
- exploration of the use of secondary heating, including appropriate measurements, resulting temperature changes and reasons for its use.

Chapter 8: References

This chapter contains all references from literature sources which are referred to within all sections of this thesis.

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Chapter 9: Appendices

This chapter contains additional resources, information and detailed results which may be of further interest to the reader.

Appendix 4-A: Call script and screening questions

<u>Call script and screening questions</u>

[Receive name and daytime contact number]

Hi is that **Mr/Mrs/Miss [X]**, hi this is Ashley from Loughborough University. Thank you for phoning to show interest in taking part in the domestic heating use study. I am just phoning to see if you would still like to take part and if there is any additional information you would like about it?

This study is being carried out to understand more about how people use their heating within their homes and the reasons behind using it a particular way. To do this you will be asked to take part in one interview which will ask questions revolving around the use of your heating. The interview itself should take no longer than a maximum of 40 minutes and it can take place in your home.

Would it be possible to ask a few quick questions now to help see what type of household characteristics are showing interest in the study?

Thank you.

1. Firstly could you tell me where it was that you heard about this study (just so we can see the most successful method)?
2. And what type of dwelling is it that you live in?
3. How many people live within the household?
4. Finally what type of heating do you have within your home? (gas central heating, electric, storage heaters etc.)

That's brilliant thank you. Now if I could take your full address and an idea of when would be best for yourself for me to come and carry out the interview?

[ADDRESS – check location]

[Date – within diary book time slot of 1 hour]

Thanks again **Mr/Mrs/Miss [X]** for agreeing to take part in the study and I shall see you on **[Day at Time]** at **[Address]**

Appendix 4-B: Final interview script

How do people actually heat their homes and why?

<u>Interview script</u>

Thank you for agreeing to be interviewed as part of my PhD study. The main structure of this interview will be focused around the use of heating within your home and the reasons behind the way you use it. The aim of this study is to uncover the variety in use of heating systems and the reasons and drivers behind those heating habits. To help identify if there are any trends within similar households I shall also ask you to complete a short questionnaire at the end of the interview which should only take you a few minutes.

All information you provide during this interview shall be anonymised and in no way identifiable to anyone other than myself, however if there are any questions you do not want to answer then please simply say and I shall move on. I would also like to check you are ok for this interview to be audio recorded?

Household – *To start I would like to know some facts about your household and its occupants to help identify trends in heating use with similar households.*

1. Would you say you have a set pattern for your daily routine? – *if yes probe about when in/out?*
2. Would you say any of the other household members have set daily routine patterns?
3. How are weekdays different to weekends for your household?

Dwelling – *And now a few questions regarding your actual home*

4. Do you rent or own the home?
5. [If Renting] Is heating included within the rent?
6. Within your home are there any particular rooms which are used more often than others? – *which ones?*

Heading use – *Thank you, now I would like to move on to talk about your heating use in more detail*

7. What is your primary source of heating within your home? (Gas, Electric, Other)
8. Which of the following control devices do you have within your home – thermostat, timer, thermostatic radiator valves (TRVs)?
9. Were your heating controls here when you moved here? If not what have you changed, why and when?
10. Would you consider your home to be warm enough during winter?
11. Are there some parts of your home which seem warmer or cooler than others? *[If yes – ask for detail as to where and how much of a difference they think there is – is it only during certain times of day or during certain seasons?]*
12. Do you heat all rooms equally? If not how do the rooms differ? – *does this reflect different needs across the different rooms?*
13. How do you tend to adjust your heating within your home? – *do you use radiator valves, manual thermostat, digital thermostat/timer, secondary heating?*
14. When you heat your home what factors are the most important to you? – *young children, pets*
15. What, if any, would you say are your main priorities in relation to heating your home? – *cost, comfort, health*
16. [If thermostat is present] Do you change settings on your thermostat often?

    What makes you change the settings?

    What is it you tend to change – boost, on/off, set-point temperature? (Does location of thermostat influence level of interaction?) Are there any functions on the thermostat which you do not use? (probe understanding) – anything that is unclear/confusing?
17. What about radiator settings – do you change these often? Are the radiator settings different between rooms? Ask when and why/why not – stiff, understanding, usability, numbers on it?
18. [If thermostat is present] Do all members of the household interact with the thermostat to change settings or is it only certain members? If so who is likely to change settings? Is there ever arguments regarding the heating

within your home? Is there an ideal temperature you tend to have the thermostat on?

19. Do you have any other sources of heating within your home aside from the main heating system? How often do you use these? Are they used only by particular household members?
20. When you are feeling uncomfortably cold within the dwelling what actions do you tend to carry out to feel more comfortable?
21. Similarly when you are feeling uncomfortably hot within the dwelling what actions do you tend to do?
22. Do you ever regulate the temperature of rooms or the whole dwelling by opening windows? If so how often?
23. Do you use your heating for any other reasons aside from providing warmth?
24. Do you have any frustrations or worries regarding your heating system?
25. How satisfied are you with your heating system and meeting your heating needs?
26. Do you regularly check your gas/electricity use?
27. How do you tend to pay your energy bills? *(Direct debit, prepayment, bills on arrival)*
28. Finally do you happen to know or have access to your typical gas/electricity consumption? (monthly/annual)
29. To what extent would you say cost plays a part in how you heat your home?
30. What, if anything, do you currently do to minimise your spending on heating?
31. Finally is there anything else you would like to mention about your heating system or how you use it?

Thank you again for participating in this interview and for your thoughtful contributions

Appendix 4-C: Participant information sheet and consent form

How do people actually heat their homes and why?

Participant Information Sheet

Main Investigator: **Miss Ashley Morton**,
Department of Civil and Building Engineering,
Loughborough University, LE11 3TU, UK,
A.Morton@lboro.ac.uk, Tel +44 (0)1509 223728
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V.J.Haines@lboro.ac.uk, Tel +44 (0)1509 226915
Dr David Allinson,
Department of Civil and Building Engineering,
Loughborough University, LE11 3TU,
D.Allinson@lboro.ac.uk, Tel +44 (0)1509 223643

What is the purpose of the study?

This study will collect information about how people use their heating at home, through use of an interview. The interview shall be focused on how participants heat their homes and the reasons behind their heating habits. The study forms part of a PhD research project.

Who is doing this research and why?

This study is being conducted by Ashley Morton, a PhD student at Loughborough University, who is part of the LoLo Centre for Doctoral Training in Energy Demand Reduction within the Built Environment.

Are there any exclusion criteria?

Only people over 18 can take part in these interviews.

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have, you shall be asked to complete an Informed Consent Form, however if at any time, before, during or after the session you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

How long will it take?

The interview should last around 20 – 30 minutes, no longer than 40 minutes maximum.

What will I be asked to do?

At the beginning of the interview you shall be asked to fill in a consent form to say you agree to take part and at the end there is a short questionnaire to complete about yourself and your home. During the interview you will be asked questions on the topic of heating in your own home and your heating habits.

What personal information will be required from me?

A short questionnaire shall be used to gather some information about you including your gender, age, employment status and some information regarding your home. This information shall only be used to describe the types of people within the sample of interviews and shall not be passed onto anyone other the main investigator. No information that identifies you individually will be released to anyone else.

Will my taking part in this study be kept confidential?

Your participation with this interview shall be confidential. You will be assigned a code number so that no one taking part is identifiable to anybody.

What will happen to the results of the study?

The answers received during the interview shall be used to help inform a larger study about how people control their heating at home. All responses given during the interview shall be kept anonymous. The researcher will audio record the interview to help with transcribing your responses to the interview questions, but this audio recording shall not be heard by anyone else aside from the main investigator and supervisors listed on this sheet.

What do I get for participating?

Unfortunately it is not possible to give participants any token of gratitude for taking part in the interview.

I have some more questions who should I contact?

If you have any questions relating to the interview then please do not hesitate to contact the main investigator Ashley Morton at any time.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Mrs Zoe Stockdale, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Mrs Z Stockdale, Research Office, Rutland Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email:Z.C.Stockdale@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Loughborough University

How do people actually heat their homes and why?

INFORMED CONSENT FORM

(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Approvals (Human Participants) Sub-Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name ____

Your signature ____

Signature of investigator ____

Date ____

Appendix 4-D: Questionnaire

How do people actually heat their homes and why?

Household Demographic Questionnaire

The following questions will be used to look for similar heating use across different categories. All answers will be kept annoynomous and be treated with the strictest confidence.

1. Can you identify all members of your household in the following table (an example is given)

	Name	Age	Gender	Employment Status
Eg.	Sally	43	F	Part time
1				
2				
3				
4				
5				
6				

2. What is the total household income?

Weekly		Annual	
Up to £99 □	£500 up to £599 □	Up to £5,199 □	£26,000 up to £31,199 □
£100 up to £199 □	£600 up to £699 □	£5,200 up to £10,399 □	£31,200 up to £36,399 □
£200 up to £299 □	£700 up to £999 □	£10,400 up to £15,599 □	£36,400 up to £51,999 □
£300 up to £399 □	£1000 and above □	£15,600 up to £20,799 □	£52,000 and above □
£400 up to £499 □		£20,800 up to £25,999 □	

3. How long have you lived in the property?

____

4. In what year was the property built?

____

5. Could you mark on the following scale how you generally feel within your home during winter;

Hot | Warm | Slightly warm | Neutral | Slightly cool | Cool | Cold

6. This project shall be carrying out other similar studies in future, would you like to be sent information regarding these and if so tick the type of study you would be happy to take part in;

YES, happy to participate again ☐ **NO**, please leave me out of future studies ☐

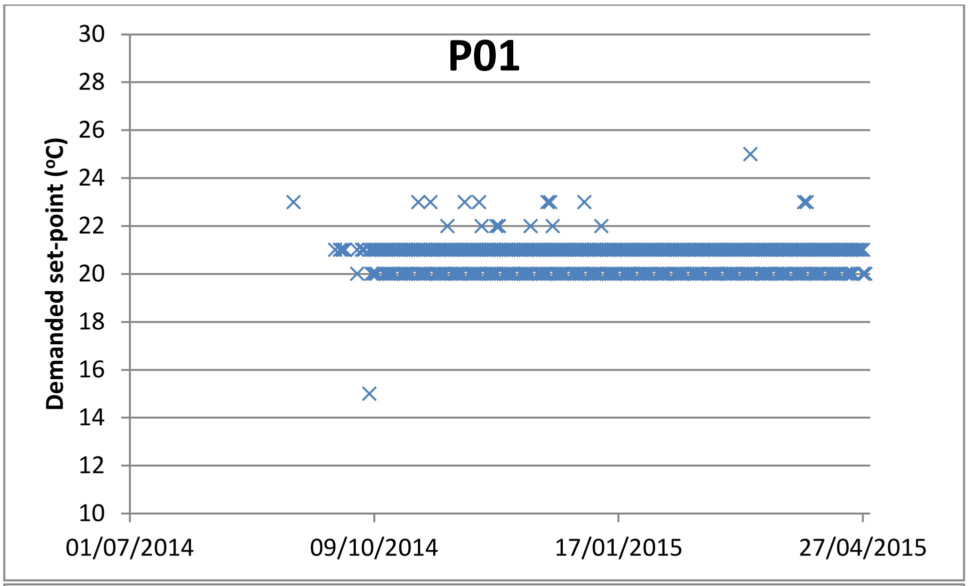
If **YES**; Face to Face interviews ☐, Telephone interview ☐, Questionnaire ☐, Online survey ☐, Energy monitoring study (where equipment would be installed in your home) ☐

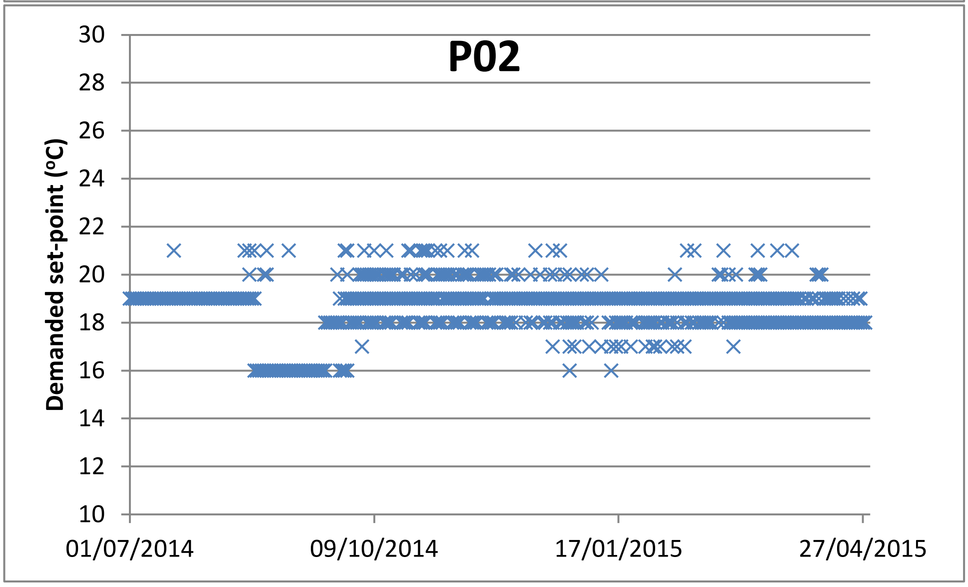
Appendix 5-A: Test house experiments schedule

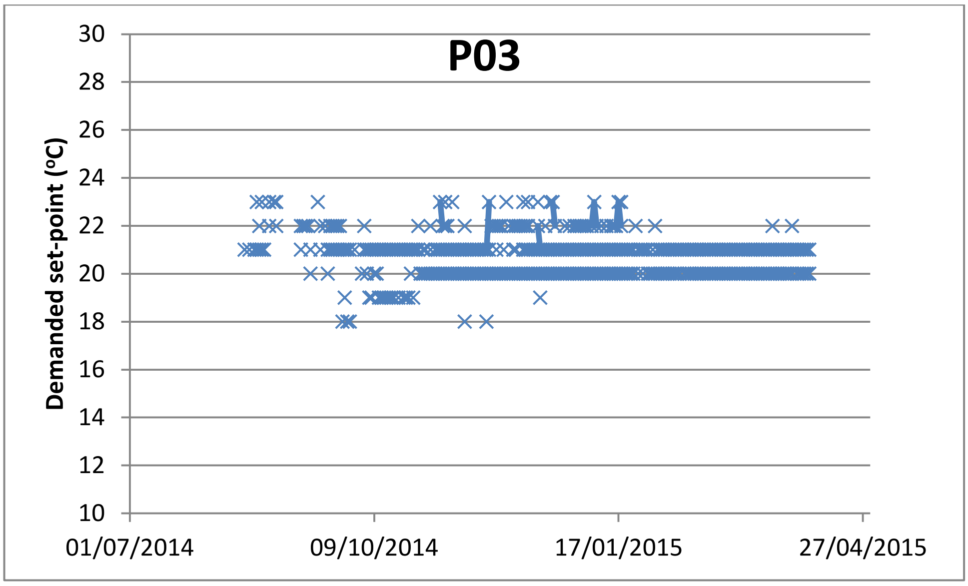
Date	Time	Set schedule	Manual interaction	Remote access
28/05/14	15.38	6.30am - 8.30am at 22°C, evening 5.30pm - 11pm at 22°C		
30/05/14			Morning set-point lowered to 18°C	
02/06/14	12.45		Accidently switched to auto	
		Set to 'HOLIDAY' mode for 3rd-5th		
06/06/14		Issue with boiler so testing paused		
07/06/14		Boiler lost pressure again		
09/06/14		Switching experiment to different test house		
13/06/14		Weekday 7am-8am at 22°C 6pm-10pm at 24°C, Weekend 9am-11am at 22°C, 4pm - 10pm at 22°C		
19/06/14	8.30			App registration
	8.32			Set to 21°C via app
	10.30			App checked back on AUTO not ON at 21°C
	10.45			Switched to 'ON'
	12.21			Switched back to 'AUTO'
20/06/14	11.15			Switched to 'ON'
	13.00			Switched back to 'AUTO'
23/06/14	14.25			Heating switched 'ON' and turned up to 23°C
				App switched on/off/on in space of around 20s
		Left switched on until evening to see if schedule works		
	20.45			Switched off via app
24/06/14	9.16-9.20	Schedule Mon - Sun 23°C during 7am-9am, 7pm-10pm		
	15.03			Set to AUTO
26/06/14	8.40			Deleted schedule
		Schedule set to 23°C		Set schedule via app

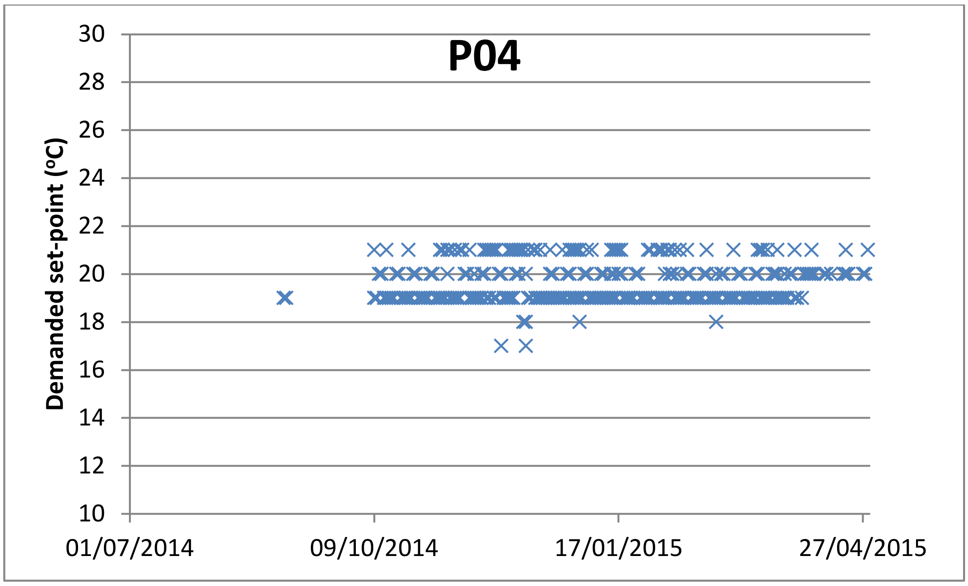
		6.40am - 8am, 4.40pm - 9.30pm		
		Message on app of "no current schedule"		
02/07/14		Schedule showed day setting Weds 6.45am - 8.45am, 4.30pm - 10pm at 22^{o}C		
	9am	Switched on, 21^{o}C		
	9.20am	Switched back to AUTO		
	9.25am		Changed economy temp to 18^{o}C	
03/07/14	7.40pm			Halo switched "OFF"
	8.51pm			Switched back to 'AUTO'
04/07/14	10.30am	Switched to "OFF" - goes to 5^{o}C		
			Changed to 12^{o}C whilst set to OFF"	
	13.34		Frost protection set to 12^{o}C	
	13.46	Switched to OFF		
	14.00		Heating programmes "reset"	

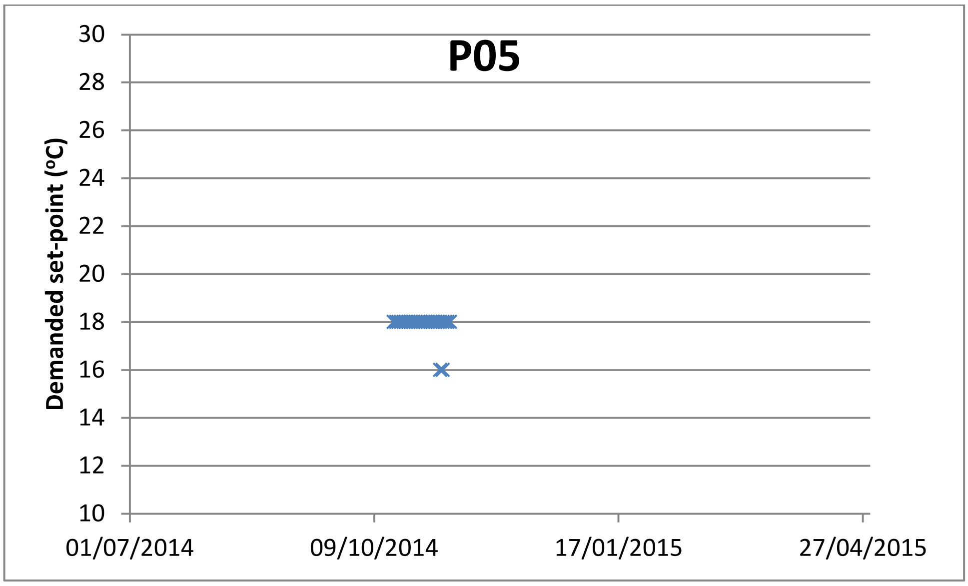
Appendix 5-B: Demanded set-point temperatures across sample

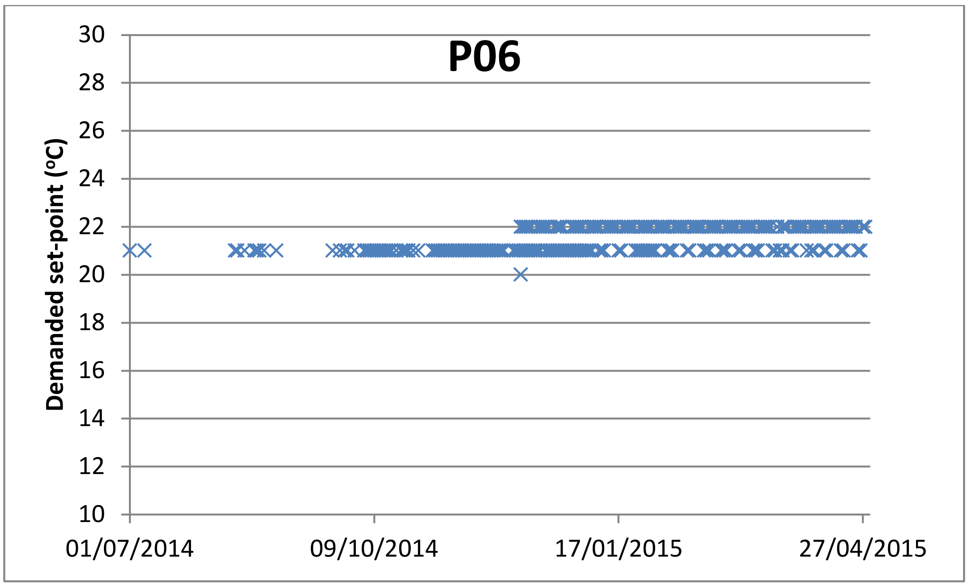







P04
Demanded set-point (ºC)
30
28
26
24
22
20
18
16
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P05
Demanded set-point (ºC)
30
28
26
24
22
20
18
16
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P06
Demanded set-point (ºC)
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22
20
18
16
14
12
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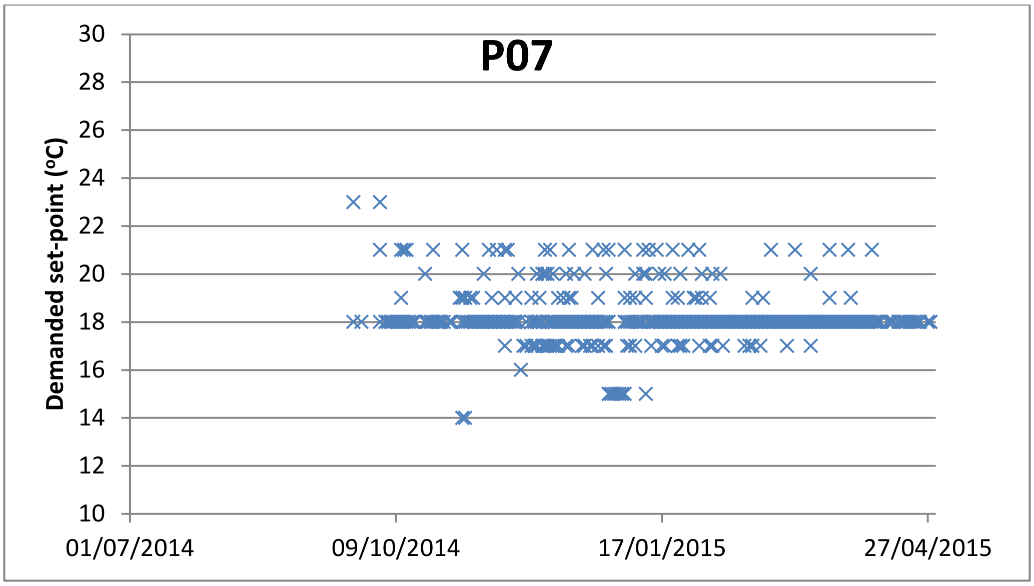
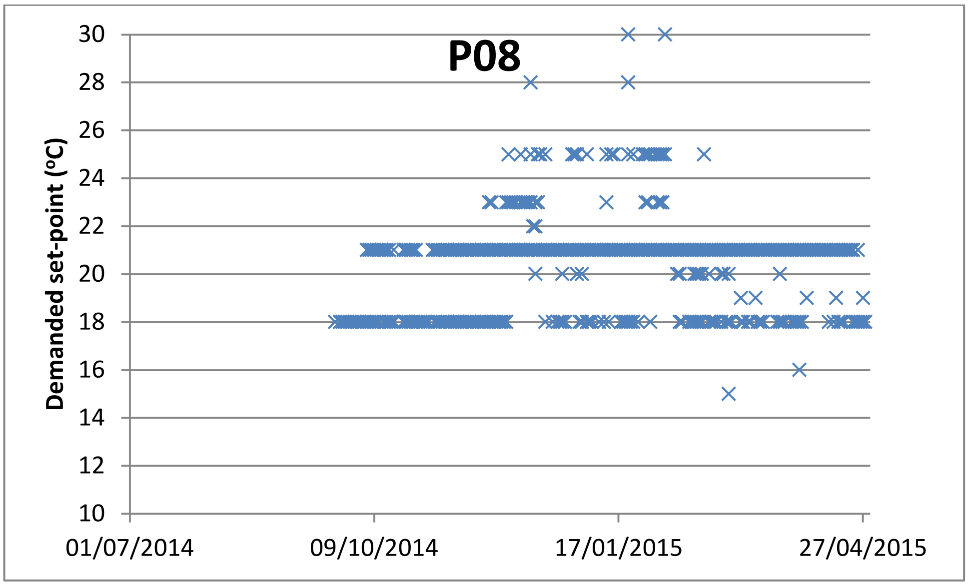
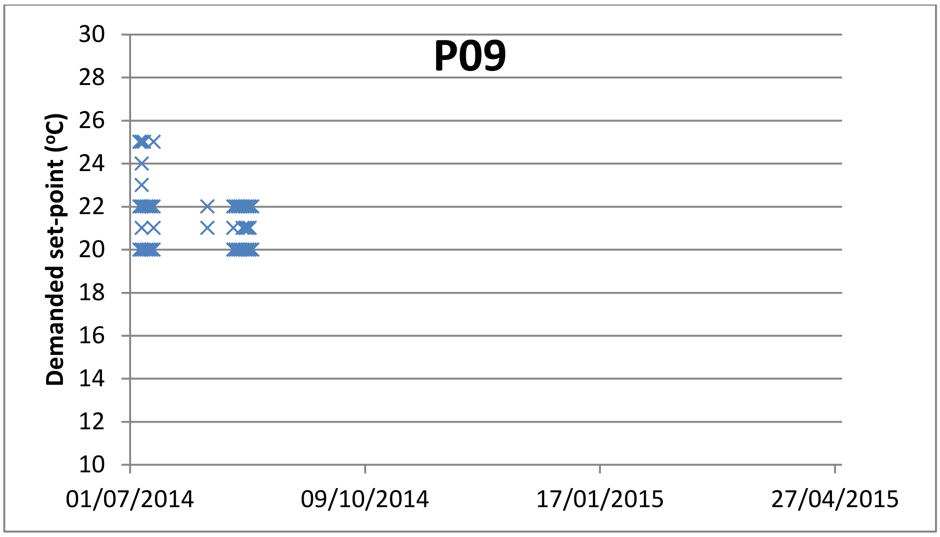
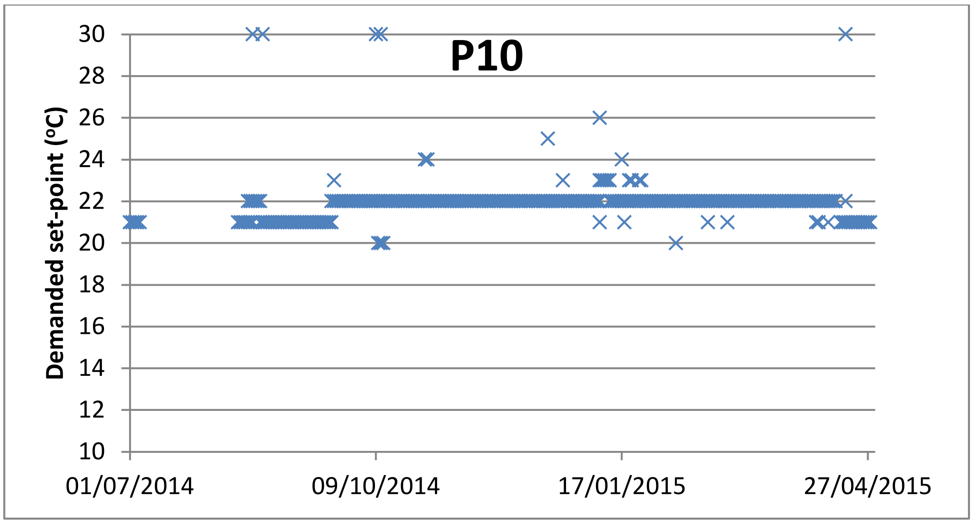
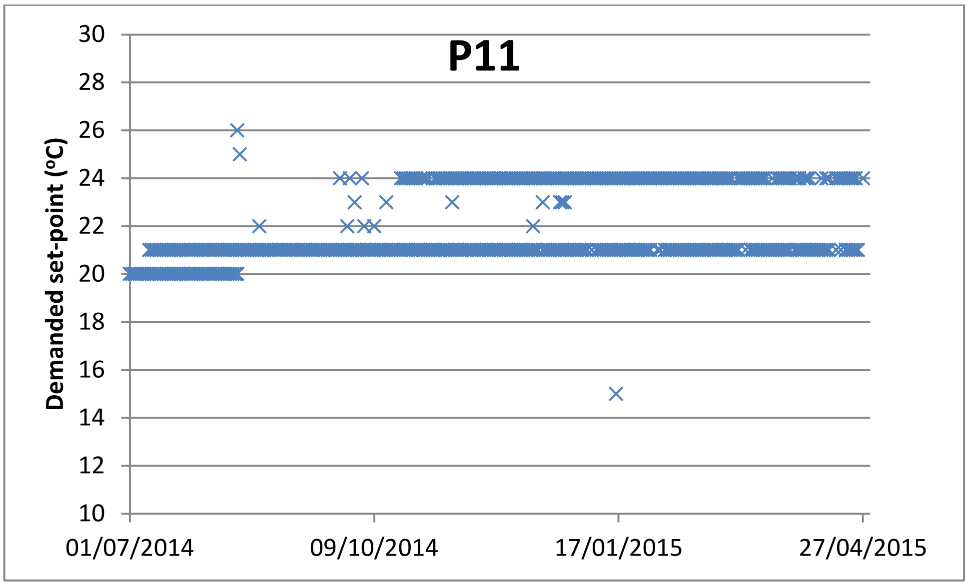
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P07
Demanded set-point (ºC)
30
28
26
24
22
20
18
16
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P08
Demanded set-point (ºC)
30
28
26
24
22
20
18
16
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P09
Demanded set-point (ºC)
30
28
26
24
22
20
18
16
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P10
Demanded set-point (ºC)
30
28
26
24
22
20
18
16
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P11
Demanded set-point (ºC)
30
28
26
24
22
20
18
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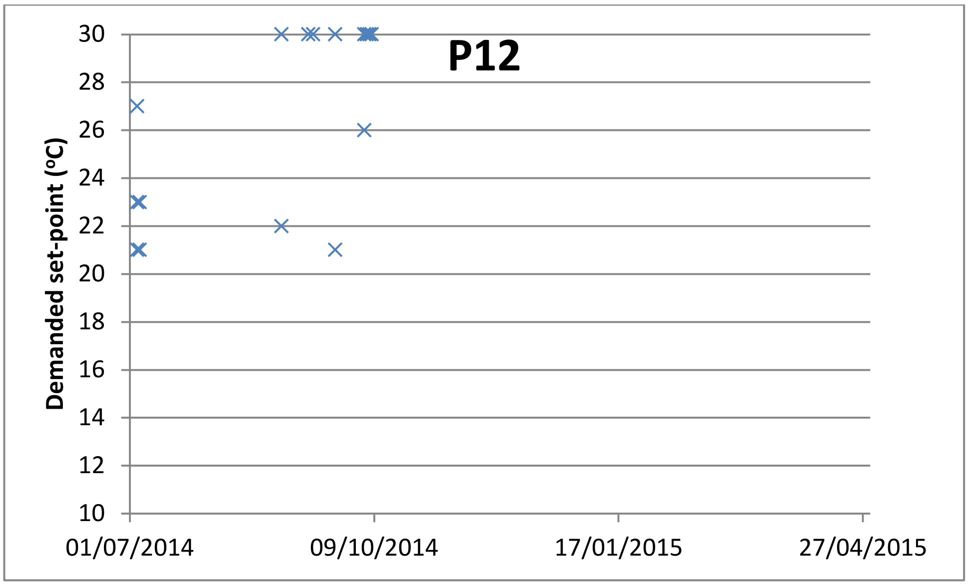
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015


P12
Demanded set-point (ºC)
30
28
26
24
22
20
18
16
14
12
10
01/07/2014
09/10/2014
17/01/2015
27/04/2015

Appendix 5-C: Summary of Advance data files for households

P01 Advance

	Frequency	Percent	Cumulative Percent
.00	54011	61.1	61.1
5.00	29514	33.4	94.5
21.00	4048	4.6	99.1
22.00	480	.5	99.6
23.00	355	.4	100.0
24.00	1	.0	100.0
25.00	3	.0	100.0
Total	88412	100.0	

P02 Advance

	Frequency	Percent	Cumulative Percent
0	74455	88.0	88.0
5	334	.4	88.4
11	6	.0	88.4
12	2	.0	88.4
13	1	.0	88.4
16	57	.1	88.5
17	702	.8	89.3
18	3325	3.9	93.2
19	4128	4.9	98.1
20	1178	1.4	99.5
21	403	.5	100.0
22	2	.0	100.0
Total	84593	100.0	

P03 Advance

	Frequency	Percent	Cumulative Percent
0	22153	53.0	53.0
4	1	.0	53.0
5	14084	33.7	86.7
6	1	.0	86.8
10	85	.2	87.0
11	1	.0	87.0
12	1	.0	87.0
16	4	.0	87.0
17	136	.3	87.3
18	315	.8	88.0
19	109	.3	88.3
20	878	2.1	90.4
21	2119	5.1	95.5
22	1561	3.7	99.2
23	323	.8	100.0
24	3	.0	100.0
Total	41774	100.0	

P04 Advance

	Frequency	Percent	Cumulative Percent
0	27704	58.0	58.0
3	2	.0	58.0
5	8890	18.6	76.6
6	76	.2	76.8
10	23	.0	76.8
13	2	.0	76.8
16	1	.0	76.8
17	41	.1	76.9
18	416	.9	77.8
19	4689	9.8	87.6
20	948	2.0	89.6
21	4969	10.4	100.0
29	1	.0	100.0
Total	47762	100.0	

P05 Advance

	Frequency	Percent	Cumulative Percent
.00	3635	100.0	100.0

P06 Advance

	Frequency	Percent	Cumulative Percent
0	30329	47.6	47.6
5	24850	39.0	86.5
21	8588	13.5	100.0
Total	63767	100.0	

P07 Advance

	Frequency	Percent	Cumulative Percent
0	32500	52.4	52.4
5	24140	39.0	91.4
7	1	.0	91.4
11	1	.0	91.4
16	8	.0	91.4
17	1859	3.0	94.4
18	2910	4.7	99.1
19	400	.6	99.8
20	57	.1	99.8
21	89	.1	100.0
22	3	.0	100.0
23	1	.0	100.0
29	1	.0	100.0
Total	61970	100.0	

P08 Advance

	Frequency	Percent	Cumulative Percent
.00	43055	46.0	46.0
5.00	28221	30.2	76.2
11.00	16	.0	76.2
15.00	37	.0	76.2
16.00	25	.0	76.2
17.00	5	.0	76.2
18.00	4787	5.1	81.4
19.00	411	.4	81.8
20.00	894	1.0	82.8
21.00	12962	13.8	96.6
22.00	103	.1	96.7
23.00	1100	1.2	97.9
24.00	27	.0	97.9
25.00	1856	2.0	99.9
26.00	2	.0	99.9
27.00	1	.0	99.9
28.00	55	.1	100.0
29.00	3	.0	100.0
30.00	33	.0	100.0
Total	93593	100.0	

P09 Advance

	Frequency	Percent	Cumulative Percent
0	2491	20.3	20.3
5	9280	75.5	95.8
21	381	3.1	98.9
22	106	.9	99.7
23	6	.0	99.8
24	7	.1	99.8
25	17	.1	100.0
26	1	.0	100.0
30	1	.0	100.0
Total	12290	100.0	

P10 Advance

	Frequency	Valid Percent	Cumulative Percent
0	213	.3	.3
5	9590	11.2	11.5
18	1	.0	11.5
20	425	.5	12.0
21	15358	18.0	29.9
22	57844	67.7	97.6
23	1566	1.8	99.4
24	362	.4	99.9
25	50	.1	99.9
26	3	.0	99.9
27	2	.0	99.9
28	1	.0	99.9
29	1	.0	99.9
30	66	.1	100.0
Total	85483	100.0	

P11 Advance

	Frequency	Percent	Cumulative Percent
0	32663	92.4	92.4
10	1665	4.7	97.2
11	1	.0	97.2
15	75	.2	97.4
18	41	.1	97.5
21	353	1.0	98.5
22	1	.0	98.5
23	264	.7	99.2
24	233	.7	99.9
25	4	.0	99.9
26	32	.1	100.0
30	1	.0	100.0
Total	35333	100.0	

P12 Advance

	Frequency	Percent	Cumulative Percent
0	4	.0	.0
5	17453	97.7	97.7
19	1	.0	97.7
21	80	.4	98.2
22	2	.0	98.2
23	42	.2	98.4
24	1	.0	98.4
25	1	.0	98.4
26	32	.2	98.6
27	10	.1	98.6
28	1	.0	98.7
30	241	1.3	100.0
Total	17869	100.0	

Appendix 6-A: All three interview scripts used in Phase 2 (highlighted questions relate to those of interest to this doctoral research)

Go Digital Household Interview 1

1) How do you tend to heat your home?
2) Are you able to heat your home to how you want it?
    a. Why not?
3) In an ideal world, how would you heat your home?
    a. Why don't you do that?
4) How often do you adjust something on your heating?
    a. Less than once a day
    b. Once a day
    c. Twice a day
    d. More than twice a day

……

……

5) Do you have a?
    a. Thermostat: Y/N
    b. Programmer: Y/N
    c. TRVs: Y/N

……

……

6) Which of these do you mainly use to adjust your heating?
    a. Is this on a daily/weekly basis or over the course of a year
    b. Why do you use one method over another?

……

……

7) How often to do you use each of the following to adjust your heating?
    a. Thermostat
        a. How do you use the thermostat to control your heating?
        b. Who does this?

c. Do you have specific temperature(s) which you set the thermostat to? [Day/night/weekend]
d. What is the minimum temperature you set the thermostat to?

………

………

b. Programmer
   a. How do you use the programmer to control your heating?
   b. What times does it go on/off?
   c. Who does this?

………

………

c. TRVs
   a. Do you use all/some/none of the TRVS
   b. When do you use them? Why?
   c. Under what circumstances would you use the TRVS rather than the programmer or thermostat?

………

………

8) Who in your household usually controls the heating?
   a. Do people within your household differ in opinion over the heating
   b. In what way?

………

………

9) What do you do with your heating system when you go on holiday or away for a few days?

………

………

10) How do you decide when to turn the heating off after the winter?

....

....

11) Do you use any other ways of heating your home (apart from central heating)?
   a. Where?
   b. When? (all the time or just when the heating isn't on?)
   c. What?

....

....

12) Are there any room which you don't use? (Or use less)
   a. Do you heat these rooms differently?

....

....

13) Rank the following in terms of priority for heating within the home:

- Cost
- Comfort
- Health

....

....

14) How would you draw your heating pattern routines?

00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23

If hot water tank, draw hot water heating

00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23

15) What is the typical occupancy pattern in your household?
   a. On a weekday

00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23

b. At a weekend

00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23

16) How well do you feel you know how to use:

a. Your thermostat?

[Participant looks at crib sheet and interviewer marks on sheet. Mark if participants have different answers]

Not at all confident	Not very confident	Neither confident nor unconfident	Somewhat confident	Very confident
1	2	3	4	5

b. Your programmer

Not at all confident	Not very confident	Neither confident nor unconfident	Somewhat confident	Very confident
1	2	3	4	5

c. Your TRVS

Not at all confident	Not very confident	Neither confident nor unconfident	Somewhat confident	Very confident
1	2	3	4	5

17) What is your opinion of the new types of thermostats and smart heating controls such as those you may have seen advertised on the TV?

………

………

18) Do you use this kind of personal smart technology for anything else?

a. What sort of thing? (e.g. Mobile banking, Interactive TV etc.)

………

………

Scenario task 1

I'm now going to give you a number of scenarios and after each one please explain the actions you would take and your reasons for this.

1) You have been away for the weekend, you get home and the house is cold – what do you do?

………

………

2) You're working at home for the day – you don't want to be cold, what would you do?

………

………

3) You want part of your house to be cool and another part warm – how would you do that?

………

………

4) The heating is on but it's warm outside, what would you do?

………

………

Scenario task 2

I am now going to ask you some questions relating specifically to the way your heating system works, please describe what you think happens when you take the following actions – using the magnets where applicable."

1) Firstly, can you explain the elements of your heating system so we can map them out

Now can you describe how you would carry out the following tasks [and then explain how you think the system works]

1) If you adjust the heating up to 22°C (through the thermostat)
2) If you turn the heating off (using the boiler controls)
3) If you want to increase the temperature in one room (through the TRV)
4) If the heating is on and you turn the shower on (What happens to the heating in this instance?)

Questions

15) Do you think the temperature of the thermostat has an effect on the speed at which the house heats up?

………

………

16) Do you think the temperature of the radiators differs depending on the thermostat temperature?

………

………

17) Do you think the output of the boiler differs at all depending on the thermostat temperature?

………

………

18) Are there any other factors which you think affect the way in which your house heats up?

……

……

19) Do you think it is most efficient to:
   a. Keep your heating on low all day
   b. Turn your heating on and off at different times throughout the day?
   c. Use your heating on a demand basis (i.e. when you feel cold)

……

……

……

Is that how you heat your home?

……

……

……

Scenario task 3 (filmed)

I would now like you to show us how you would perform the following tasks with your heating system, I will film you completing the tasks, but only your hand and the system will be in the shot.

1) Adjust your heating so that it is at 22°C in your home
   a. How easy was that task to perform?

Difficult	Somewhat difficult	Neither easy nor difficult	Relatively easy	Easy
1	2	3	4	5

2) Set the heating to come on between 6-8am and 7-9pm

Difficult	Somewhat difficult	Neither easy nor difficult	Relatively easy	Easy
1	2	3	4	5

3) Adjust your heating to ensure the temperature in the house doesn't drop below 15°C

Difficult	Somewhat difficult	Neither easy nor difficult	Relatively easy	Easy
1	2	3	4	5

Questions

20) Have you ever attempted to do something with your heating controller which you were not able to do?
    a. What?
    b. Why weren't you able to do this?
    c. Have you since been able to do this?

....

....

....

Meter readings

Gas supplier: ____________________

Gas Meter reading: ____________________ Photograph taken? ☐

Gas Meter Serial number: ____________________

Meter Point Reference Number [MPRN] ____________________

Electricity supplier: ____________________

Electricity Meter reading: ____________________ Photograph taken? ☐

Electricity Meter Serial no.: ____________________

Gas Meter signed consent ☐

House map

House map drawn?: ☐

Energy Bills

Photographs of energy bills taken?: ☐

Photos of controls taken? ☐

Data loggers

Number of data loggers used: ☐

Data logger positioned noted? ☐

Number of i-buttons used: ☐

Survey

Survey collected?: ☐

Go Digital Second Household Interview

Firstly, thank you for allowing us to come and visit you again. This shouldn't take more than an hour, and similarly to the first visit we would like to ask you some questions and ask you to perform some tasks with your heating system. There are no right or wrong answers; we are just really interested in your thoughts.

We won't be able to give specific advice or instructions on the use of your system as the study is interested in seeing how people get on with the system and use it but all of your queries should be answered in the manual and if not, there is a helpline.

Firstly, I would like you to answer the first few questions on the installation of your new heating controls.

1) How did you find the installation of the controls?

____

____

   a. What were you told at installation by the installer?

____

____

   b. Did the installer talk you through using the controls at all?

____

____

   c. Is there anything else you have liked to have been told at the time of installation?

____

2) Did you play around with the controls much when you first had them installed?

3) Did you read the instruction manual when the controls were installed?

a. Was this useful?

b. Was there anything information which you couldn't find?

c. Do you have any general feedback on this instruction manual?

4) Following the installation of your new heating controls, do you think this will/has change the way you heat your home? (if so in what way?)

5) In the previous interview you suggested that you tend to adjust your heating by [ ] do you think your new controls will change the way you use your heating at all?

6) Has the new system changed who controls the heating? Or do you think it will when you start using your heating more?

7) Have you used the app to control your heating or hot water?

   a. What did you use it for?

   b. Who else has/hasn't used it?

   c. How many people in your house have downloaded the app?

   d. Do you find you are using this more than the controls?

   e. Do you feel it will make you more likely to adjust something on your heating?

8) How confident are you in the use of your new heating controls?

[Participant looks at crib sheet and interviewer marks on sheet. Mark if participants have different answers]

Not at all confident	Not very confident	Neither confident nor unconfident	Somewhat confident	Very confident
1	2	3	4	5

f. What would help to make you more confident?

9) Have you tried to do anything with the new heating controls which you were not able to do?

g. What was this?

h. Why weren't you able to do this?

i. Did you work out how to do it?

10) Are there any terms used in/on the controls that you don't understand or any pictures/buttons/icons which you find confusing?

j. How would you prefer them to be referred to?

11) In general, what do you think of the system as a physical product? Size, shape, ease of use etc.?

12) Thinking back to when you were using your heating, did you ever put your heating on for a short time outside of the times you've set your heating to come on? What would you call this?

13) Could you define what the following terms mean to you?

k. Boost

l. Advance

m. Set-point

n. Frost protection

o. Auto

p. Economy

14) If HW – How do you find using the new controls for your hot water?

q. Did you have any issues setting up the schedule?

r. Did you change your schedule to how you had it previously?

____

____

s. Do you use the boost function, and if so how often?

____

____

15) Do you think the way you heat or use the space in your home will change at all with the new system?

____

____

16) You originally said that you were [ ] about this new type of technology, has your opinion changed at all now that you have had it installed?

____

____

t. What do you like about the new controls currently?

____

____

u. Do you have any concerns regarding the new controls for using your heating when it gets colder?

____

____

17) Have you used any other ways of heating your house over the summer months?

d. How often? (Less than once a day, once a day, twice a day, more?)

e. Where?

f. When? (all the time or just when the heating isn't on?)

g. What?

h. What was the reason for needing to heat the house?

18) With the new system, so you think it is more efficient to:

a. Keep your heating on low all day

b. Turn your heating on and off at different times throughout the day?

c. Use your heating on a demand basis (i.e. when you feel cold)

19) Do you think the new system will make your heading use more efficient?

____

____

Heading system map

You will remember that in the last interview, we asked you to help us map out your heating system. We would now like to explore this is a little more detail.

v. Could you choose the elements of your new heating system from these magnets and arrange them on the board and name them
w. Could you draw the links between the components and explain what your thought process is?
x. Please can you describe (and draw on the diagram) what happens when:
    i. You turn the thermostat temperature up (on the control)
    ii. You use the app to adjust the temperature
    iii. You adjust a TRV
    iv. You use hot water

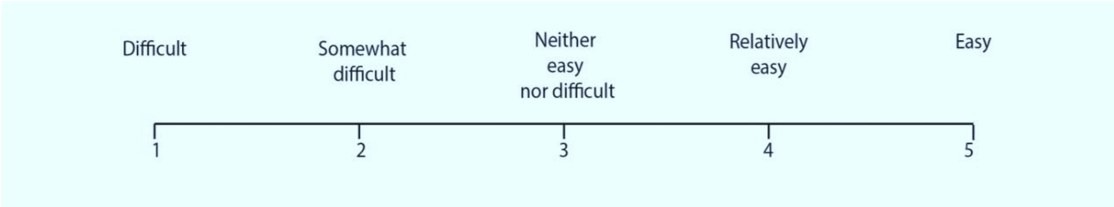
20) Have the new controls changed your understanding/perception of the way the heating system works?

____

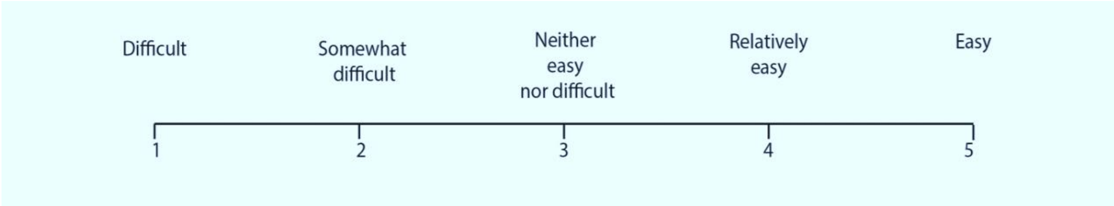
____

I would now like you to show us how you would perform the following tasks with your new heating controls, I will film you completing the tasks, but only your hand and the system will be in the shot.

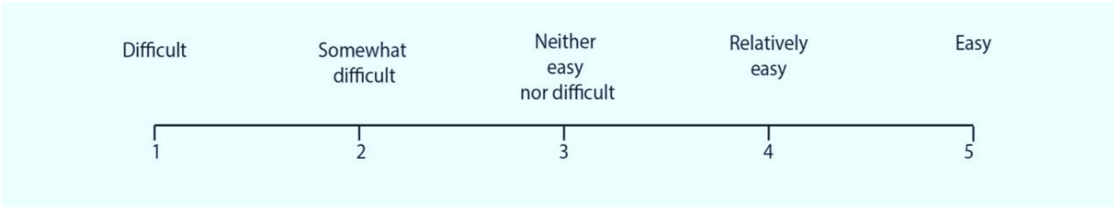
4) Adjust your heating so that it is at 22°C in your home
    a. How easy was that task to perform?



5) Set the heating to come on between 6-8am and 7-9pm



6) Adjust your heating to ensure the temperature in the house doesn't drop below 15°C



That is all of the questions that we would like to ask you, what we would now like to do is:

- *Have you had to move any of the sensors?*
- *Check that you are willing to continue being part of this study which requires a further household activity and interview. These additional requirements are explained in the provided information sheet and you will be compensated for this extra involvement.*
- *Ask if you would be interested in/willing to have a Green Deal Assessment (worth up to £150)*

That's about all for today, thank you so much again for taking part in the study and for allowing us to come to your house this evening.

Third Household Interview

Introduction

Firstly I'd like to thank you for your continued participation and for allowing me to come and visit you again. This shouldn't take more than an hour, and similar to previous visits I would like to ask you some questions regarding your heating system and how you are getting on with the new controls. Just to remind you there are no right or wrong answers to us, we are just really interested in your thoughts and how you are getting on with the controls

I would also like to check with you that you are happy with this interview being audio recorded?

Since I'm going to ask you some questions about how you and the rest of your household use your heating please answer with the things that you do and the things you know other people do in your house.

Interview Questions

1) Have you been able to use your heating fine over the winter?
   a) Have there been any issues?
   b) Are you able to heat your house to how you want it?
   c) Why not?

2) Has anything been changed on your heating system since the new controls?

3) Now that you have had the controls over a winter what is your opinion of them?
   a) How has that changed from when you first had them installed

4) How often do you adjust something on your heating?
   a) Less than once a day
   b) Once a day
   c) Twice a day
   d) More than twice a day

5) What is it that you tend to adjust?
   a) Does this happen regularly?
   b) What tends to happen to make you adjust something?
   c) Would you say that how often you adjust something is dependent on what month it is?
   d) Why do you use one method over another?

6) I'm now going to ask you in a bit more detail about how you adjust your heating.
   a) Thermostat
      i) How do you use the thermostat to control your heating?
      ii) Do you have specific temperature(s) which you set the thermostat to? [Day/night/weekend]
      iii) What is the minimum temperature you set the thermostat to?
      iv) What is the maximum temperature you set the thermostat to?

   b) Programmer (AUTO function)
      i) How do you use the programmer to control your heating?
      ii) What have you scheduled it to come on at?
      iii) Has this changed from what you had it programmed to before the new controls?
      iv) Have you changed the schedule at all through winter?
         Why was this?

   c) TRVs
      i) Did you adjust the TRVS over winter?
      ii) Why was that?
      iii) In what rooms did you adjust them?
      iv) How often did you adjust them over winter?
      v) Who tended to adjust them?
      vi) Under what circumstances would you use the TRVS rather than the programmer or thermostat?
7) If HW programming also – how do you tend to control your hot water using the new controls?
   a) When have you scheduled it to come on at (if applicable)
   b) At what setting is it set to?
   c) Have you changed this over winter?
   d) Did you have any issues setting it up how you wanted?

8) How well do you feel you know how to use the Halo controls?
   a) Do you feel you know how to use the programmer function with ease?
   b) Do you feel that you can change the following using the controls;
      i) Different schedules for weekdays and weekend?
      ii) Different temperatures for different heating time settings?
      iii) Put the heating onto holiday mode?
      iv) Change the frost protection temperature?

9) Who in your household usually controls the heating?
   a) Do people within your household differ in opinion over the heating
   b) In what way?
   c) Has the new controls changed who controls the heating at all?

10) What do you do with your heating system when you go on holiday or away for a few days?
   a) What did you change on the controls?

11) Over winter did you or anybody else use any other ways of heating your house besides from the Halo controls?
   a) Where?
   b) When? (all the time or just when the heating isn't on?)
   c) What?

12) Have you used the app at all to control your heating over winter?
   a) What did you use it to do?
   b) How often have you used it?
   c) Who tends to use the app?
   d) Did you have any difficulties in using the app?
   e) Did it allow you to control the heating better? Why?

13) Have you tried to do anything with the new heating controls which you were not able to do?
   a) What was this?
   b) Why weren't you able to do this?
   c) Did you work out how to do it in the end?

14) Are there any rooms which you don't use? (Or use less)
   a) Do you heat these rooms differently?
   b) Has this changed over winter?

15) What is the typical occupancy pattern in your household?

a) On a weekday
b) At a weekend

16) Has your occupancy of the house changed over winter?
   a) Has there been any changes to the house since you had the controls
      i) Extension
      ii) Changes to the building fabric
      iii) New heaters

17) How do you decide when to turn the heating off after the winter?

18) How do you see your use of the controls changing as it starts getting warmer moving into Spring/Summer?

19) Now that you have had the controls over a winter has your initial opinion of them changed?
   a) What do you prefer over your old controls?
   b) What do you miss about your old controls?
   c) Did you or anybody else do anything differently with your old controls?
   d) Is there any particular function that you like the most?
   e) Do you wish it had any additional function(s)?

20) Do you think how you adjust your heating has changed over winter?
   a) In what way?

21) Has your priority for heating your home changed over the past winter?
   a) You might remember we asked you to rank the following in terms of priority for heating within the home at a previous interview but could you rank them again:
      i) Cost
      ii) Comfort
      iii) Health

22) Is your house warmer or cooler now with the new controls?

23) Do you know if you heating bills have changed?

24) Do you feel that the new controls have changed the way you heat your home?
   a) If so why?
   b) In what way?

25) Do you think you interact with the heating system more with the new controls than with your previous controls?

Tasks

I just have a couple of additional short tasks to complete with you, again don't worry there are no right or wrong answers I am just interested in your opinion and views.

1.) I would now like you to think about the temperatures within rooms in your home. Using the board
    a. Which do you think is the warmest room in your house? (If you put that to the top)
    b. Which room would do you think is the coolest?
    c. How do the other rooms in the house sit between these two – if you would like to rank them? Feel free to put rooms side by side if you think the temperature is the same in them.
    d. How different do you think temperatures in different rooms are?
        i. If you were to estimate the difference in degrees Celsius, what would you say the difference is?
    e. Show traces of a month then a week to show patterns of temps rising and falling

2.) The Department of Energy and Climate Change (DECC) published heating characters a year ago (flash card).
    a. What character do you think you were before your controls were changed?
    b. Do you think that has changed with the new controls?
    c. Why do you think that is?
    d. If I now give you the description for each character do you still agree with your choice?
        i. Rationer – want to save money therefore keep their heating use to a minimum and are more likely to control their heating manually for that reason.
        ii. Planner – think in advance about their heating needs and tried to avoid use when not needed. More likely to change their heating through the timer or thermostatic radiator valves.
        iii. Reactor – who 'react' to variations in internal and external temperatures either through changing settings on their heating controls or through use of secondary heating
        iv. Hands off – would rather not interact with their heating system or change regularly yet still desire their home to be

warm with the option to demand different temperatures if they had to.

v. Egocentric - use their heating in relation to their own comfort regardless of how others may feel and similarly to rationers most likely to control the heating manually

House characteristics

And finally I would just like to get some basic information about the house to ensure that our records are correct.

House type:

Detached ☐

Semi-detached ☐

Flat/Maisonette ☐

Terraced ☐

Year of construction: _______________

Construction type:

Solid brick ☐

Cavity brick ☐

Timber frame ☐

Solid stone ☐

Other ____

Conservatory: YES ☐ NO ☐ If YES, heated? YES ☐ NO ☐

Presence of loft: YES ☐ NO ☐

Insulation:

Type of insulation	Yes, Insulated	Level of insulation?
Cavity		
Solid wall		
Roof/Loft		
Floor		
Draught proofing		
Window insulation		
Tanks/Pipes/Radiators		

Number of floors: _________________

Garage/Conservatory: YES ☐ NO ☐

Extension: YES ☐ NO ☐

Secondary heating: YES ☐ NO ☐

If YES, details:

Number of occupants: ________________

Boiler type:

Combi-boiler ☐

Regular boiler ☐

Other ____

Brand (if known) ____________________________________

Boiler age: ____________________

Final Checklist

Well that is all the questions I have, so thank you again for allowing me to carry out the interview.

We would like to continue collecting data from your house this won't have any effect on your heating as before. We will at some point over the next few months ask you to return the sensors back to us but we will provide a pre-paid envelope to do so.

We will also send a letter giving you all the details of us officially ending the study at that point.

Of course if you would like to finish the study now, I can collect the sensors today and contact the relevant people about stopping the monitoring.

Give household voucher of thanks ☐

Get signed confirmation for voucher ☐

Appendix 6-B: Heating diary information (cover letter and info leaflet)

Loughborough University

[ ] September 2014

Dear [ ]

Thank you for your continuing support of the Go Digital study. We now need information on how you heat your home at the start of the winter.

Please will you help us by completing the enclosed *heating diary*.

We need 4 weeks of information- starting from the first day you use your heating this winter. If you post it back to us we will send you some high street vouchers for £25, as a token of our thanks. You can post it using the stamped addressed envelope in this letter.

Remember, you don't need to start the diary until the first day you switch the heating on. Then just fill it in every day- it should only take a few minutes. It's not a problem if you've already started using the heating, just start the diary today.

Thank you again for helping with this important work. Please do not hesitate to contact me if you have any questions.

Yours sincerely,

Ashley

Go Digital Team Member

Email: godigital@lboro.ac.uk

The information you provide in this study will be held securely by Loughborough University, no one will be identifiable in the results, your personal details will not be passed to other people or organisations. The research will be carried out in accordance with the Data Protection Act and Loughborough University has strict ethics procedures to control how the research is carried out.

Information Sheet

Thank you for your ongoing involvement in the Go Digital study, we really appreciate your time and interest. Following on from our second interview with you and checking your interest in continuing to be a part of the Go Digital study this leaflet gives some further detail on the additional involvement.

Heating Diary

A diary will be posted out to you at the start of September and we would like you to fill this diary in when you first start using your heating again for a total of 4 weeks. The diary will be designed so that it shouldn't take more than a few minutes to complete daily.

When the 4 weeks are over simply post it back and we will send out a voucher for £25 as a thank you.

Third Interview

We would like to carry out a third interview sometime around February which shall be similar to the previous interviews you have already taken part in. In this interview we are keen to know how you got on with heating your home over the winter.

You will receive a further £25 voucher at the end of this interview as a token of our thanks for your time and effort with this study.

If you would rather not be involved with the study any more please send us an email to let us know.

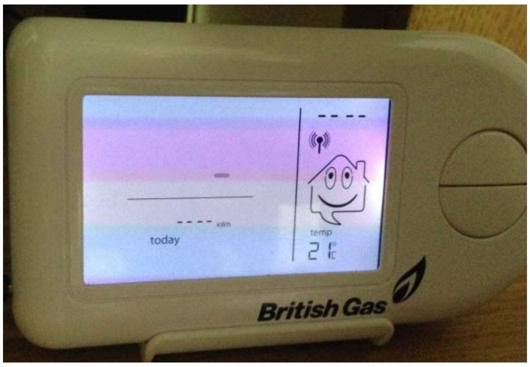
The Go Digital team, Godigital@lboro.ac.uk

Appendix 6-C: Photos of existing controls within sample households

P01: Programmable digital thermostat and boiler controls

P02: Digital programmer, Boiler controls

P03: Manual thermostat, Boiler controls (with digital timer interface), Smart meter

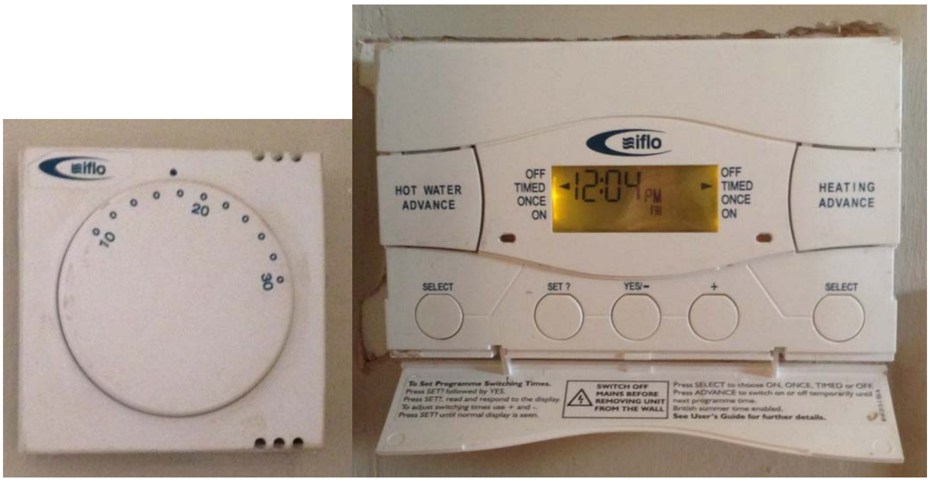


P04: Manual thermostat, timer

P05: Boiler controls (timer)

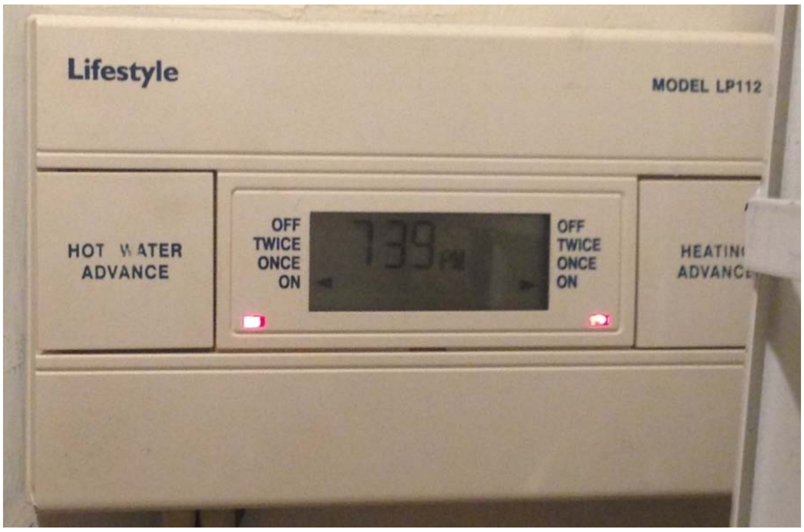
P06: Programmable thermostat

P07: Manual thermostat, timer



P08: Boiler controls (timer)

P09: Timer



P10: Manual thermostat, digital timer

P11: Digital timer and manual thermostat

P12: Thermostat, Boiler controls (with digital timer)