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How household thermal routines shape patterns of heating demand

by

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Abstract

This study introduces the concept of household thermal routines, defined as the regular patterns in time of heating use and other actions taken to achieve thermal requirements in the home. A unique dataset of heating controller settings and internal temperatures is analysed to investigate the thermal routines for 338 UK homes with smart heating controllers during January and February 2016, quantifying the diversity in the time and temperature settings entered by users. Interviews with seven householders explore the factors affecting choices of controller settings.

A significant minority of the sample studied made frequent changes to their temperature settings and nearly a quarter of the sample had higher setpoint temperatures in the evening than in the morning.

The high level in synchronicity across the sample of heating start times in the morning leads to a steep increase in space heating energy demand between 06:00 and 07:00. The peak level of space heating demand is higher in the morning than in the evening. Household thermal routines around 07:00 in the morning are a particularly important consideration for a transition to future energy systems with a high proportion of low carbon heat.

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1 Introduction

1.1 Context for the study

Reducing emissions from heating homes will be an important step towards achieving the UK's commitment to an 80% reduction in greenhouse gas emissions by 2050 (UK Parliament, 2008) as domestic space heating accounts for 11% of the UK's greenhouse gas emissions (DECC, 2012a) . Currently natural gas is the predominant heating fuel: 82% of UK dwellings have gas central heating (Palmer and Cooper, 2014). Energy systems modelling suggests that it will not be possible to reach 2050 carbon reduction targets without a very substantial shift away from gas heating to lower carbon heat sources such as heat pumps and district heating networks[1].

Demand for energy for heating has very clear seasonal and daily patterns (DECC, 2012b). Diurnal patterns of heat demand are related to the requirements for heating at different times of day. It is very common in the UK to operate heating intermittently, with the heating switched off (or with a much lower setpoint) when the occupants are asleep at night and out during the day. Plots of temperatures during the day frequently show a pattern of peaks and troughs (Shipworth et al., 2010; Kane et al., 2015). This pattern for temperatures is reflected in power demand: Summerfield et al.'s (2015) analysis of 30 minute power usage data for 567 UK dwellings states "all quintiles exhibited characteristic morning and longer evening periods of peak power demand" (p198). These patterns of heating operation have important consequences for energy networks.

As the transition to low carbon heating progresses, patterns of heat demand will become increasingly important as the task of meeting peak demand periods is moved away from the gas supply system to electricity and district heating networks. For natural gas, the storage available as a result of the volume of the supply pipework means that demand can be 'smoothed' over the day (Uraikul et al., 2000), but electricity supply has to match demand on a second by second basis so the electricity network has to be designed to supply short term demand peaks (Strbac, 2008). High penetration of electric heat pumps would have a significant impact on these peaks (Redpoint, 2013). Peak demand is also an issue for the economic viability of district heating schemes. The initial capital investment forms a large share of the lifetime cost of these networks and significant elements of this, for example pipework costs, will depend on the size of the peak demand (Lund et al., 2010).

There are two aspects of peak demand that are of concern to electricity network operators. The distribution network in a particular area must be sized to cope with the highest instantaneous demand over a period of years (gas networks are planned to meet a '1 in 20' cold winter (Delta-ee, 2016)). Also, each day the system operator must ensure supply meets demand in peak periods, bringing additional generation sources online to match the rate of increase in demand. Wholesale energy supply prices increase at peak times as higher cost generating plant is dispatched (UK Power Networks, 2014).

Running patterns can be influenced by variable time of use tariffs, designed to encourage shifting away from peak times (National Grid, 2015), and by control algorithms designed to smooth demand, but ultimately these will only be successful if they sufficiently satisfy residents' thermal comfort requirements. User preferences may constrain optimum heating patterns; for example there is a conflict between a widespread preference for cooler night-time temperatures and op-

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[1] For example, Delta-ee's balanced transition scenario for the Energy Networks Association shows 67% of homes with heat pumps or other electric heating and 27% with district heat achieve an 89% reduction in UK domestic heating emissions by 2050 (Delta-ee, 2012)

timised running of heat pumps during the night (Owen et al., 2012; Fell, 2016). It is important for a successful transition to understand current requirements for patterns of temperature over time and how these vary between households.

1.2 Overview of the study

This study introduces the concept of thermal routines, the pattern in time of heating use and other actions taken to achieve thermal requirements in the home. A dataset of heating controller settings was used to investigate the thermal routines for a group of 337 homes with gas and oil boilers during January and February 2016, quantifying the diversity in the time and temperature settings entered by users. Interviews with seven householders to explore the factors affecting choices of controller settings provided an alternative perspective on the findings from the quantitative analysis.

This is the first time, to the author's knowledge, that analysis of heating controller setting data for a group of several hundred UK homes has been published; previous studies (e.g. Kane et al. (2015), Huebner et al. (2013)) have inferred heating controller settings from temperature measurement or answers to surveys because records of the actual settings were not available.

The literature review in Section 2 outlines how the concept of thermal routines draws on aspects of thermal comfort theory and social practice theory and introduces the research questions. Section 3 outlines the methodology and the quantitative and qualitative methods used. Section 4 discusses the findings of both data analysis and interviews under three thematic headings: Routines, Temperature settings and Patterns of demand. Section 5 summarises the findings and their relevance to energy policy and research.

2 Literature Review

2.1 Introduction

This section outlines relevant aspects of two theoretical traditions which contribute to the understanding of variable patterns of heating use in domestic settings. The concept of thermal routines (which draws on both these traditions) and the research questions for this study are introduced.

2.2 Thermal comfort

Thermal comfort theory offers important insights into the factors which influence whether people feel comfortable in particular thermal conditions. In this section the principles of the heat balance and adaptive thermal comfort approaches are outlined, and the challenges of applying these to conditions in UK homes in the heating season are discussed.

ASHRAE Standard 55-2013 *Thermal Environmental Conditions for Human Occupancy* defines thermal comfort as building occupants' 'satisfaction with the thermal environment' (ASHRAE, 2013, p. 3). A key aim of thermal comfort research is to provide input to building design standards 'the crucial link between thermal comfort research and thermal comfort practice' (de Dear, 2004) (de Dear makes it clear that he is referring to the practice of architects and engineers designing buildings and equipment, not considering the actions of the occupants). There is a long tradition of work investigating the conditions in which occupants report they are thermally comfortable (Fanger, 1972). This is predominantly in the context of providing guidance for engineers when they are sizing heating, ventilation and air conditioning (HVAC) equipment for non-domestic buildings such as schools and offices (de Dear and Brager, 1998). Since individual occupants have little control over their environment in these buildings, it is unsurprising that comfort is generally assessed by measures of occupant reported sensations (as opposed to actions) such as the 'predicted mean vote' (PMV), which assesses the average comfort ratings for a group of people (Nicol et al., 2012).

The 'heat balance' model of thermal comfort is based on equations for heat exchange with the environment (Fanger, 1972) and calculates a PMV from six 'primary factors': air and radiant temperature, air movement, relative humidity, clothing level and metabolic rate of the person (ASHRAE, 2013). There is an implicit assumption in this model that the results will be repeatable in consistent conditions. More recent work has looked at variation by sex and age, expanding the modelling of physiological factors beyond Fanger's single metabolic rate term (Kingma and van Marken Lichtenbelt, 2015).

'Adaptive thermal comfort' is a term that covers a range of approaches which acknowledge that comfort is not an absolute, unchanging property of particular environmental conditions but also depends on the expectations of the occupants and the opportunities available to them to adapt. Two aspects of the adaptive approach can be illustrated by the explanations they provide for the difference in occupant satisfaction at the same temperature in different types of building. Extensive databases of comfort data collected in buildings from around the world databases show good agreement between measured and predicted PMV in mechanically conditioned buildings, but not in those which are naturally ventilated, indicating that there is something different about these buildings which cannot be explained by the heat balance model (Brager and de Dear, 1998; de Dear, 2004).

Reactions A basic principle of adaptive thermal comfort is that 'if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' (Nicol et al., 2012, p. 29). Humphreys and other researchers have pointed out that there is range of things people can do to become comfortable such as altering clothing, moving position, and opening windows (Humphreys, 1995). This approach suggests that a key factor in the wider range of acceptable temperatures in naturally ventilated buildings is that the occupants are able to take actions to adjust the conditions, for instance by opening windows. Hellwig (2015) provides a conceptual model of perceived control in a building, and points out that the perception of control is important even if the adaptive opportunity is not exercised.

Expectations Another angle is to emphasise the role of expectations: 'the adaptive theory of comfort construes thermal acceptability in a relativistic framework, and so a given indoor thermal environment is evaluated relative to the subject's thermal expectations rather than some objective environmental criteria' (Luo et al., 2016). This approach stresses the psychological and physiological adaptations which lead to people becoming accustomed to conditions to which they are regularly exposed. Humphreys first highlighted the strong relationship found in field studies between mean outdoor temperature and the temperature that people find comfortable indoors (Humphreys, 1978). It has been suggested that since occupants of naturally ventilated buildings are more exposed to external conditions than those in mechanically conditioned spaces their expectations are based on their experience of the outdoor environment (Nicol et al., 2012; de Dear and Brager, 1998). This provides an additional explanation for the greater temperature range within which occupants report being comfortable in this type of building.

The heat balance and adaptive approaches are not necessarily incompatible. As de Dear and Brager point out 'the static heat balance model can be viewed as a partially adaptive model, accounting for the effects of behavioural adjustments that directly affect inputs such as clothing or air velocity'(de Dear and Brager, 1998, p. 14). However, adaptive thermal comfort opens up many possibilities for parameters influencing thermal comfort beyond those in the heat balance equations. Brager and de Dear's frequently cited 1998 paper suggests that methods of adaptation can be classed in three categories - physiological, psychological and behavioural.

The adaptive thermal comfort approach envisages an interactive process in which occupants are both adapting, and adapting to, their thermal conditions. This is directly relevant to space heating behaviour in the home but there has been little research into heating control actions in dynamic domestic environments. The focus of most thermal comfort research on measuring what people feel, not what they do, is more relevant for buildings where occupants have limited opportunities to control conditions than for domestic settings. As Tweed et al. (2014) point out, 'the key difference between the home and other environments is that householders are usually in charge of their own comfort'. Research quantifying actions in response to thermal discomfort such as the a set of experiments in a climate chamber with one facade exposed to the exterior (and with openable windows) described by Schweiker et al. (2012) is rare.

The idea that people adapt to, and even expect, different temperatures at different points in the day and in different locations arises from the principles of adaptive thermal comfort theory. Nicol's concept of a thermal pathway seems particularly relevant to the very variable thermal conditions in homes:

> People who regularly occupy a particular space will have a customary temperature that they associate with that place for a particular time of day or year. It will be part of a thermal pathway that they follow each day, a pathway that at times my be too hot or too cold, but on average constitutes a well-understood pattern for a generally

> comfortable life. (Nicol et al., 2012, p. 69)

Brager and de Dear (1998) list many possible reasons for discrepancies between predicted and actual thermal comfort levels in the highly variable conditions of real buildings, which include non-uniformities of temperature within the building and the incorrect assumption of steady state conditions. These factors are likely to be important when considering the dynamic temperature environment of a typical UK home where there are significant swings between the maximum and minimum internal temperature during the day. While there has been some research on occupant reactions to temperature drift (e.g. Hensen (1990) reviews thermal comfort in transient temperatures; Schellen et al. (2012) compare thermal preferences in constant temperature and gradual drift over eight hours) this research is not in domestic settings and does not replicate the diurnal temperature cycle typical in UK homes.

2.3 Practices and routines

In contrast to the thermal comfort tradition's focus on the sensations of individuals, social practice theory emphasises what people do (practices) in a social context, conceptualising practices as entities which are replicated across social groups (Shove et al., 2012). Walker (2014) discusses how 'most social practices entail some form of energy "demand"'(p50) and links energy services such as heating to the performance of practices. He describes how regular rhythms in practices generate rhythmic patterns of energy demand.

Daily patterns in energy use will be influenced by occupant routines (e.g. when they are out at work, or asleep) which are in turn influenced by social rhythms (Shove et al., 2009). Zerubavel points out the influence of social factors on the schedules of individuals: 'parts of one's schedule are obviously going to be shared by others who belong to the same social circles. Otherwise family dinner, church services, work conferences, seminars and basketball games, for example, would not be possible' (Zerubavel, 1985, p. 68). Work on time use and routines within the social practice tradition provides useful insights into how society-wide practices shape the schedules of individuals and how this can be linked to patterns of energy and water demand (Shove et al., 2009).

Most investigation of the links between practices and energy use has been qualitative and more interested in illustrating the multiple and complex causes of variations between households than with methods for quantifying these; see for example Gram-Hanssen's (2010) study of five families living in similar houses but using very different amounts of energy. Similar insights into the complex interactions between family members which shape household energy use are provided by Davidoff et al. (2006) who point out that 'families resist categorization as users. The user tends to be singular, while families are, by definition, plural' (p20).

A limited amount of quantitative work on energy-using practices has focused on electricity for appliances rather than heating demand; for example Powells et al. (2014) describe how the household coming together at particular points in the day impacts on the timing of demand. Anderson (2016) sums up the situation: 'not only is there little data on variation and change in energy-demanding practices but with a few notable exceptions there is also very little consideration of variation in the extent and timing of the practices that underpin or constitute energy demand' (p3).

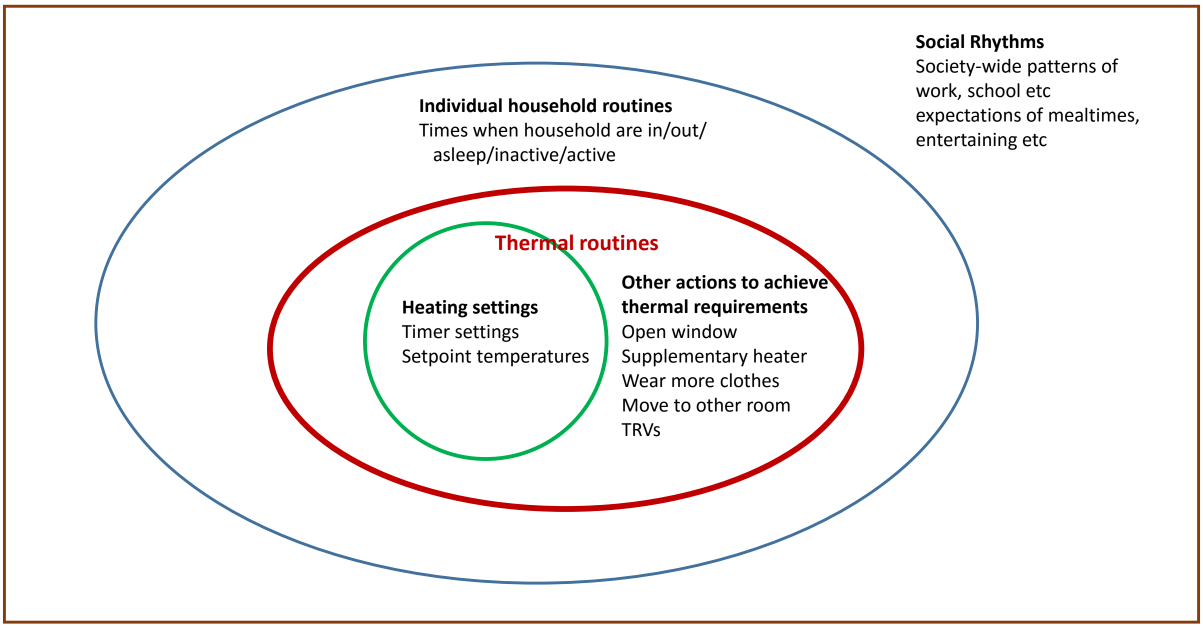
The recognition that heating demand is linked to range of social practices, not just individual thermal comfort preferences, brings a wider social context to the consideration of heating demand patterns. It introduces methodological challenges for a researcher wishing to link the qualitative investigation techniques usual in the practice tradition with the much more quantitative approach of thermal comfort tradition. A focus on routines (in particular the times at which heating is switched on and off) allows quantitative assessment of a key aspect of heating practices.

2.4 Thermal routines

The concept of thermal routines draws on relevant aspects of thermal comfort and social practice theory and aims to represent how both rhythms of daily activities in the home and requirements for particular internal temperatures at different times influence daily patterns of heating demand. Thermal routines are defined as regular patterns in time of heating use and other actions taken to achieve thermal requirements. The term ‘thermal requirements’ is used rather than ‘thermal comfort’ to indicate that heating may be operated to satisfy requirements beyond individual thermal comfort, for example to dry laundry.

The diagram in Figure 1 indicates how thermal routines include actions such as use of supplementary heat sources (e.g. a wood burner) or wearing extra clothing. Thermal routines, including the operation of heating systems, are a subset of the more general set of all regular activities carried out in the home.

Figure 1: Thermal routines as a subset of household routines



The thermal routines followed by a household will result in a variable pattern in time of temperatures in the home and of energy demand for heating. Viewed from a practice perspective, thermal routines are influenced by the social context of practices carried out in the home and society-wide rhythms of activity. From an adaptive thermal comfort perspective, it is the physical context - the adaptive opportunities afforded by the building - that influences the actions of the occupants. Heating control settings, and use of supplementary heat sources, will be affected by factors such as occupants’ expectations of how long a room will take to reach their required temperature.

2.5 Considering variation

A key theme for this study is variability. Energy networks have always relied on diversity of demand patterns between different customers to 'smooth out' peaks in demand: the network capacity is significantly lower than the sum of the individual peak demands as these never coincide exactly (Strbac, 2008). An important factor influencing the level of peaks in demand is the amount of variability in running patterns between different homes connected to the network. The theoretical approaches discussed above suggest many possible reasons for variation in the patterns of temperature and space heating energy demand in the home.

In order to understand diversity in heating demand it is important to examine the variation in key parameters rather than concentrating on the mean. Shove's reaction (from a practice perspective) to the focus on the response averaged across many occupants in thermal comfort studies, reflected in parameters such as PMV, is :

> Standardized comfort equations . . . built on averaged data . . . anchor definitions of optimal or 'normal' conditions in a statistical mean . . . when statistical normality is taken to represent normality in the 'real world', the range of practices and conditions that might be so described is inevitably narrowed. (Shove, 2003, p. 33)

Shipworth et al. (2016) point out that if a wide range of comfort votes is represented by a linear regression model between comfort votes and a single environmental parameters such as indoor operative temperature, this discards a great deal of useful information which could be used to capture the diversity of comfort requirements.

Stephen Jay Gould's *Full House* stresses the 'need to focus on variation within entire systems and not always upon abstract measures of average or central tendency' (Gould, 1996, p. 49). In a wide ranging discussion which includes case studies of baseball statistics and the evolution of complex organisms, he illustrates the value of tracking not just the mean of a parameter over time, but also its variability. Gould points out that distributions are often bounded by fundamental limits, which he calls 'walls' (for example it is not possible to find an organism with less than one cell) and that this leads to highly skewed distributions which do not represent a random variation around a mean. This concept of 'walls' is relevant to limits of variation in factors affecting the indoor thermal environment; for example variable temperature preferences will be within a certain range determined by human physiology (Nicol et al., 2012).

2.6 Introduction to research questions

This study applies the concept of thermal routines to the question of variability in home heating demand over the day. The overall heating demand seen by the energy supply network is an aggregations of daily demand patterns for individual homes. The over-arching research question is:

- How are daily patterns of space heating demand for a group of homes related to individual household thermal routines?

In order to answer this question, a clear picture of variation and synchronicity in thermal routines is required. This study investigates thermal routines by examining heating controller time and temperature settings. The supplementary research questions specific to the dimensions of time and temperature are :

- What is the level of synchronicity and diversity in heating timer settings and what factors influence this?
- What is the level of diversity in temperature setpoints and what factors influence this?

3 Methods

3.1 Overview of methodology

The research questions introduced in the previous section are:

- What is the level of synchronicity and diversity in heating timer settings for a group of homes, and what factors influence this?
- What is the level of diversity in temperature setpoints and what factors influence this?
- How are daily patterns of space heating demand for a group of homes related to individual household thermal routines?

Two different methods were combined to answer these questions. Quantitative analysis is required to assess synchronicity and diversity across the sample of homes. A dataset from PassivSystems heating controllers allowed quantification of heating operation times and the level of variation both for individual homes and across the whole sample. However it is only by consulting the households concerned that the reasons they have made their choices of control settings can be explored. This qualitative approach allows the investigation of questions such as :

- How do patterns of heating control relate to the times residents leave and return to the house, or are sleeping?
- Are there differences in temperature requirements at different times during the day?
- How does a multi-person household negotiate a thermal routine that works for all of them?

The combination of quantitative investigation looking at variability in data for several hundred homes and qualitative investigation, gathering information from interviews with a small group of householders is an example of a pragmatic mixed methods approach, an ‘attempt to fit together the insights provided by qualitative and quantitative research into a workable solution’(Johnson and Onwuegbuzie, 2004, p. 16).

3.2 Quantitative methods

3.2.1 Description of PassivSystems controllers

The data were supplied from PassivSystems units controlling either oil or gas boilers. These send ‘call for heat’ signals of either 1 (run) or 0 (heat not required) to the boiler.

There are several generations of equipment, but all involve a wall mounted unit containing a temperature sensor with a stated accuracy of +/-0.5°C (the recommendation to installers is that this should be mounted on an internal wall). There are differences in configuration, with some models having a detachable ‘in home display’ unit on which temperature settings can be changed. Some customers have additional features, such as a button by the front door to switch the heating off as they leave.

Customers can set their preferred temperatures (in increments of 0.5°C or 0.5°F) via a web portal or mobile phone app, and directly on the unit. Customers are told they are not setting boiler on and off times, but the time they plan to wake up, go out etc and the controller will operate the boiler to provide the temperature levels required in these periods. The user sets up an ‘occupancy schedule’, entering what times each day they will be IN, OUT and ASLEEP (these terms are capitalised throughout the report to indicate the controller ‘occupancy states’, which may not coincide with the actual times residents leave and return to the house). Different schedules can be set up for different days of week, or to differ between weekday and weekend. There is also the option of an AWAY vacation setting

The unit records whenever a change takes place in the temperature setpoint or call for heat. The frequency of recording of the air temperature at the unit depends on how fast it is changing. The Zigbee unit (majority of those in study) records every time the temperature changes by 0.1°C. The ZWave unit records with a resolution of 0.2°C. A measurement of temperature at the nearest of over 200 Met Office weather stations (Met Office, 2016) is recorded every hour, and this is used as the external temperature for control algorithms.

The controller operates using algorithms which ‘learn’ the characteristics of the home and anticipate users’ wishes. One example of this (of particular significance to the study) is the ‘optimum start’ algorithm. The principle is to start the heating before the beginning of an IN period, so that the home has been brought up to the desired temperature at the beginning of the period. With some controller models, users can choose to limit optimum start to a particular maximum time, or to disable this option. The maximum optimum start is 60 minutes but the actual start time will depend on external temperature - the algorithm will estimate the time required to reach temperature required at the beginning of the IN period.

3.2.2 Data description and clean up

Data were supplied from PassivSystems Controllers from 500 homes geographically distributed across the whole of the UK. Meta-data about the buildings and their residents were not available. While the units are fitted in dwellings of a wide variety of types and ages they are not necessarily representative of overall building stock. The data were anonymised, with homes only identified by a number. There is the possibility for larger buildings to operate two heating zones: only the first zone was considered for the small number (6) of homes in the sample with two zones.

The controller data were preprocessed by PassivSystems into files for each home giving readings every five minutes for five variables recorded by the unit:

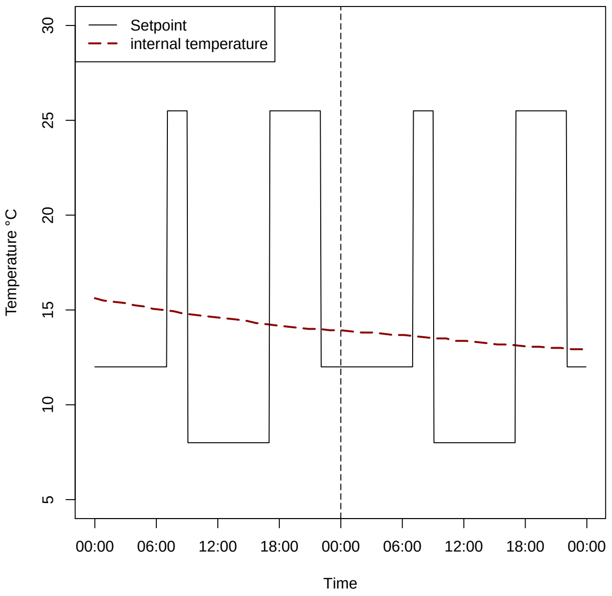
- Setpoint temperature
- Internal temperature (measured at PassivSystems unit)
- External temperature (at nearest Met Office weather station)
- ‘Call for heat’ - 1 if asking boiler to run, 0 if not
- ‘Call for hot water’ (not considered in this study)

The five minute interval was chosen as it is frequent enough to give good resolution of changes in settings while generating a manageable amount of data to transfer and process.

The data were processed and statistical analysis carried out using R software. Data for eight weeks in January and February 2016, from 00:00 on 4/1/16 to 00:00 on 29/2/16 were read into R. This was chosen as a period during the heating season, with no major holiday periods (such as Christmas) included. The highest daily mean external temperature at the location of any of the homes in the period was 13.0°C and the lowest daily mean was -3.7°C. The analysis focused on the 40 weekdays in the period.

Preprocessing of the data were carried out to filter out homes with a significant number of N/A points in the data and 158 homes (with more than 4,000 N/As - 6.2% of the total data points) were removed. The R zoo package was used to fill in remaining N/A points by linear interpolation between the two nearest available data points, to provide an estimate of missing values for each five minute period.

Figure 2: Example of 'unit not controlling' home removed from sample. Internal temperature drops steadily over two days despite IN period temperature setpoints considerably higher than the actual temperature.



The final stage of pre-processing was to remove 'unit not controlling' homes. These are the homes in which even though a PassivSystems controller is installed, it is not the main means of controlling internal temperature (possibly because the boiler is faulty or out of action). In these homes the times when the internal temperature is rising and falling do not correspond with times that the the heating is switched on and off by the controller:

- Visual inspection of temperature traces for all the homes in the sample found eight 'unit not controlling' homes. A typical example is shown in Figure 2 above. Homes where the controller was triggering boiler operation and temperature rise, but doing this infrequently because of very low setpoints (probably because the home was unoccupied) were not removed.
- In three homes there were no calls to heat recorded for the boiler in the period.

Following this pre-processing, the main analysis was carried out on data for 337 homes.

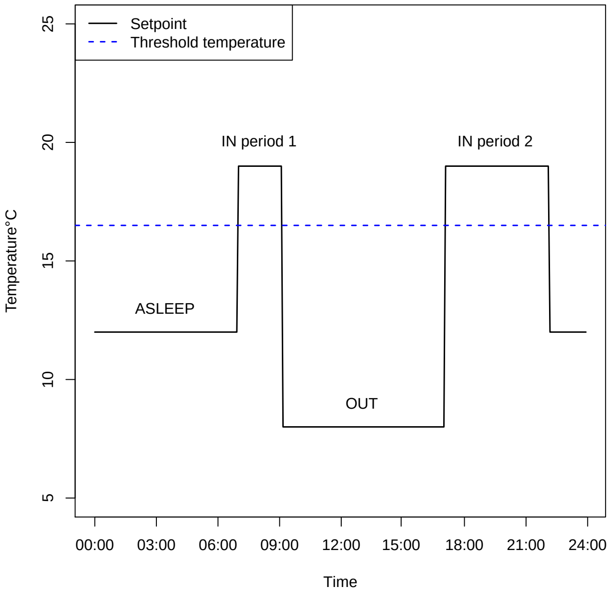
3.2.3 Data processing

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

Matrices for internal and setpoint temperature were created with each row representing a five minute period and each column an individual home. These were divided into daily matrices of 288 rows (one for each five minute period) in order to find the maximum and minimum setpoint and internal temperature and mean internal temperature for each day for each home.

IN period detection. A key step in the analysis was to use the setpoint temperature data to distinguish between IN 'occupancy' periods and other periods set as OUT, ASLEEP or AWAY 'occupancy'. Since the setpoints are very variable between homes (some homes have an ASLEEP temperature setting of 18°C while others have an IN setting of 17°C or below), a method was devised to distinguish between the IN and other operating periods for each home. Initially an arbitrary 'threshold' of 16.5°C was assumed and this was tested for each home, to see if it provided a clear distinction between periods of relatively high setpoint (assumed to be the IN period) and periods with relatively lower setpoints (assumed to be OUT or ASLEEP). Figure 3 shows the default operating pattern with clear steps in setpoint between IN and other periods. Typically there is a step between the ASLEEP and IN setting at around 07:00 each day, but allowance must be made for homes with different patterns, for instance for night-shift workers. Visual inspection was used to distinguish between the periods of highest setpoint (assumed to be IN) and other periods with relatively lower setpoints (assumed to be ASLEEP or OUT - for the purposes of the analysis the only requirement was to distinguish between IN and 'not IN').

Figure 3: PassivSystems weekday default settings, showing how threshold of 16.5 °C distinguishes between IN periods and those when occupancy is set to OUT or ASLEEP.



Initial filtering was based on the frequency of occurrence of particular setpoint levels in the data for each home. For a home with unchanging IN, OUT and ASLEEP setpoints, these will be the three most frequent temperature setpoints recorded in the five minute data and the IN value will be the highest of the three. Data for homes for which the second highest of the three most frequent setpoints was above 16.5°C were inspected, as this could indicate that the ASLEEP or OUT setting was higher than the threshold assumption. If inspection confirmed that this was the case, a new higher threshold was chosen to distinguish the periods of relatively higher setpoint operation (24 homes out of 337).

For homes where all the three most frequent setpoints were below 16.5°C, a plot of the setpoint

Figure 4: Threshold raised to 17.1 °C: home 186

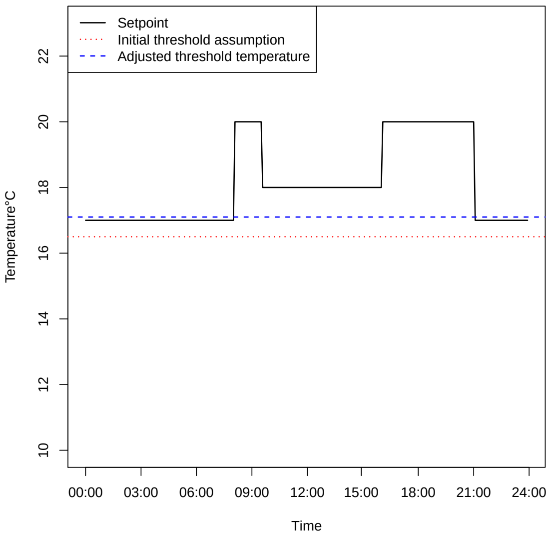
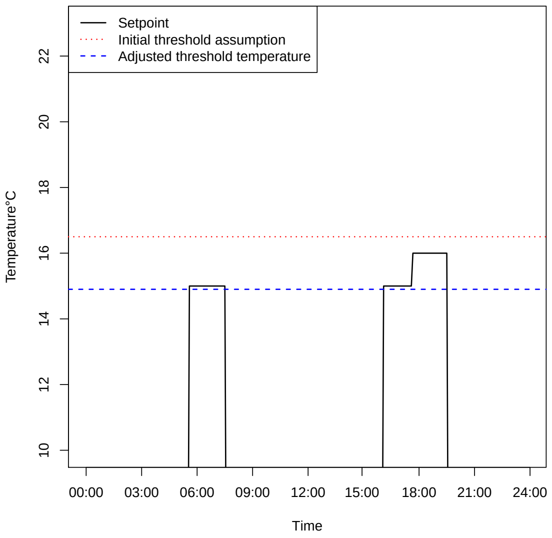


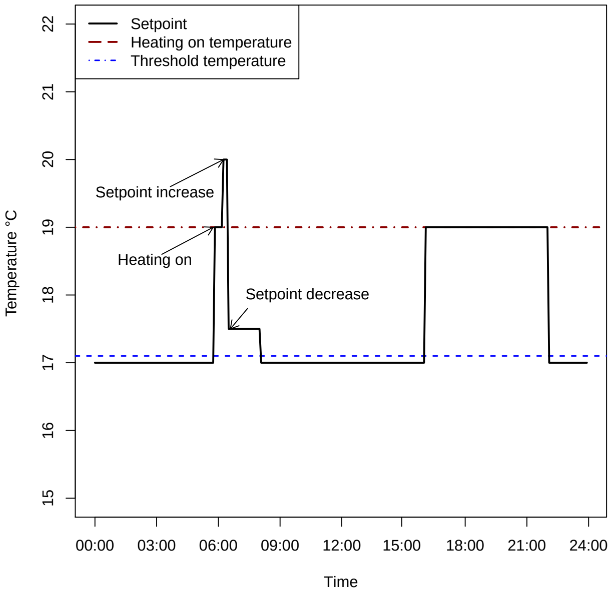
Figure 5: Threshold lowered to 14.9 °C: home 163



over time was examined to find typical daytime and night-time setpoints and a new threshold below the highest setpoint levels was set (nine homes).

A matrix showing whether the setpoint was higher than the threshold temperature for each home in each five minute period was created and the length of the IN periods was summed over each day. The five minute resolution of the data means that the level of accuracy for a typical two period daily operation pattern is +/- 10 minutes. The data for each day was analysed to identify the times when IN periods started and stopped - these times are accurate to within the five minute data resolution.

Figure 6: Example of identification of setpoint increases and decreases.



Pattern of setpoint changes. In order to investigate whether the temperature setpoint was changed during the IN period (i.e. there was a change in setpoint to another value above the threshold level) the ‘heating on setpoint’ at the beginning of the first IN period was recorded. Then all other points during IN periods in the day were examined, and any changes in setpoint recorded (see Figure 6). The proportion of homes at each five minute point for which a) this was an IN period and b) the setpoint had increased or decreased compared to the ‘heating on setpoint’ was calculated. This value was then averaged over all days to give a vector of the mean proportion of homes with increased or decreased setpoints at each five minute point in the day.

Pattern of demand PassivSystems controllers are not connected to energy meters so direct energy use data were not available. The call for heat signal was used to determine the coincidence of boiler operation as a proxy for demand. There is not a simple linear relationship between this ‘boiler coincidence factor’ - the proportion of homes with the controller calling for heat - and the absolute level of total power demand. Many modern boilers incorporate sophisticated modulating control systems which means that they will run at a range of fuel consumption rates. The boiler may be satisfying a call for hot water simultaneously with space heating demand. The call for heat data can be used to investigate the pattern of demand over time since increases and decreases in number of boilers running will lead to increases and decreases in the total amount of energy used, even though the absolute energy values may not change by the same percentage.

3.3 Qualitative methods

Interaction with heating users can provide extra insights by identifying which factors affecting thermal routines are most important to them. This may bring to light factors not anticipated by the researcher. It also provides an opportunity to check the interpretation of quantitative data from the household. Three alternative methods were considered for consulting users of PassivSystems controllers.

- Face to face interviewing in the home gives opportunities to view the configuration of heating system and controllers and to meet several household members . Practical factors ruled out this approach. Limited time and budget was available for travel and the potential interviewees were spread all over the UK.
- An online or postal survey might have received a higher response rate than a request for interviews (Dillman, 2000). This method was rejected as it provides less opportunity for asking open-ended questions and to identify factors important to the respondent which had not been anticipated by the researcher.
- Semi-structured telephone interviews using a pre-determined set of open questions was the method selected (Robson, 2011). This allowed personal interaction and open-ended questioning, while being convenient and minimally intrusive for the householders who volunteered to take part.

This report uses a number of terms to refer to the users of heating controls and the occupants of homes. Shipworth points out that the widespread use of the term ‘occupant’ to describe a person in a building has a simplifying, de-humanising effect which ‘probably arises from the tradition of defining ‘occupancy schedules‘” within models . . . Such schedules remove variability and standardize human influences’ (Shipworth, 2013, p. 251). The terms ‘household’ and ‘family’, with their connotations of distinctive groups as opposed to undifferentiated individuals, are used when appropriate to the context.

3.3.1 Recruitment

The interviewees were recruited by two tranches of emails sent out by PassivSystems to groups of customers (see e-mail text in Appendix A). The recruitment process was designed to be as easy and as attractive as possible, while conforming with data protection requirements (Dillman, 2000). Those who were willing to participate were directed to a web ‘survey’ which collected their contact information and confirmed consent to collect and store personal data under the terms of the UK Data Protection Act (see Appendix B). The response rate was low: 120 e-mails were sent out and ten responded initially but the final number of interviews was seven (three people failed to respond to repeated interview requests despite having supplied their contact details). Once volunteers had confirmed they were willing for PassivSystems to release their controller data, the data for their home was made available to the researcher.

3.3.2 Interview process

The telephone interviews were carried out in March to early June 2016 and varied from 12 min to 60 min in duration. The interview guide is included in Appendix C, and covers questions about the heating system, the type and age of the building and the household demographics. Open questions were also asked about the respondent’s thought process when setting heating controls. Detailed notes were made during interviews.

The table in Appendix D summarises key features of the households. Within the small sample there was considerable diversity of house types, location and demographic make up of the household.

3.3.3 Analysis of interview findings

The interview responses were not formally coded but a spreadsheet was created to collect statistics and yes/no answers on key details. Answers from all respondents were collected together under headings related to each of the open questions in the interview guide. Common themes and contrasts across the sample were identified.

When considering the interview responses it is important to note they represent the point of view of only one member of the household. The person responding to the interview request appeared to be the family member most actively involved in programming control but could not report what was happening when they were not present. Pre-analysis of data for each interviewee’s home allowed cross checking and comparison of the impression gained from the interview and quantitative results, for example how frequently setpoints were changed and how quickly homes heated up.

3.4 Strengths and weaknesses of approach

Investigation of the links between the heating controller settings and the temperature in a building faces an ‘under-determination problem’. There are many possible actions by the occupants which could affect the thermal conditions; not just how they interact with the heating controls, but also other actions they takes such as opening windows. The properties of the building fabric also introduce considerable complexity. The response of the building to patterns of heating operation will depend on many factors such as the air tightness and thermal mass of the building, as well as the external climatic conditions.

Although access to data on heating controller settings provides valuable information, there are still very significant areas of uncertainty about the response of the buildings (for which no information about properties of fabric or heating system is available) and the actions of the occupants. In many cases there are multiple possible explanations for an effect (such as the maximum internal temperature reached during the day discussed in Section 4.2.4). This issue applies to deductions from temperature settings but not to those on timing since the impact of timer settings can be directly observed and assessed.

The interviews with households provided a valuable additional perspective on inferences from data analysis and insights into points that could not be derived from the data, for example the reasons for increases in temperature setpoint. This does not solve the ‘under-determination problem’, but does provide information on factors that apply in some households, and suggest avenues for further investigation with a wider sample and/or additional measurements.

The sample for interviews was small, and not necessarily representative of all those with PassivSystems controllers. Volunteers who responded to the request to participate in the study are likely to be more interested in, and aware of, energy use in the home than the general population. The expectations built into the design of the PassivSystems user interface, and the way the key parameters for user input are described, may shape user interaction in a way that differs from households with less sophisticated control systems and those who operate their heating manually.

3.5 Data management and ethics

Ethics approval was obtained through the BSEER process ahead of contacting PassivSystems customers to arrange interviews. An assessment of factors such as informed consent, possible harms and risks was carried out. The department ethics co-ordinator (M Shipworth) confirmed that the project is low risk and did not require an application to the UCL Research Ethics Committee.

Before any personal data were collected an application for inclusion on the UCL Data Protection Registration was approved (No Z6364106/2016/02/84 social research). The only personal details collected were the name, postcode and telephone number of those who volunteered to participate in interviews. This was stored on an encrypted, password protected drive. All the interviewees confirmed that they were happy for their answers to be used and quoted in reports. As is standard academic practice, they have been identified by pseudonyms in this report.

4 Results and discussion

This section of the report discusses the findings from data analysis and interviews. Section 4.1 brings together the results on repeated patterns in time, Section 4.2 discusses the findings on temperature settings and Section 4.3 describes demand patterns and how these relate to the earlier discussion.

Data were analysed for controllers in 337 homes for 40 weekdays between 4 Jan 2016 and 26 Feb 2016. This produced data for 337 x 40 = 13,480 ‘sample days’. All figures and charts are for the full sample unless otherwise noted.

4.1 Routines

4.1.1 Introduction

An important precursor to understanding coincidence of demand for heating is assessing synchronicity - the degree to which heating starting and running times coincide - across different homes. This section addresses the time dimension of thermal routines, and the research questions:

- What is the level of synchronicity in heating timer settings across the sample?
- What factors influence this synchronicity?

The discussion of the time dimension of thermal routines starts with an assessment of the synchronicity and variability of the IN ‘occupancy’ periods - the times when the users have indicated that they wish the boiler to run as necessary to reach their chosen IN setpoint. The findings from interviews provide additional insights about the link between heating operation patterns and the times when residents are in the home.

4.1.2 Data analysis

As Figure 7 shows there is a wide variation in the length of the IN periods during the day. This is in line with the conclusions of previous researchers (Shipworth et al., 2010; Kane et al., 2015) that the assumption in SAP(and frequently used in BREDEM) of a regular operation period of consistent length does not represent the diversity of actual heating operation practice. This diversity is not simple due to variation between homes. Most homes show variation in running times: only 17 of the 337 homes had no variation in daily IN period duration over the period of 40 weekdays.

The default weekday schedule for PassivSystems controllers is two IN periods from 07:00 to 09:00 in the morning and 17:00 to 22:00 in the evening - a total running time of 7 hours. This corresponds to the modal value for running times across the sample, but only 6.6% of sample days had IN period duration of 7 hours +/- 10 minutes.

The number of IN periods varied across the sample. Figure 8 shows the breakdown of running modes, and highlights how 45% of the 13,480 sample days do not show the default two period

Figure 7: Distribution of IN period duration for each sample day

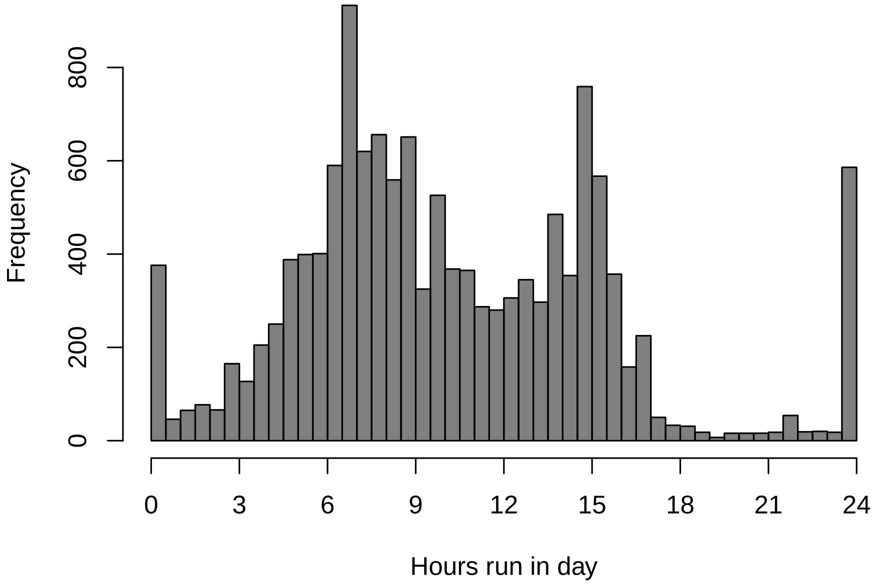
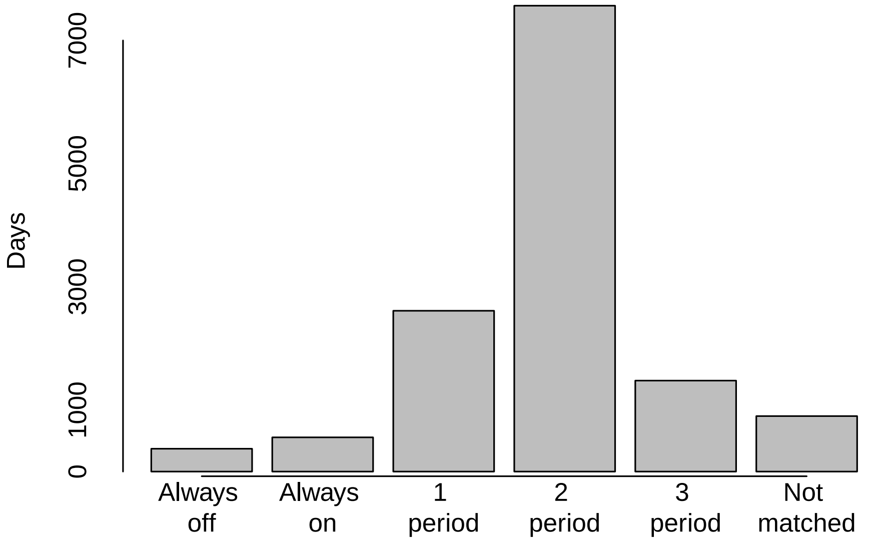


Figure 8: Distribution of IN period duration for all homes all days



operation assumed in the PassivSystems defaults (and in SAP modelling). The ‘not matched’ days are ones when the number of times the heating switches on does not match the number of times it switches off, since the heating was operating in an irregular pattern which included periods running after midnight.

The proportion of homes with two running periods can be compared with that inferred from a sample more representative of the general housing stock. An analysis of daily temperature profiles for 275 homes by Huebner et al. (2015) grouped these into clusters based on the shape of the profile. 30.9% had a relatively flat, unchanging profile through the day, 40.0% had a 'two-peak' profile (implying two heating periods, in the morning and evening) and the remaining two clusters had a clear daily cycle with the highest temperatures in the evenings and lowest at around 7am. The lower proportion of two heating period homes in these data from the CaRB HES survey will be influenced by the inclusion of homes with electric storage heaters, which are typically run for one period during the night.

Table 1 shows the statistics for key points in the heating routine. The method for determining these points is described in Section 3.2.3. The median and inter-quartile range (IQR) were used as the main measures of central tendency and degree of variation for these parameters since, as can be seen from the histograms in Figures 9 and 12, the distributions are not normal, and have outliers. The median identifies the time at which half the sample have reached a particular point in the routine and the IQR indicates the spread about the median without a heavily weighted element from outliers (Rousseeuw and Croux, 1993).

Figure 9 shows a histogram of the time at which the first IN period starts. The median start time, 07:00 is the same as the PassivSystems default. An even more synchronous pattern is seen when the data for the end of the final IN period in the day (shown in Figure 12) are plotted - the IQR for this time is 65 minutes, compared to an IQR of 90 minutes for the beginning of the first IN period[2].

Passiv System's optimum start feature introduces additional complexity to the analysis, since (as described in Section 3.2.3) the boiler may operate before the start of the first IN period. The 'boiler start time' - the first time the boiler operates in the hour before the first IN period - was determined. This is not a definitive indication of optimum start operation as there is also the possibility that during the ASLEEP period preceding the first IN period, the heating starts to operate if the internal temperature drops below the ASLEEP setpoint temperature. 38% of sample days had no boiler operation in the hour preceding the first IN period, so the maximum possible percentage of sample days with an optimum start greater than the data resolution of 5 minutes is 62%. Figure 11 shows the boiler start time distribution. This is significant for the discussion of patterns of demand in Section 4.3 below as high coincidence of boiler operation leads to high aggregated demand.

The PassivSystems controller asks users to set times for when they are IN, OUT, ASLEEP, or AWAY on a screen titled 'occupancy'. This is in line with the common assumption in energy modelling that the heating will be on when house is occupied and the residents not asleep (Richardson et al., 2008; McKenna et al., 2015). The results discussed above appear to link well with expected patterns of activity during the day. The 2005 Time Use Survey (Lader et al., 2006) shows that the point at which 50% of people are no longer in the 'sleep, resting' state occurs at approximately 07:10, close to the median first IN period start time of 07:00. The time use study also shows that by 09:00 the activity of nearly half the population is classified as employment, study or travel, supporting the assumption that many homes are unoccupied at this point in the day. The point at which half the population have gone to bed is approximately 22:50, nearly an hour later than the median final heating off time. This may indicate that some householders decide to let the heating turn off and allow the temperature to start falling some time before the actual time they go to bed.

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[2] The small number of points with final IN period ending early in the day are those with single heating periods running over midnight.

Table 1: Statistics for IN occupancy period lengths

	Sample N	median	IQR min	mean	Homes with no change in period
First on time	12499	07:00	90	07:23	26.1%
Final on time	9606	16:00	150	15:45	-
Final off time	12478	22:00	65	21:23	29.1%
Boiler start time	12391	06:25	75	07:05	-

Figure 9: Start time of first IN period in day, N=12499

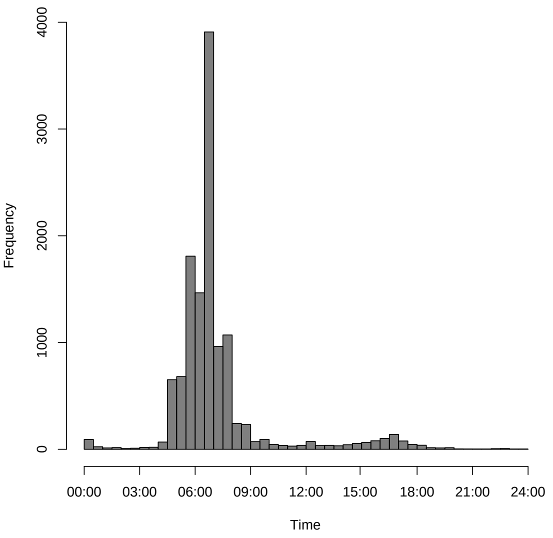


Figure 10: Start time of final IN period in day, N=9606

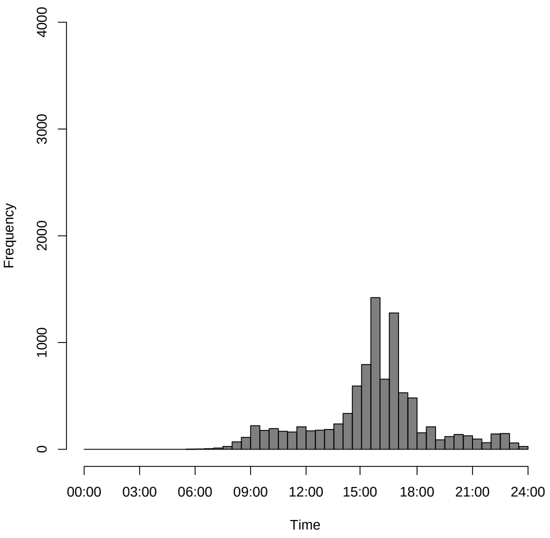


Figure 11: Boiler start time, N=12391

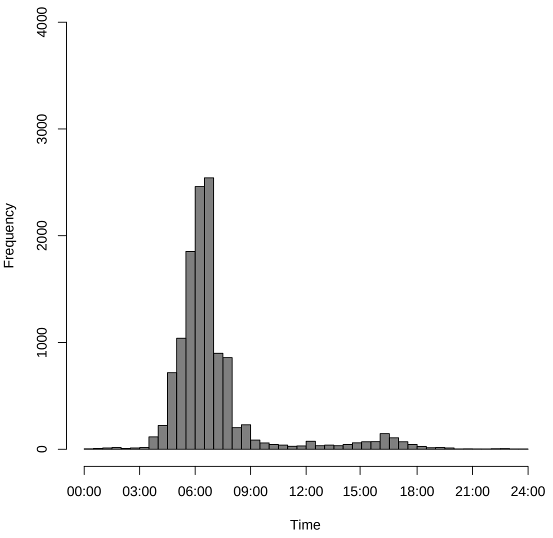
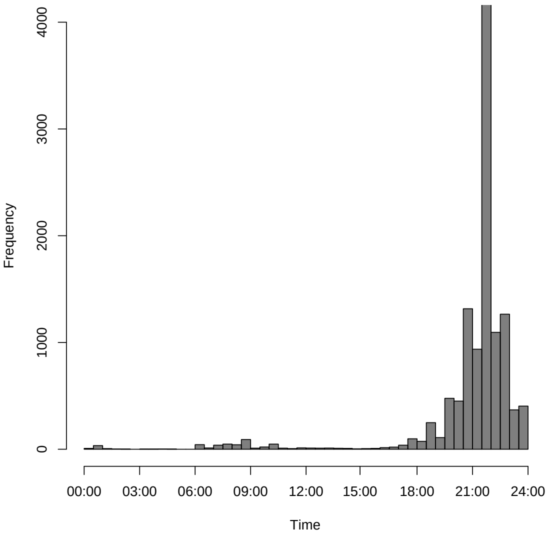


Figure 12: End time of final IN period in day, N=12478



For ‘sample days’ with two or more running periods, the time at which the last IN period in the day started was investigated. The median last heating on time is 16:00 (12.0% of sample days) - which is not the same as the PassivSystems default time of 17:00 (which is found on 10.9% of days). The histogram in Figure 10 shows that the variation in this second time is much wider than the first on time and the difference in the inter-quartile ranges is clear in Table 1. This is likely to be linked to the more variable end times (compared to the highly consistent start times) for the ‘employment, study’ category evident in the 2005 Time Use Survey (Lader et al., 2006).

4.1.3 Insights from interviews

Interviews allowed exploration of the extent to which heating time settings matched recollection of actual activity patterns for the households concerned, in particular the times when the occupants are asleep and out of the house. It soon became clear that timer settings did not match actual times in/out/asleep for some interviewees. Eleanor is usually in the house during the day but still chooses to have two heating periods as this ‘seems sensible’ and she is not ‘sitting round feeling the cold’ during the middle of the day. John (who works shifts and whose wife is often in during the day) says the default two period setting ‘tends to suit us’ even though there is often someone in the house in the OUT period in the middle of the day. He described his house as retaining heat well. He was not concerned about the occasions when he had to get up early and the heating was not on. Similarly David, who sometimes has to leave for work very early in the morning, did not set the heating to come on earlier than usual on these occasions - his stated intention was to program a regular routine to suit his wife and children.

In the only other case of shift work mentioned by interviewees, Michael said that his wife sometimes works early shifts, and that they do change the occupancy times in their controller for these days. It is interesting to note that this home, a 100 year old terrace, seemed to lose heat more quickly than David and John’s well-insulated, more modern homes, but the sample size is too small to draw general conclusions about the relationship between building thermal properties and adjustments to schedules.

One interview also indicated the diversity that can be introduced into household routines as different members of the family come and go. Catherine mentioned that her parents came into the house to meet her son when he came home from school, and that this might trigger an additional heating period.

All the interviewees answered the question about what time their heating started in the morning confidently. Eleanor mentioned hearing the boiler come on each morning. Some respondents were quite vague about the time the heating switched off in the evening and there was a general sense this was not such an important event in their thermal routines. This suggests that further investigation of the link between heating off times and actual bedtimes would be useful in order to investigate whether there is flexibility to run the heating for shorter periods.

It is clear that, at least for a proportion of this small interview sample, heating timer and occupancy patterns are not the same. Their thermal routines involved heating timer settings which deliver a satisfactory result for the household, even though they do not map to actual occupancy patterns of the occupants. This shows how an apparently clear story about society-wide patterns becomes more complex when individual households are considered. It also questions the basic principle underlying the occupancy assumptions used in many building models, which assume that heating operation coincides with times when the dwelling is occupied and the occupants not asleep (Richardson et al., 2008; McKenna et al., 2015). It seems that at least some users accept a default two period operation because this offers an acceptable level of comfort and conforms to their expectations of how a heating system should be run, rather than matching their actual patterns of occupation.

The interviews also highlighted an element of thermal routines beyond the setting of heating controls. There may be regular periods of using supplementary heating, in this case directly related to when the occupants are in, awake and not very active. John mentioned that he and his wife frequently use a wood burner ‘when it’s cold’ but that they will only light this in the evening (16:00 at the earliest) and Hugh reported using the wood burner in the living room ‘every evening’.

4.2 Temperature settings

4.2.1 Introduction

A key factor underlying diversity in heating energy demand is the variability in thermal requirements, both for the same dwelling at different points in time, and for different dwellings at the same time. This section addresses the research questions:

- What is the level of diversity in temperature setpoints across the sample?
- What factors influence variability in setpoints?

The investigation of the temperature dimension of thermal routines starts with an assessment of the variability of temperature setpoints. The patterns of setpoint changes during the day are examined. The degree to which temperature setpoints indicate thermal requirements is discussed. Findings from interviews provide a user perspective on temperature setpoints and thermal preferences, and how these change over the day.

4.2.2 Variation in temperature setpoints

Table 2 summarises the statistics for IN period temperature setpoint and number of changes in the day. In this case the mode has been selected as the appropriate measure of central tendency for these skewed distributions of discrete variables (setpoint temperature is changed in 0.5°C increments).

Table 2: Statistics for maximum setpoint and setpoint change

	Mode	Mean	% at mode	Homes with no change in period
Maximum setpoint in day	20.0°C	20.5°C	20.6%	19.9%
No of changes in setpoint	0	0.73	86.4%	21.1%

A histogram of the maximum setpoint temperature for each day for each home (Figure 4.2.2) shows a wide range. The variability of setpoints includes within-home variability. Some homes (19.8%) did not change the IN period setpoint at all during the period but the vast majority made at least one change. Figure 4.2.2 shows the histogram of the number of changes made to the setpoint each day: occupants made one or more changes to their IN period setpoint on 38.0% of sample days.

Figure 13: Maximum setpoint temperature in day

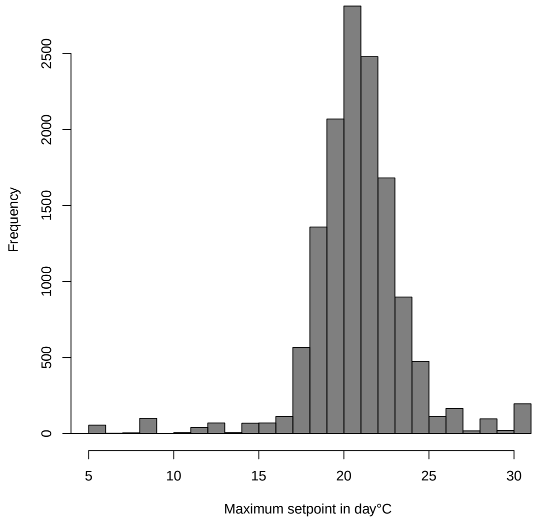


Figure 14: No. of setpoint changes in day

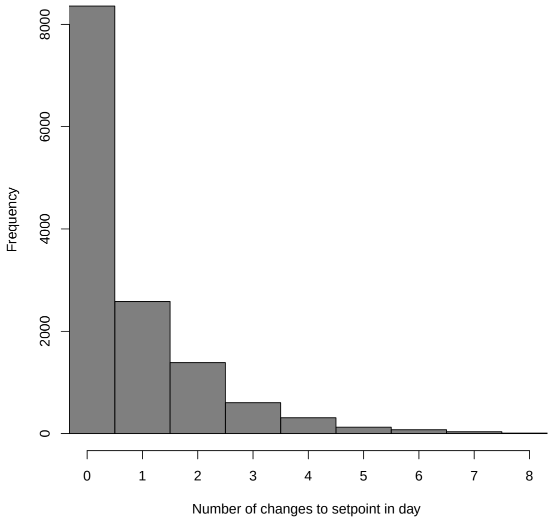


Figure 15: Example of home with no change in setpoint. Home 185 4-5 Jan 2016

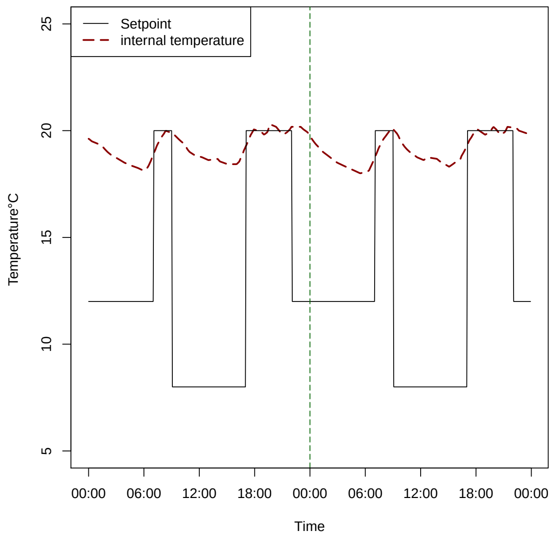
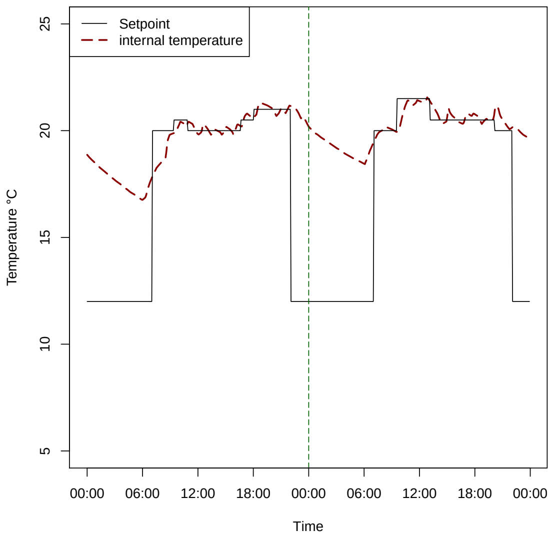


Figure 16: Example of home with frequent change in setpoint. Home 137 4-5 Jan 2016



4.2.3 Changes in setpoint

The focus in this section is short term changes which move the setpoint away from the normal IN period setpoint on a particular day. Changing the temperature setpoint is the main way users can directly intervene in the operation of the heating system, so an increase or decrease in the setpoint strongly suggests that the user is not satisfied with the current conditions (or foresees a need for a changed conditions in the near future). The characteristics of desired conditions may go beyond air temperature: other primary factors such as radiant temperature and air movement may also be important (Fanger, 1972). In the discussion that follows 'thermal requirements' refers to the combination of air and radiant temperatures which the person who is operating the controller aims to achieve. These requirements may change if other primary factors such as metabolic rate or clothing levels change.

The thermal requirements may not relate directly to the thermal comfort of the people operating the controls, as they could be making the change for other reasons including drying laundry, preventing mould, protecting pets or bringing the home to a socially appropriate temperature for guests (Strengers et al., 2014; Hitchings and Day, 2011). It should be noted that the temperature households try to achieve using the controller may not be the same as their ideal temperature. The user may lack understanding of the controls, be constrained by budget or other concerns, or know that their ideal conditions cannot be achieved with the equipment available.

In order to justify using changes in setpoint as an indication of changing thermal requirements, it is necessary to consider two other possible explanations; that changes in setpoint are a response to gains from heat sources other than the main heating system or that they are a result of the difference between the temperature measured by the controller and that experienced by the user, especially when the controller is not in the living room.

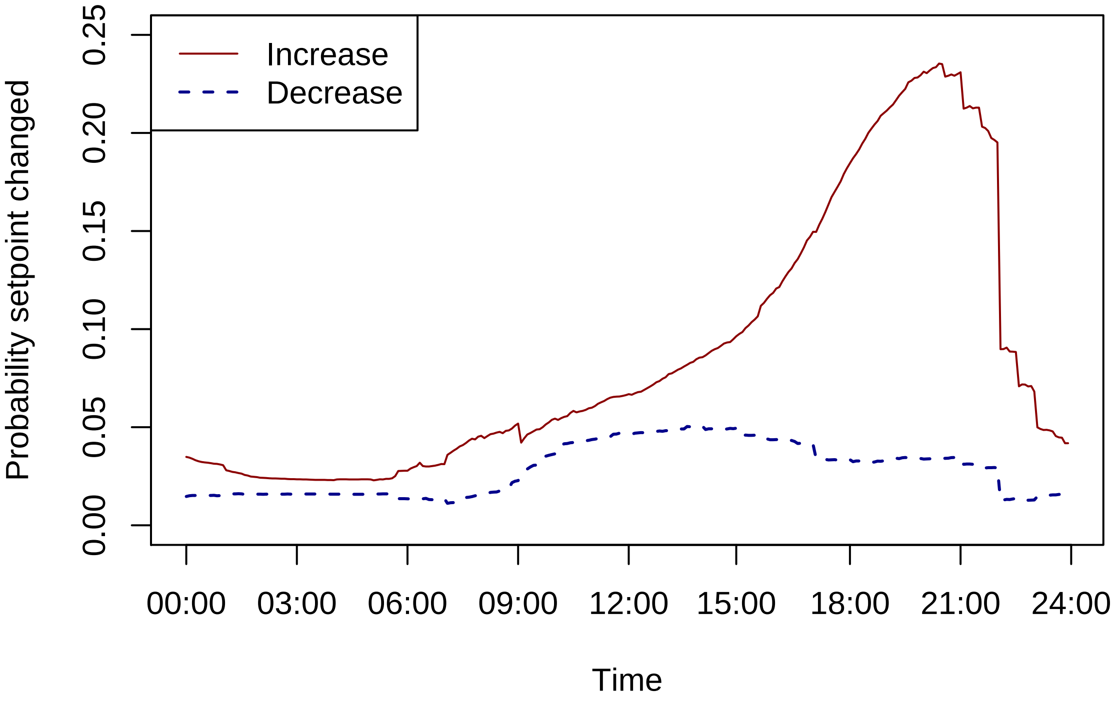
It is likely that there will be variations in the air temperature in different locations in the home so the temperature measured at the controller may not be same as that experienced by occupants, especially when differences in operative temperature (which takes into account radiant temperature, and air movement if the relative air speed is $> 0.2m/s$ (ASHRAE, 2013, p16)) are taken into account. If the offset - the difference between the measured and sensed conditions - is constant, any change is setpoint does represent a change in requirements. It is only in the cases where the offset is variable that a change in setpoint may be simply an adjustment to ensure that the conditions experienced by the user remain constant. The level and variability of the offset cannot be determined from the data available. Differential thermal gains and losses in different rooms in the home may lead to variations in the offset. This could add extra 'noise' to the data but seems unlikely to affect consistent trends in patterns of changes.

It is possible that heat gains (from supplementary heat sources, appliances or solar gains) could heat the space to a higher temperature than the minimum required. This could lead to users reducing the heating setpoint to try to reduce the temperature. Evidence for possible gains was examined. The maximum internal temperature exceeded maximum setpoint by more than one degree in only 6.6% of sample days. Solar gain could lead to a temperature higher than desired but this would be during daylight hours. During the period in question, latest sunset in the south of England was at 17:57 (Penzance, 26/2/16) so solar gain is unlikely to be a contributor to a higher temperature than required later in the evening.

In summary, short term adjustments of setpoints upwards from the normal IN period setting are likely to indicate a requirement for a higher operative temperature, while adjustments downward indicate either a requirement for a lower temperature or compensation for gains.

Figure 17 shows the mean probability that the setpoint has been changed at different times of day, distinguishing between times when the setpoint is increased above the value at the time when the heating came on, and times when it is decreased below this value (see Section 3.2.3). The percentage of changes involving a decrease is low and relatively constant through the day, while the percentage of increases is low in the first half of day but gradually increases to peak at 23.5% of sample days with increased setpoint at 20:25 and then drops very steeply at 22:00 (the median time at which the final IN period ends).

Figure 17: Proportions of homes with increased / decreased setpoint during day



The thermal comfort ‘heat balance’ approach (Fanger, 1972) offers a possible explanation for the increase in setpoints in the evening: lower activity levels at this point in the day could lead to lower metabolic rate and hence a requirement for a higher operative temperature to attain the same level of thermal satisfaction. The trend of an increasing proportion over several hours could be due to an increasing number of households with low metabolic activity as the evening progresses. There is the also the possibility that those with a low activity rate over a period of several hours require more than one setpoint increase as they become progressively more ‘chilled’ over time. Measurement of activity levels and thermal satisfaction through the evening period would be required to investigate this effect further.

Nicol’s concept of a daily thermal pathway (Nicol et al., 2012), mentioned in Section 2, offers a possible alternative explanation from an adaptive perspective, that the variation in requirements is likely to be influenced by expectations of what is a normal temperature for a particular place at a particular time of day.

4.2.4 Level of setpoint as an indication of thermal requirement

Section 4.2.3 justifies relating a change in setpoint to a change in thermal requirements, but can absolute temperature levels also be linked to requirements? Potential objections to this hypothesis are that some occupants are unable or unwilling to change setpoints and that for those who do, the setpoints are not always reached because the heating system capacity is too low or it is not run for long enough. The first objection does not apply for the majority of this sample as in 310 (80.1%) homes there was at least one change to the setpoint in the period, showing that a significant majority of the households are actively engaging with their controller.

The data were analysed to investigate the proportion of sample days when the maximum setpoint was actually reached. The maximum internal temperature is within one degree of the setpoint for 79% of sample days. This suggests that in many homes, residents are consistently achieving the conditions they require. To shed further light on the circumstances when internal temperature reaches the setpoint temperature, the analysis of maximum setpoint and temperature achieved was repeated for two halves of the day. Comparing the values for before and after 12:00 shown in Table 3 shows that the setpoint is reached less often in the morning. It seems likely that this is linked to shorter running hours in the morning period and the pattern of longer heating operation in the second part of the day allow the temperature to reach the setpoint in more cases. Examples of homes where the morning setpoint is, and is not, reached are shown in Figures 18 and 19.

Table 3: Temperature setpoint statistics

Period	% of sample days when max internal temperature > (max setpoint - 1°C)	Mean of max setpoint temperature °C	Mean of max internal temperature °C
Whole day	79.0%	20.5	20.1
00:00-11:59	71.0%	19.6	19.2
12:00-23:59	78.8%	20.4	20.0

Figure 18: Example where morning setpoint not reached. Home 210 22 Jan 2016

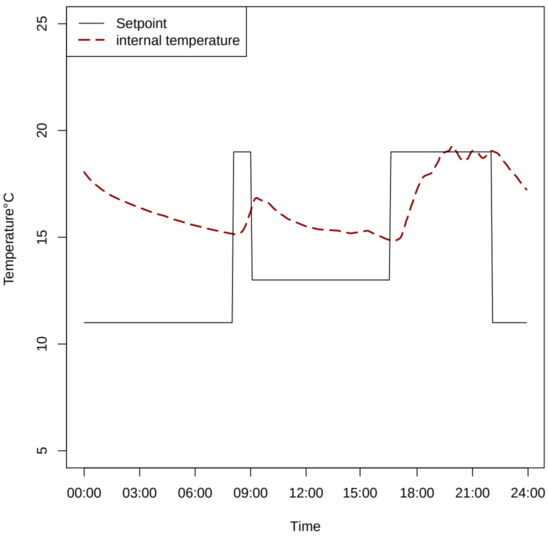
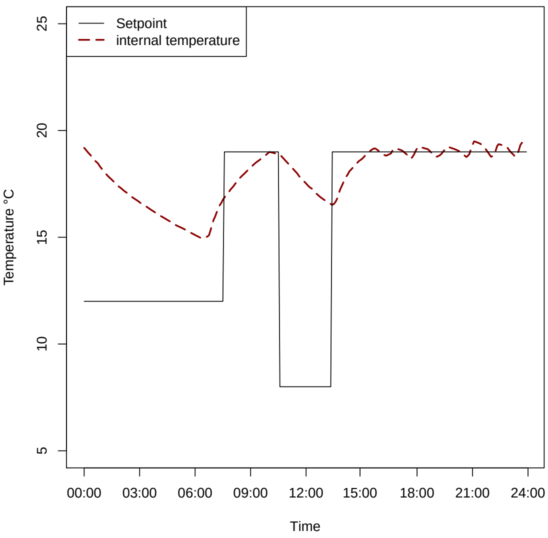


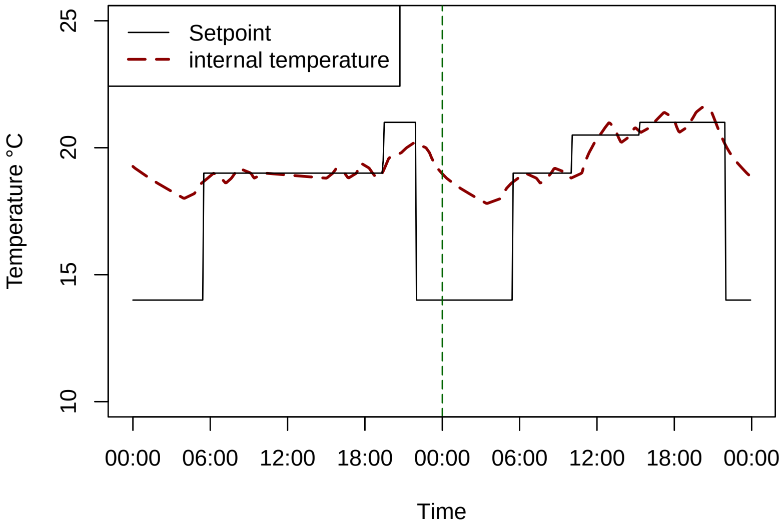
Figure 19: Example where both am and pm setpoint reached. Home 202 22 Jan 2016



4.2.5 Insights from interviews

Some responses of interviewees shed light on how temperature setpoints are chosen and when these are changed.

Figure 20: Stephen's house: setpoint changes at irregular times: 12 - 13 January 2016



Setpoint choice. Stephen and his wife use the PassivSystems mobile phone app to change the setpoint quite frequently, at irregular times but with a clear trend to higher evening temperatures (Figure 20). He described the condition when the setpoint would be increased as 'when we are cold and sitting still'.

Two families did not report frequent setpoint changes and this was confirmed by the data from their homes. They did report occasional changes on specific occasions. Michael mentioned increasing the temperature when bathing the children on a cold day and Catherine said she sometimes turns up the temperature when she has 'emergency laundry' to dry for the next day and wants a radiator on. These is an instance of Strengers et al.'s (2014) point that it is not simply the adults in the household that determine the temperatures chosen but also children, pets and valued objects such as plants and wine collections.

All respondents in multi-person households were asked whether there were differences of opinion about preferred temperature levels between family members. Sometimes a specific family member was mentioned as the main influence on temperature setting - for example Catherine said that she preferred cooler temperatures than her husband and son and that 'I try to keep everyone happy'. The morning setpoint was chosen to suit her son who 'feels the cold'. David said that his wife and daughters liked higher temperatures than he did. In one household the respondent said that ill health of one family member had led to a preference for higher temperatures than previous years.

Supplementary heat and solar gain. Four of the seven households said they did not use any supplementary heating, and one reported that they had used their open fire only once in the winter period. Hugh said he and his wife use their wood-burning stove in the living room 'every evening in winter' and John also reported using a recently installed wood burner 'when it's cold'.

The interview did not include questions about solar effects but two of the interviewees mentioned solar gains in south facing living rooms when they were speaking about how they controlled temperature. Eleanor mentioned that the lounge sometimes gets very hot when it is sunny and she ‘turns down the heating’ setpoint (her thermostat is in the hall) and David mentioned a similar reduction of setpoint ‘when things seem to be overheating’. This illustrates the possible explanation for reductions in setpoints during daylight hours mentioned above, and was the only time a variable offset between controller and experienced temperature was mentioned in the interviews.

The interviews highlighted some factors underlying patterns of heating operation which were not apparent from analysing the data.

Radiant heat. Michael’s view is that his 100 year old terrace warms up quickly and he sets the heating to come on 15 minutes before getting up. Data analysis shows it can take more than four hours for his home to reach the setpoint temperature (Figure 21). One possible explanation for this discrepancy in interpretation is that having the radiators on when they get up is the important factor for Michael and his family, not the air temperature. This was not explored in this interview but inspired an investigation of attitudes to radiant heat in subsequent interviews.

Hugh explained that he wants to have a radiator on when getting up in the morning but does not want it it too hot (17/18° C ‘is fine’) so has deliberately set up a ‘short burst’ - a short time period when heating comes on every morning. He set up another short burst ‘at lunch time’ aiming to get the heating to come on in the middle of the day if the weather is very cold (Figure 22). Catherine clearly has a picture in her mind that differentiated between having hot radiators and the heating set at IN (but the boiler not necessarily running). She said that particularly when it’s cold outside she puts the heating ‘back on’ ‘to get heat radiating’. Eleanor mentioned she sometimes ‘puts it [the setpoint] up a bit’ when she comes in from walking the dog and feels cold.

Figure 21: Michael’s house: slow rise in temperature. 21 Jan 2016

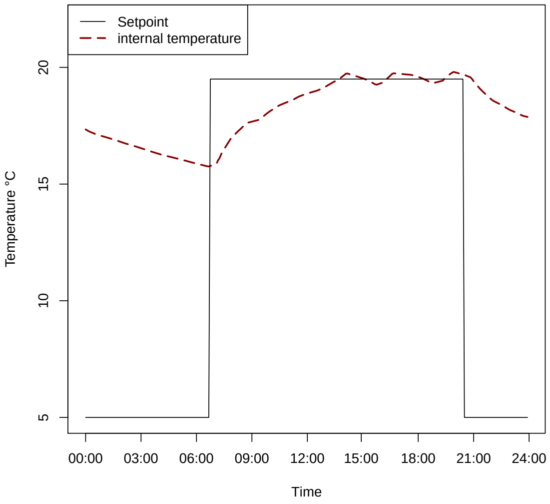
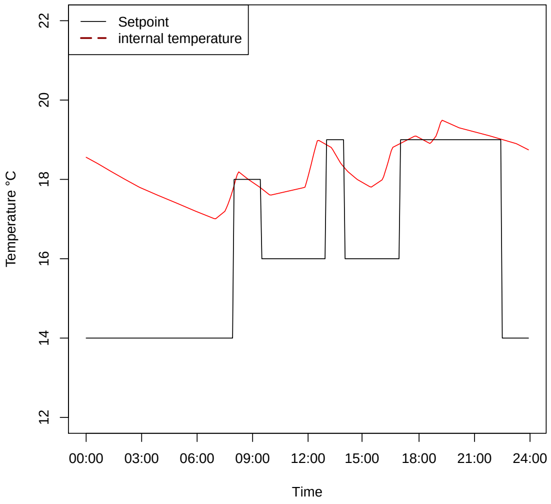


Figure 22: Hugh’s house: two short bursts early in the day. 23 Jan 2016



These findings, combined with the lower temperatures seen in the morning than evening in the data sample (Table 3), suggest that some occupants may be happier with lower temperatures early in the day, perhaps because they are more active in the morning or they are more concerned about radiant than air temperature at this point in the day.

Overnight temperature. The interview included open questions about temperature preferences at different times and in different parts of the home. A theme mentioned by four respondents was a preference for lower temperatures in the bedroom when sleeping at night. Catherine and her husband 'like a cool bedroom' and keep a bedroom window open at night and Stephen said that he kept upstairs cooler than downstairs using TRVs. This preference for lower temperatures when sleeping has also been noted by other researchers (Owen et al., 2012; Fell, 2016).

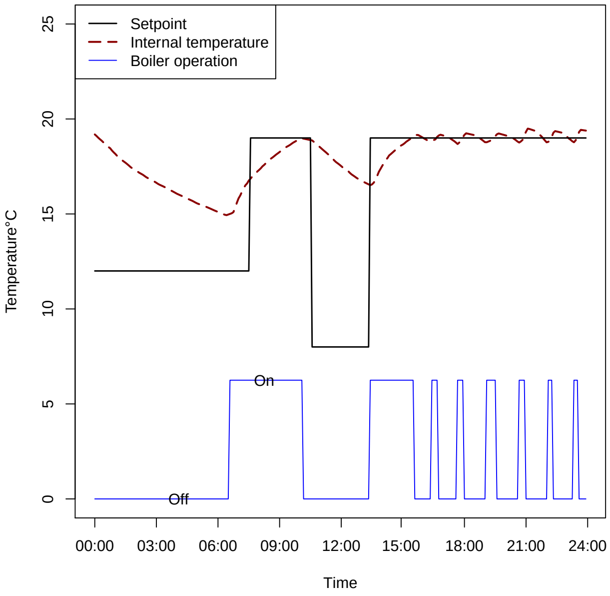
4.3 Patterns of demand

Having examined both the time and temperature dimensions of thermal routines, the final research question can now be addressed: how are patterns of space heating demand for a group of homes shaped by the combination of time and temperature controller settings from individual household thermal routines?

The discussion that follows uses the call for heat data to examine the pattern of cumulative demand for all 337 homes in the sample during the day. A boiler coincidence factor (the proportion of homes with boiler running at this point) is calculated for each five minute period in the day. As discussed in Section 3.2.3 the boiler running data do not map directly to total power used, but they do allow investigation the pattern of space heating demand over time.

The boiler is not running all the time during IN periods as it will cut in and out as required by the control system to maintain the desired temperature. Figure 23 shows a typical pattern of calls for heat in which the boiler initially operates continuously until the setpoint temperature is reached and then operates intermittently to maintain temperature.

Figure 23: Typical boiler operation pattern. Home 202 22 Jan 2016



In the example in Figure 23 the boiler starts in the morning before the setpoint rises. This shows the operation of the 'optimum start' feature of PassivSystems controllers described in Section 3.2.1. This feature also explains the fact that in Figure 24 below, in the period before the morning peak, the mean boiler coincidence factor starts to rise before the proportion of homes where the 'occupancy' is set to IN increases.

Figure 24: Daily pattern of boiler coincidence and IN occupancy period

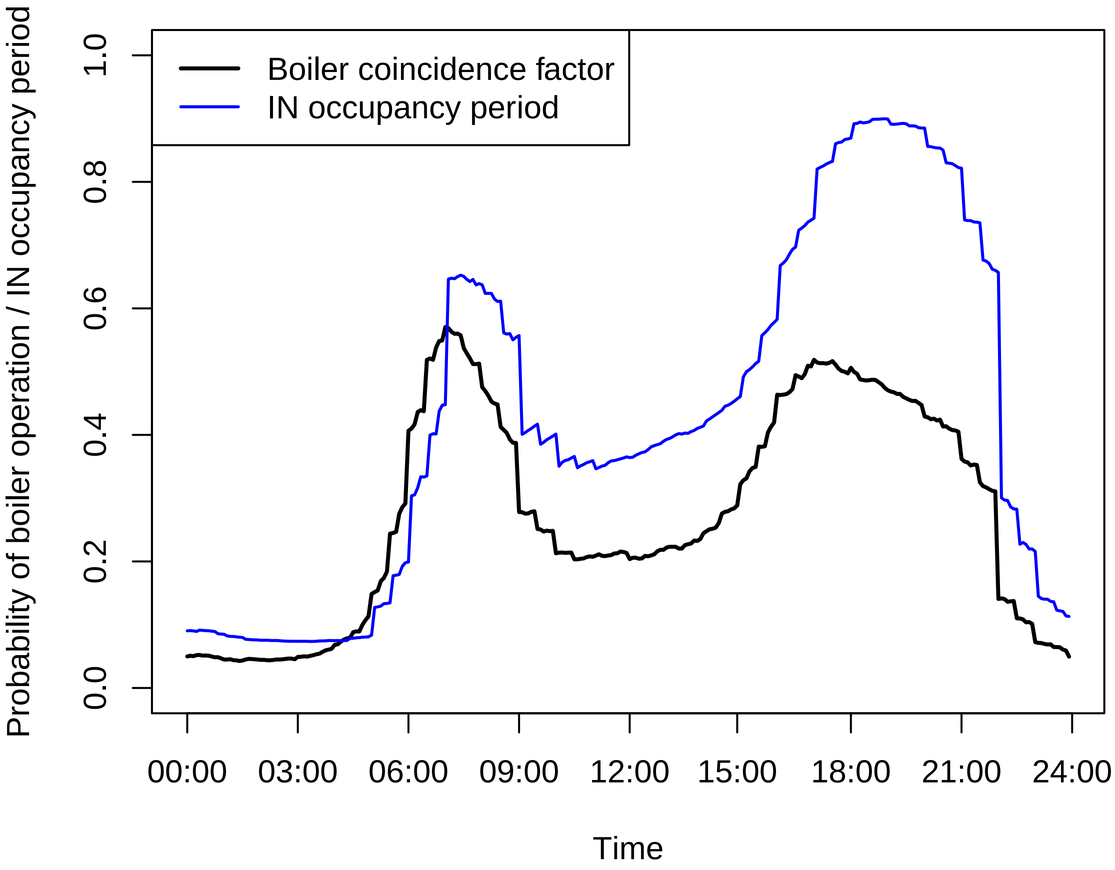


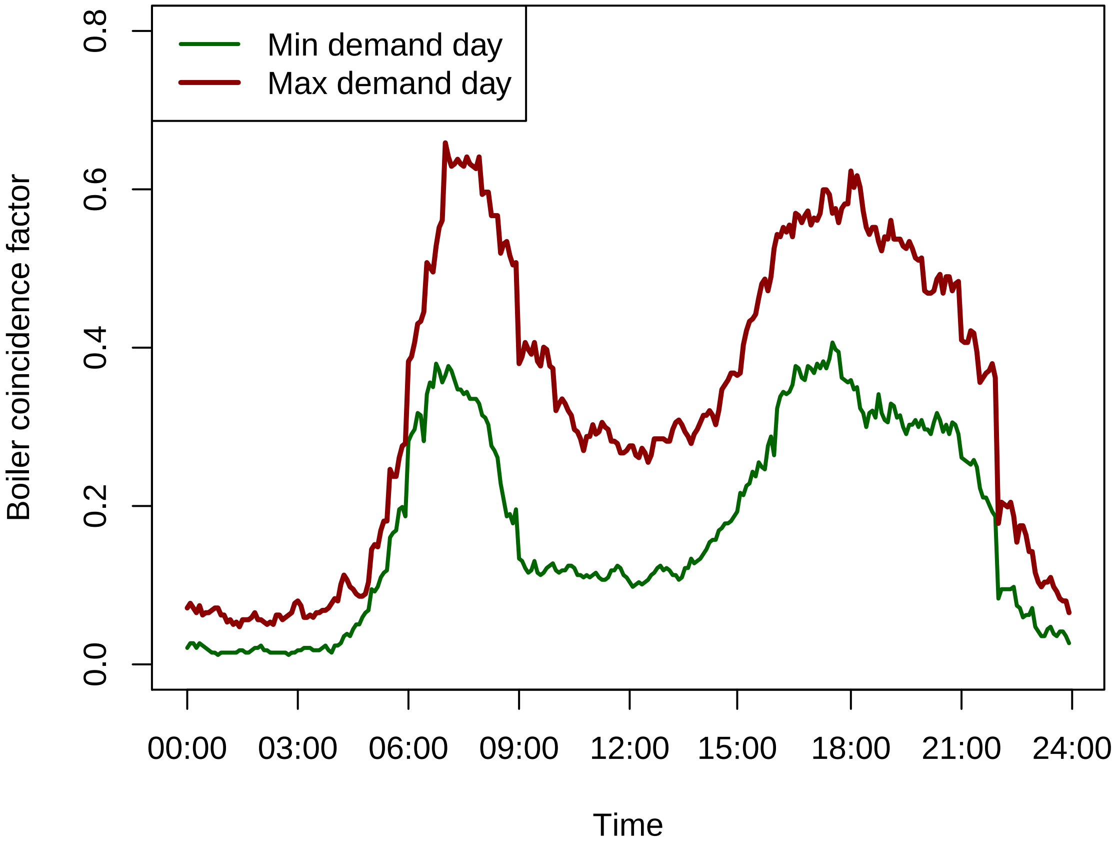
Figure 24 shows the mean for the 40 day period of the boiler coincidence factor for each five minute period in the day. The graph shows that there are particular times of day when demand across many homes coincides. Also plotted is the mean proportion of homes with 'occupancy' set to IN. It is noticeable that both parameters have a clear pattern of morning and evening peaks. However the morning peak in boiler coincidence (at 07:00) is higher than that in the evening (at 17:00), while the peak proportion of IN 'occupancy' occurs in the evening (at 18:55), not the morning. As demonstrated in Table 1, the morning routine (in which a large proportion of heating systems start up in the period around 07:00) contrasts with the less synchronous starting up of heating systems in the early evening.

If the interview findings that supplementary heat sources are more likely to be used in the evening can be extrapolated to the whole sample, this would suggest this is another factor likely to be causing a difference between morning and evening demand patterns. In homes where supplementary heating (such as a wood burner) is the main heat source in the living room in the evening, the demand on the boiler is likely to be lower at this time of day than in the morning.

The convergence of morning thermal routines is linked to society wide patterns of times when people get up to go to work, school and other regular activities. There is also a temperature dimension to the concentration of demand in the morning. The internal temperature averaged across all homes for all days reaches a minimum at 05:35 and there is clearly a widespread preference to minimise the use of heating when households are sleeping, so very few boilers are operating in the early hours of the morning. This means that, unlike in the early evening period, when there has been a preceding period of IN 'occupancy' in many homes (36.4% of homes have IN 'occupancy' set at noon in contrast to 7.4% at 03:00), there are a large proportion of boilers starting to operate at the same time. In Gould's (1996) terminology the preference for a low night-time temperature is acting as a 'wall' to bound the energy demand. This 'wall' is likely to be driven by a combination of physiological (cooler night time temperatures to trigger the sleep cycle), social (societal norms for heating operation) and socio-technical (dislike of heating system noise in the night) expectations.

This concentration of demand in the morning is an important factor when considering the impact of electrification of heat. The current focus of Demand Side Response activity is to move electricity demand away from the evening peak (Chan et al., 2014), but it seems likely that morning peaks in electricity use will become an increasing issue - these have already been identified in trials of heat pump use (Delta-ee, 2016).

Figure 25: Pattern of boiler coincidence for days with maximum and minimum total demand in the period



The sum of calls for heat for all homes for each day was calculated and used as a proxy for total heating demand in that day, so that variability in demand over the period could be investigated.

The total energy used in the day will depend on external temperature as there a higher rate of heat loss from the building when the outside temperature is lower. Figure 25 shows the mean boiler coincidence curves for the day with highest total demand and the one with lowest total demand. The difference in magnitude of the peaks of the boiler coincidence curve gives an indication of the variability in peak demand over the period studied. The figure shows that the timing of the peaks on the two days is very similar, even though the magnitude of the peaks is significantly lower on the low demand day.

The maximum demand day in the period is of most relevance for Distribution Network Operators (DNOs) since their network is designed to meet the peak load, and DNOs are concerned about the potential for local congestion (Balta-Ozkan et al., 2014). The relatively mild winter of 2015-16 does not represent the 1 in 20 extreme conditions used for network design (Delta-ee, 2016).

The timing of each daily peak in demand is important for the Transmission System Operator and energy suppliers tasked with matching supply and demand as demand rises towards a peak. The results from this investigation suggest that, if electrical heating operation patterns mirror those of gas boilers, electrification of heat could create a consistently timed peak in electricity demand on winter mornings.

5 Conclusions

5.1 Summary of findings

During the heating season there is a steep increase in domestic space heating energy demand between 06:00 and 07:00 in the morning, with the peak coincidence of boiler operation in the morning being higher than that in the evening peak period. The high level in synchronicity of heating start times in the morning contrasts with the less synchronous start times for the evening heating period, which contribute to a slower rate of rise and lower peak in demand (as represented by boiler coincidence factor) in the second half of the day.

The first time the heating switches on and the last time it switches off are reasonably consistent between homes and show a clear relationship to society-wide patterns that influence when people are asleep. As Shove points out in a discussion of Lefebvre (2004) ‘going to sleep and waking up are effectively collective processes even for those who do them alone’ (Shove et al., 2009, p.21). However the time at which the final (evening) running period starts and the total time for which the heating is run during the day vary considerably. This is in line with the results of other researchers (Shipworth et al., 2010; Kane et al., 2015) showing that actual heating operation hours in UK homes are very variable.

Interviews with householders show that thermal routines and patterns of occupancy do not necessarily coincide, for instance having the heating off in the middle of the day may be acceptable to occupants who are normally in the house during this period. This suggests that the assumption often made in energy modelling, that the heating will be set to run whenever the dwelling is occupied and the occupants are not asleep (Richardson et al., 2008; McKenna et al., 2015), is a significant simplification of the actual situation.

Analysis of changes made to temperature setpoints suggests that it is not correct to assume all households are satisfied with a consistent temperature whenever they are present in the home. A significant minority of the sample of households studied made frequent changes to their temperature settings and there is a clear pattern of increases to the temperature setpoint in the evening, peaking with nearly a quarter of the sample operating at an increased setpoint (compared to earlier in the same day) at 20:25.

There are indications that reaching a consistent setpoint may not be a key concern for some households in the morning, and that they are more concerned about the sensation of radiant heat from radiators. Quantifying the extent to which this applies would require further investigation and in-situ measurement.

The interviews with householders confirmed that the ‘primary factors’ identified by thermal comfort theory, especially air and radiant temperature and metabolic rate, are important in assessing whether residents of UK homes are satisfied with their their thermal conditions. However the focus of most thermal comfort research on measuring occupant satisfaction levels in a static environment is of limited value in the dynamic conditions of domestic buildings. In order to follow through from the insights of adaptive thermal comfort theory, more investigation of actions and expectations is required. Social practice theory’s focus on actions is very relevant to the interactions of householders with their heating controllers, offering an explanation of both regularities linked to wider social rhythms and irregularities as the timing of practices varies between households, or in the same household over time.

The concept of thermal routines, drawing on both thermal comfort and social practice theory, is a useful framework for examining the variability in heating controller settings. The results from this study suggest that household thermal routines around 07:00 in the morning are a particularly important consideration for a transition to future energy systems with a high proportion of low carbon heat. The close connection between thermal routines and regular practices in the home (particularly getting up and leaving for work or school) may need to be broken, so that the home is heated when residents are asleep in order to avoid high energy demand in the morning peak period. This challenges both current perceptions of the 'normal' way to operate heating systems and preferences for cooler night time temperatures.

5.2 Relevance

It is important for the designers of low carbon heating systems to understand the aspects of thermal routines that matter most to users of conventional heating. To provide systems that are acceptable to their users, designers need to understand which aspects of thermal routines are flexible, and which alterations are likely to face significant unpopularity. Homeowners considering heating retrofits (a key audience if carbon reduction targets are to be met (Delta-ee, 2012)) are unlikely to make the necessary investment of money and effort to install a low carbon system if their social networks report unsatisfactory performance.

The findings are also relevant for policymakers interested in reducing CO_2 emissions from heating. Households will (within constraints of capacity, knowledge and cost) operate their heating systems in ways that deliver the temperatures and running patterns that meet their perceived needs. If low carbon heating technologies seem to meet these expectations less well than established (gas boiler) central heating systems, firstly it will be very difficult to persuade householders to adopt these new technologies, and secondly those households which do install them may not follow optimum operating practice (Caird et al., 2012). This is also an issue for those wishing to provide Demand Side Response services based on flexible heating demand. Understanding constraints on flexibility in thermal routines will be important to electricity network operators assessing the impact of the electrification of heating on electricity networks.

Investigation of thermal routines may identify ways that energy can be saved by delivering the thermal patterns required with less energy. For example, if the sensation of radiant heat is the key concern of the occupant, it might be possible to deliver the radiant heat at a lower air temperature. Algorithms to ensure temperature levels match different requirements at different times of day, rather than delivering a consistent temperature whenever the heating is on, may also lead to savings.

The findings on actual heating operation patterns are relevant for energy modelling. When modelling energy demand in the home, assumptions must be made about when the heating is running and what 'demand temperature' has been set by the users. The BREDEM family of models is a foundation for many UK building stock models used to assess the impact of different energy efficiency measures (Kavgic et al., 2010; Shipworth, 2013). Modelling using BREDEM usually assumes that the heating will run for two periods on weekdays, in the morning and evening (Anderson et al., 2002). This assumption has important implications for policy since the pattern of demand is a fundamental driver of the heating energy used, and if the actual operational pattern is different to (or more variable than) the one assumed, there is a risk that the modelled savings will not be achieved (Huebner et al., 2015). For measures where the savings are sensitive to the variability of operation patterns (this may apply particularly to measures which affect the dynamic performance of the building fabric) the expected savings for a range of different heating routines should be assessed.

5.3 Limitations and recommendations for future work

Users of Passiv Systems controllers may not represent the wider population as they are encouraged by the default setting and assumptions built into the PassivSystems user interface to choose different temperature settings for regular periods. It would be valuable to compare findings from this study with those across a wider group, including households which control their heating manually.

The interviews provided valuable insights into the user perspective, but only reached one person in each of a small number of households. Extending the investigation to a wider group, and several members of each household, would give more confidence in the general applicability of the findings.

This investigation focused on a winter period in the middle of heating season. Extending the analysis to the shoulder seasons would provide a seasonal dimension to thermal routines.

Tentative findings from this study which appear to warrant further investigation are:

- The range of temperatures within which people feel comfortable in a domestic setting changes with time of day and activity level.
- The sensation of radiant heat in particular locations is a key factor for some households' morning thermal routine. In order to investigate this surveys of perceptions of radiant heat, ideally combined with physical measurements of the radiant conditions encountered by the respondents, would be required.

References

Anderson, B. (2016). Demanding times. In *Proceedings of DEMAND Centre Conference, Lancaster, 13-15 April 2016*.

Anderson, B., Chapman, P., Cutland, N., Dickson, C., Hendrson, G., Henderson, J., Iles, P., Kosima, L., and Shorrock, L. (2002). *BREDEM-8 Model desciption 2001 update.* BRE, Garston, Watford.

ASHRAE (2013). *Thermal environmental conditions for human occupancy. ASHRAE Standard 55-2013*. ASHRAE, Atlanta, Ga.

Balta-Ozkan, N., Watson, T., Connor, P., Axon, C., Whitmarsh, L., Davidson, R., Spence, A., Xenias, D., Cipcigan, L., and Taylor, G. (2014). *Scenarios for the Development of Smart Grids in the UK - Synthesis Report*. UKERC, London.

Brager, G. S. and de Dear, R. J. (1998). Thermal adaptation in the built environment: a literature review. *Energy and Buildings*, 27(1):83–96.

Caird, S., Roy, R., and Potter, S. (2012). Domestic heat pumps in the UK: user behaviour, satisfaction and performance. *Energy Efficiency*, 5(3):283–301.

Chan, A., Moreno, J., and Hughes, M. (2014). Further analysis of data from the HEUS Electricity price signals and demand response. https://www.gov.uk/government/collections/household-electricity-survey. [accessed 18/08/2016].

Davidoff, S., Lee, M. K., Yiu, C., Zimmerman, J., and Dey, A. K. (2006). Principles of Smart Home Control. In Dourish, P. and Friday, A., editors, *UbiComp 2006: Ubiquitous Computing*, number 4206 in Lecture Notes in Computer Science, pages 19–34. Springer Berlin Heidelberg.

de Dear, R. (2004). Thermal comfort in practice. *Indoor air*, 14:32–39.

de Dear, R. and Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *Center for the Built Environment*.

DECC (2012a). Emissions from heat : statistical summary. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/140095/4093-emissions-heat-statistical-summary.pdf. [accessed 20/01/2016].

DECC (2012b). The future of heating: A strategic framework for low carbon heat in the uk. https://www.gov.uk/government/publications/the-future-of-heating-a-strategic-framework-for-low-carbon-heat. [accessed 28/06/2016].

Delta-ee (2012). 2050 pathways for domestic heat final report 16th october 2012. http://www.energynetworks.org/gas/futures/2050-pathways-for-domestic-heat.html. [accessed 20/01/2016].

Delta-ee (2016). Managing the future network impact of electrification of heat. final report for ENWL. http://www.enwl.co.uk/about-us/the-future/nia-lcnf-tier-1/demand-scenarios. [accessed 20/07/2016].

Dillman, D. A. (2000). *Mail and internet surveys: The tailored design method*, volume 2. Wiley New York.

Fanger, P. (1972). *Thermal comfort: analysis and applications in environmental engineering*. McGraw-Hill, New York.

Fell, M. (2016). *Taking Charge: Perceived control and acceptability of domestic demand-side response*. PhD thesis, University College London.

Gould, S. J. (1996). *Full house*. harmony Books, New York.

Gram-Hanssen, K. (2010). Residential heat comfort practices: understanding users. *Building Research & Information*, 38(2):175–186.

Hellwig, R. T. (2015). Perceived control in indoor environments: a conceptual approach. *Building Research & Information*, 43(3):302–315.

Hensen, J. (1990). Literature review on thermal comfort in transient conditions. *Building and Environment*, 25(4):309–316.

Hitchings, R. and Day, R. (2011). How older people relate to the private winter warmth practices of their peers and why we should be interested. *Environment and Planning A*, 43(10):2452–2467.

Huebner, G. M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., and Summerfield, A. (2013). Heating patterns in english homes: Comparing results from a national survey against common model assumptions. *Building and Environment*, 70:298–305.

Huebner, G. M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., and Summerfield, A. J. (2015). The shape of warmth: temperature profiles in living rooms. *Building Research & Information*, 43(2):185–196.

Humphreys, M. (1978). Outdoor temperatures and comfort indoors. *Batiment International, Building Research and Practice*, 6(2):92–92.

Humphreys, M. (1995). Thermal comfort temperatures and the habits of hobbits. *Standards for Thermal Comfort: Indoor Air Temperature Standards for the 21st Century*, pages 3–13.

Johnson, R. B. and Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational researcher*, 33(7):14–26.

Kane, T., Firth, S. K., and Lomas, K. J. (2015). How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling. *Energy and Buildings*, 86:817–832.

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., and Djurovic-Petrovic, M. (2010). A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment*, 45(7):1683–1697.

Kingma, B. and van Marken Lichtenbelt, W. (2015). Energy consumption in buildings and female thermal demand. *Nature Climate Change*, 5(12):1054–1056.

Lader, D., Short, S., and Gershuny, J. (2006). The time use survey 2005.

Lefebvre, H. (2004). *Rhythmanalysis: Space, time and everyday life*. A&C Black.

Lund, H., Mller, B., Mathiesen, B. V., and Dyrelund, A. (2010). The role of district heating in future renewable energy systems. *Energy*, 35(3):1381–1390.

Luo, M., de Dear, R., Ji, W., Bin, C., Lin, B., Ouyang, Q., and Zhu, Y. (2016). The dynamics of thermal comfort expectations: The problem, challenge and impication. *Building and Environment*, 95:322–329.

McKenna, E., Krawczynski, M., and Thomson, M. (2015). Four-state domestic building occupancy model for energy demand simulations. *Energy and Buildings*, 96:30–39.

Met Office (2016). Further analysis of data from the heus electricity price signals and demand response. http://www.metoffice.gov.uk/learning/science/first-steps/observations/weather-stations. [accessed 18/08/2016].

National Grid (2015). *Future Energy Scenarios*. National Grid, Warwick.

Nicol, F., Humphreys, M., and Roaf, S. (2012). *Adaptive thermal comfort : principles and practice.* Routledge, London.

Owen, A., Mitchell, G., and Unsworth, R. (2012). Reducing carbon, tackling fuel poverty: adoption and performance of air-source heat pumps in East Yorkshire, UK. *Local Environment*, 18(7):817–833.

Palmer, J. and Cooper, I. (2014). UK housing energy fact file 2013. https://www.gov.uk/government/statistics/united-kingdom-housing-energy-fact-file-2013. [accessed 18/08/2016].

Powells, G., Bulkeley, H., Bell, S., and Judson, E. (2014). Peak electricity demand and the flexibility of everyday life. *Geoforum*, 55:43–52.

Redpoint (2013). Modelling to support the future of heating: Meeting the challenge. https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge. [accessed 19/04/2016].

Richardson, I., Thomson, M., and Infield, D. (2008). A high-resolution domestic building occupancy model for energy demand simulations. *Energy and buildings*, 40(8):1560–1566.

Robson, C. (2011). *Real world research : a resource for users of social research methods in applied setting*. Wiley, Chichester.

Rousseeuw, P. J. and Croux, C. (1993). Alternatives to the median absolute deviation. *Journal of the American Statistical association*, 88(424):1273–1283.

Schellen, L., Loomans, M., de Wit, M. d., Olesen, B., and van Marken Lichtenbelt, W. (2012). The influence of local effects on thermal sensation under non-uniform environmental conditionsgender differences in thermophysiology, thermal comfort and productivity during convective and radiant cooling. *Physiology & behavior*, 107(2):252–261.

Schweiker, M., Brasche, S., Bischof, W., Hawighorst, M., Voss, K., and Wagner, A. (2012). Development and validation of a methodology to challenge the adaptive comfort model. *Building and Environment*, 49:336–347.

Shipworth, D. (2013). The vernacular architecture of household energy models. *Perspectives on Science*, 21(2):250–266.

Shipworth, D., Huebner, G., Schweiker, M., and Kingma, B. (2016). Diversity in thermal sensation: drivers of variance and methodological artefacts. In *Proceedings of 9th Windsor Conference: Making Comfort Relevant, 7-10 April 2016, Cumberland Lodge, Windsor*, London. Network for comfort and energy use in buildings.

Shipworth, M., Firth, S. K., Gentry, M. I., Wright, A. J., Shipworth, D. T., and Lomas, K. J. (2010). Central heating thermostat settings and timing: building demographics. *Building Research & Information*, 38(1):50–69.

Shove, E. (2003). *Comfort, cleanliness and convenience: the social organization of normality*. New technologies/new cultures. Berg, Oxford.

Shove, E., Pantzar, M., and Watson, M. (2012). *The Dynamics of Social Practice: Everyday Life and how it Changes*. SAGE Publications Ltd, Los Angeles.

Shove, E., Trentmann, F., and Wilk, R. R. (2009). *Time, consumption and everyday life: practice, materiality and culture*. Cultures of consumption series. Berg, Oxford.

Strbac, G. (2008). Demand side management: Benefits and challenges. *Energy Policy*, 36(12):4419–4426.

Strengers, Y., Nicholls, L., and Maller, C. (2014). Curious energy consumers: humans and nonhumans in assemblages of household practice. *Journal of Consumer Culture*.

Summerfield, A., Oreszczyn, T., Hamilton, I., Shipworth, D., Huebner, G., Lowe, R., and Ruyssevelt, P. (2015). Empirical variation in 24-h profiles of delivered power for a sample of UK dwellings: Implications for evaluating energy savings. *Energy and Buildings*, 88:193–202.

Tweed, C., Dixon, D., Hinton, E., and Bickerstaff, K. (2014). Thermal comfort practices in the home and their impact on energy consumption. *Architectural Engineering and Design Management*, 10(1-2):1–24.

UK Parliament (2008). Climate Change Act 2008.

UK Power Networks (2014). Residential demand side response for outage management and as an alternative to network reinforcement. http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Low-Carbon-London-(LCL)/. [accessed 6/08/2016].

Uraikul, V., Chan, C. W., and Tontiwachwuthikul, P. (2000). Development of an expert system for optimizing natural gas pipeline operations. *Expert Systems with Applications*, 18(4):271–282.

Walker, G. (2014). The dynamics of energy demand: change, rhythm and synchronicity. *Energy Research & Social Science*, 1:49–55.

Zerubavel, E. (1985). *Hidden rhythms : schedules and calendars in social life*. University of California Press, Berkeley ; London.

Appendix A Recruitment e-mail sent out by PassivSystems

Dear X

PassivSystems are collaborating with Clare Hanmer at University College London (UCL) who is investigating how people use heating controls to achieve the conditions they want in their homes. Clare would value your input in a short telephone interview (approximately 20 minutes) about how you decide on the settings for your heating and whether you obtain the temperatures you would like in your home. Please click here if you are willing to take part.

What does the research involve?

If you agree to participate, PassivSystems will send data on your settings and the thermostat temperature in your home to Clare at UCL. She will then arrange the telephone interview at a time to suit you. The data will be held securely and all personal details will be kept confidential.

What's so important about understanding how people use their heating?

These days there's a lot of focus on saving energy but up to now there hasnt been much research on how people decide when to run their heating and what temperatures they find comfortable. Understanding what temperature people want and how this varies between households is important to make sure new energy-saving products work for everyone.

Who is doing the research?

This research forms part of Clare Hanmer's work towards a PhD in Energy Demand Studies at the UCL Energy Institute. If you have any questions about the study, please get in touch with Clare (clare.hanmer.15@ucl.ac.uk), or her supervisor, Dr David Shipworth (d.shipworth@ucl.ac.uk). For more information see http://www.lolo.ac.uk/people/clare-hanmer-2/ and http://www.bartlett.ucl.ac.uk/energy.

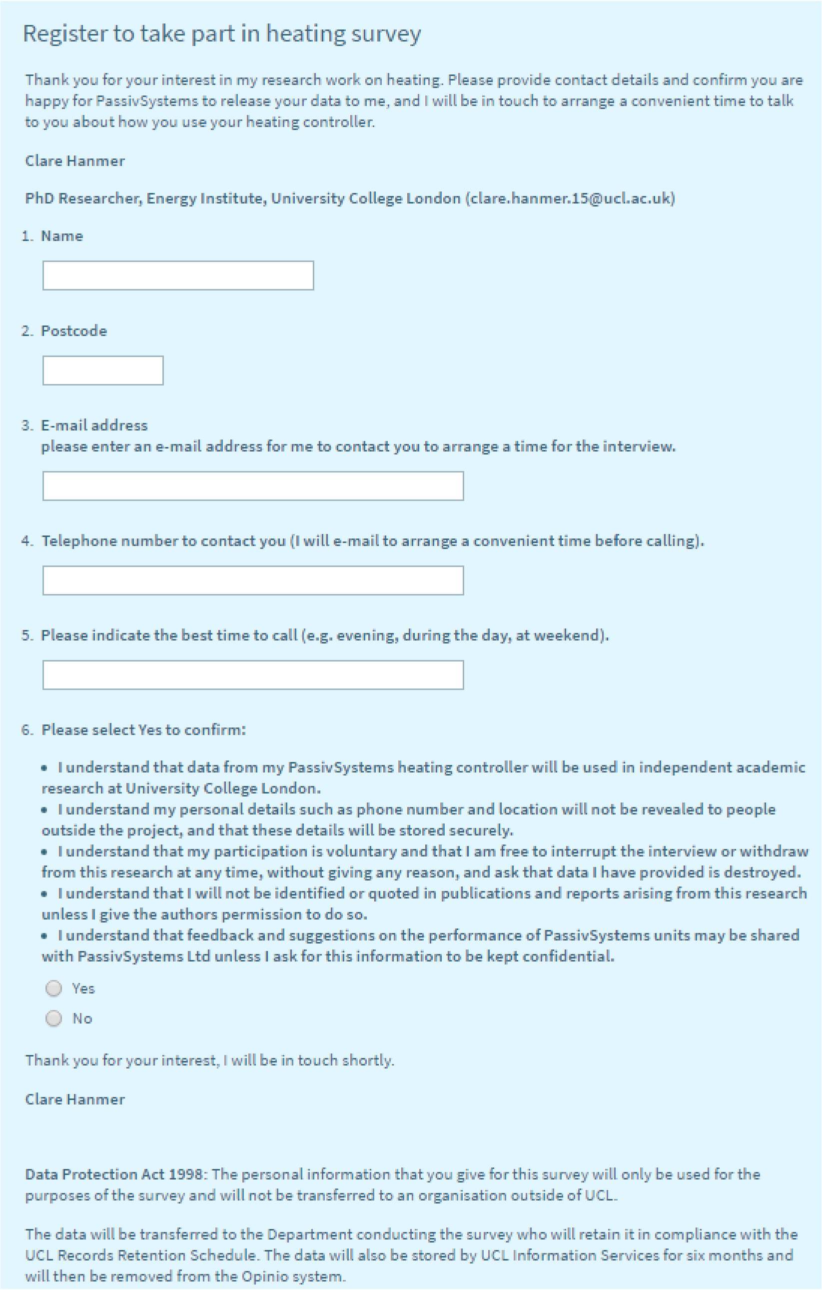
If you have any concerns about the legitimacy of this email, please contact PassivSystems Support (details below).

Kind Regards

The Support Team

PassivSystems Limited

Appendix B Registration via Opinio



Register to take part in heating survey

Thank you for your interest in my research work on heating. Please provide contact details and confirm you are happy for PassivSystems to release your data to me, and I will be in touch to arrange a convenient time to talk to you about how you use your heating controller.

Clare Hanmer

PhD Researcher, Energy Institute, University College London (clare.hanmer.15@ucl.ac.uk)

1. Name

2. Postcode

3. E-mail address
   please enter an e-mail address for me to contact you to arrange a time for the interview.

4. Telephone number to contact you (I will e-mail to arrange a convenient time before calling).

5. Please indicate the best time to call (e.g. evening, during the day, at weekend).

6. Please select Yes to confirm:
   - I understand that data from my PassivSystems heating controller will be used in independent academic research at University College London.
   - I understand my personal details such as phone number and location will not be revealed to people outside the project, and that these details will be stored securely.
   - I understand that my participation is voluntary and that I am free to interrupt the interview or withdraw from this research at any time, without giving any reason, and ask that data I have provided is destroyed.
   - I understand that I will not be identified or quoted in publications and reports arising from this research unless I give the authors permission to do so.
   - I understand that feedback and suggestions on the performance of PassivSystems units may be shared with PassivSystems Ltd unless I ask for this information to be kept confidential.

   ○ Yes
   ○ No

Thank you for your interest, I will be in touch shortly.

Clare Hanmer

Data Protection Act 1998: The personal information that you give for this survey will only be used for the purposes of the survey and will not be transferred to an organisation outside of UCL.

The data will be transferred to the Department conducting the survey who will retain it in compliance with the UCL Records Retention Schedule. The data will also be stored by UCL Information Services for six months and will then be removed from the Opinio system.

Appendix C Interview guide

Introduce study

Building and heating information

Type and age of building

Heating type

Any supplementary heating?

Location of thermostat

Information on household demographics

How many people normally live in home?

No. of children under 16

No. of adults over 65

Information on controller settings

How do you set up heating schedule?

How often do you change schedule? Under what circumstances? Have there been times when you haven't got the temperature you wanted?

Test awareness of the optimum start feature

Are there different temperatures in different parts of the home?

Do you change settings when the weather outside changes?

How quickly does the house warm up?

Do you want different temperatures at different times of day?

Are there differences in preferences for temperature levels among members of the household? How are these resolved?

What is your main concern when choosing heating settings: comfort / cost / reducing emissions?

Wrap up

Check interviewee happy to be included / quoted in report. Are you happy to be contacted again?

Appendix D Key features of interviewed households

Date	Psue-donym	Controller type	No in household	House type	House age	Region	Thermostat
18/03/2016	Michael	Zigbee	4 (2 children)	Terrace	1910s	NW	in hall
21/04/2016	David	Zigbee	4 (2 children)	Semi	1950s	NW	in lounge
26/04/2015	Eleanor	Zigbee	1	Bungalow	1970s	Yorks	in hall
17/05/2016	Hugh	ZWave	2	Detached	1960s	WM	in hall
19/05/2016	Stephen	ZWave	2	Detached	1910s	SE	in lounge
22/05/2016	Catherine	Zigbee	3 (1 child)	Semi	1970s	Scotland	in lounge
05/06/2016	John	Zigbee	2	Bungalow	1930s	NE	in hall