Household thermal routines and their impact on space heating demand patterns

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Abstract

Patterns of home heating demand during the day have significant implications for the design of energy networks and will be an important consideration in the introduction of low carbon heating systems such as heat pumps.

In homes in the UK it is very common to operate space heating intermittently; the heating is usually switched off when the occupants are asleep at night and when they are out during the day. The strong association between heating operation and household routines leads to a morning peak in demand which, if it persists following electrification of heating, will require significant reinforcement of electricity supply networks.

This paper examines factors that underlie current UK home heating practices. A unique dataset of heating controller settings from 337 UK homes with smart heating controllers allows investigation of how patterns of heating operation in individual homes contribute to daily patterns of space heating energy consumption at the group level. A mixed method approach is followed, combining quantitative analysis of data with interviews with householders, drawing on insights from social practice theory. The peak level of space heating demand is found to be higher in the morning than the evening.

The concept of thermal routines is introduced, bringing a time dimension to the consideration of domestic thermal comfort and recognising that demand for space heating is linked to patterns of practices in the home, which are themselves linked to social routines, e.g. timing of work and school. 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. Factors that currently limit flexibility of heating demand in the UK are identified and the implications for a transition to low carbon heating sources are discussed.

Introduction

This paper reports on a study investigating how schedules for heating operation in individual homes have an impact on daily patterns of space heating demand. Domestic space heating accounts for 11 % of the UK's greenhouse gas emissions (DECC, 2012) and 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.

The predominant type of heating in the UK is central heating from a gas boiler: 90 % of homes have central heating (the vast majority with hot water circulating through radiators) and 91 % of these are fuelled by natural gas (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 for example electric heat pumps or district heating from a low carbon heat source (Delta-ee, 2012).

In homes in the UK during the winter heating season, it is very common to operate space 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 internal temperatures during the day most commonly show a pattern of peaks and troughs rather than a steady temperature (Huebner et al., 2015; 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' (p. 198).

Patterns of heat demand will become increasingly important as the task of meeting peak demand periods in the UK is moved away from the gas supply system to electricity networks as the transition to low carbon heating progresses. 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, but electricity supply has to match demand on a second by second basis, which means that the electricity network must be designed to supply short term demand peaks (Strbac, 2008). A transition to electric heat pumps in many homes will have a significant impact on these peaks (Redpoint, 2013).

Running patterns can be influenced by variable time of use tariffs, designed to encourage shifting away from peak times. Providing Demand Side Response (DSR) services, in which consumption patterns are modified in response to an external signal such as price (Ofgem, 2016) will require flexible running - for example operating the heating system ahead of, but not during, a peak period in order to pre-heat the home to provide the temperature required during the peak period. If DSR management of heating is to be successful, the altered operation patterns must be acceptable to householders and sensitive to the diversity of occupant needs.

This paper focuses on typical heating patterns and expectations in UK homes. The data on which this study is based were supplied from PassivLiving HEAT units controlling either oil or gas boilers. The controllers form part of a 'smart heating service' provided by PassivSystems Ltd. This is the first time, to the authors' knowledge, that analysis of heating controller setting data for a group of several hundred UK homes has been published; previous studies (Huebner et al., 2013; Kane et al., 2015) have inferred heating controller settings from temperature measurement or answers to surveys, because records of the actual settings were not available.

The results described are specific to the UK context of intermittent heating operation with gas boilers as the predominant central heating technology, however the concepts introduced are also relevant to the analysis of heating use in other countries. Two examples suggest that heating demand also varies in a regular pattern over the day in countries with a very different supply context (a high proportion of electric heating). In Morch et al. (2013, Figure 4) shows morning and evening peaks in electricity demand for space heating in Norway and modelling for RTE (2016) suggests domestic space heating demand in France at the peak time of 20:00 is 34 % higher than that at 16:00.

The next section of the paper introduces the concept of thermal routines, which is used as a framework for the study, and outlines the research traditions on which this concept draws. The following section describes the mixed method approach that was followed to investigate thermal routines, combining analysis of data from heating controllers with interviews with households. Next, findings about individual household routines and how these combine to affect aggregated energy demand patterns are discussed. The concluding section highlights the challenges established thermal routines pose for a transition to low carbon heating.

Developing a concept of thermal routines

The concept of thermal routines aims to represent how daily patterns of space heating demand are influenced both by rhythms of daily activities in the home, and by requirements for particular internal temperatures at different times. This section describes how thermal routines build on two theoretical approaches (thermal comfort and social practice theory) to provide a framework for looking at space heating energy use in the dynamic environment of the home.

THERMAL COMFORT

The long tradition of work on thermal comfort offers insights into the thermal conditions preferred by building occupants. ASHRAE Standard 55-2013 *Thermal Environmental Conditions for Human Occupancy* defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2013, p. 3). The 'heat balance' model of thermal comfort is based on equations for heat exchange with the environment (Fanger, 1970), and relates the comfort rating reported by building occupants to six 'primary factors': air and radiant temperature, air movement, relative humidity, clothing level and metabolic rate of the person.

'Adaptive thermal comfort' is an approach which acknowledges 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. Much adaptation involves changing the 'primary factors' in the heat balance equation, for instance wearing additional clothing when the temperature drops, but there is an additional psychological dimension (not included in the heat balance model) based on the occupants' perception of the opportunities available to control their conditions (Hellwig, 2015) and on their expectations of typical or appropriate conditions (Nicol et al., 2012).

The changing thermal environment of most UK homes in the heating season is very different to the static conditions investigated in much of the thermal comfort research. UK homes experience significant swings in temperature over 24 hours making them thermally dynamic environments. Findings from historic comfort studies, which have mostly taken place in climate chambers and non-domestic buildings, are therefore less directly useful to understanding how householders might adapt to and change their thermal environments.

The focus of much thermal comfort research is on measuring occupants' *responses to* their thermal environment (typically self-reported thermal sensation and preference) – and less on occupants' *actions to create* their thermal environment, i.e. investigating what they do to achieve a comfortable state. Studying comfort response is more relevant for buildings where occupants have limited opportunities to control conditions (e.g. large office environments) than for domestic settings with adequately sized heating systems. 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'.

PRACTICES, RHYTHMS AND ROUTINES

Social practice theory offers an explanation of how heating energy use is linked to everyday activities in the home. That there is a regular temporal pattern to many practices is highlighted in Reckwitz' frequently cited definition of practice as 'a routinised type of behaviour' (Reckwitz, 2002, p. 249).

Walker (2014) describes how 'most social practices entail some form of energy "demand"'(p. 50). Heating is used to provide an appropriate thermal environment for activities in the home and so is linked to a suite of different practices (for example getting dressed, preparing and eating meals, caring for children, watching television). Some practices may have an impact on heating demand even though they are not directly related to achieving thermal comfort. For example, opening a window to ventilate cooking odours will create extra heating demand as cold air enters the house, or the heating thermostat may be turned to a higher setting because of a need to dry laundry hung on radiators.

Daily patterns in energy use in the home will be influenced by patterns of everyday practices (e.g. when the occupants 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' (Zerubavel, 1985, p. 68).

THERMAL ROUTINES

Thermal routines, as considered in this study, 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.

Shove makes a useful distinction between 'routine' and 'a routine': "the term '*routine*' represents and describes the regularity with which a practice is enacted. (…) '*a routine*' like a morning routine, or the Wednesday routine, has to do with the way in which multiple practices are ordered and scheduled" (Shove, 2012, p. 103). Household thermal routines follow this definition of 'a routine', and are created by regular practices in the home which are linked to demand for space heating.

Figure 1 indicates how thermal routines include both setting heating controllers and also actions not directly linked to the central heating, such as use of supplementary heat sources in addition to the main heating system (e.g. a wood burner or electric fan heater) or wearing extra clothing. The diagram shows how 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. The practices in individual households are influenced by society-wide rhythms of activity.

The concept of thermal routines brings a time dimension to the normally static consideration of thermal comfort. It recognises that demand for domestic space heating is linked to patterns of practices in the home. It offers a language for talking to householders about their regular activities and how these interact with their energy use for heating.

Methods

Using the concept of thermal routines as a framework, the study investigated regular patterns in time in weekday heating operation data. Quantitative and qualitative methods were combined to investigate how daily patterns of space heating demand for a group of homes relate to individual household thermal routines.

A dataset from heating controllers allowed quantitative assessment of synchronicity and diversity of heating operation times across a sample of 337 homes. This allowed description of actions taken – in terms of the settings entered into heating controllers – but it is only by consulting the households concerned that the reasons why they have acted in this way can be explored. Interviews with seven heating users explored factors affecting their thermal routines. This mixed-method approach had the additional advantage that the interviews brought to light practices not anticipated by the researcher or visible in the quantitative data.

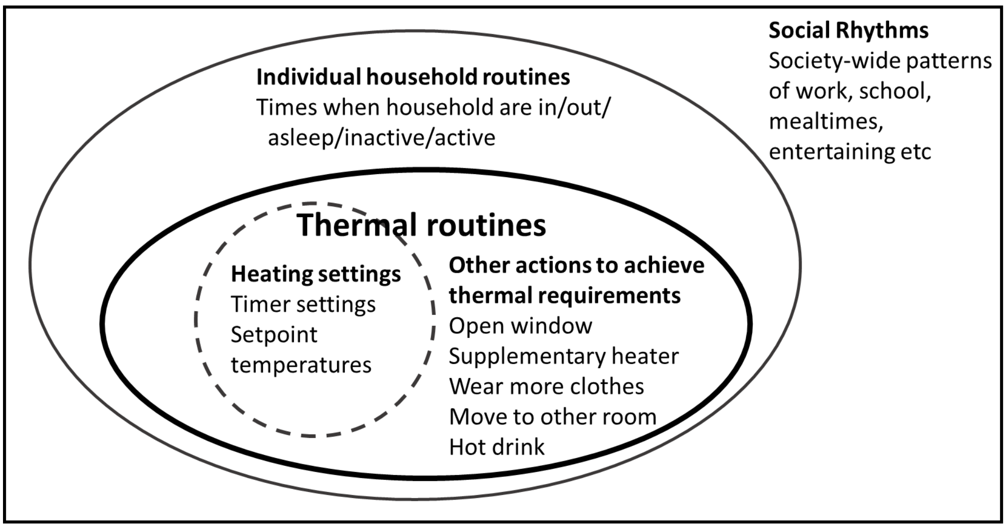

Figure 1. Thermal routines as a subset of household routines.

HEATING CONTROLLER DATA

Households with a PassivLiving HEAT unit 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 control unit. Users 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 paper to indicate the controller 'occupancy' states; these may or may not coincide with the actual times that residents are at home, out, or asleep. Different schedules can be set up for different days of week, or to differentiate between weekday and weekend.

The main focus of the analysis was the timing and length of IN 'occupancy' periods, since this is the period that the residents have decided they wish the heating to run as necessary to maintain their chosen thermal conditions. It should be noted that the boiler may also operate during OUT or ASLEEP periods if the temperature drops below the setpoints for those periods; this is most likely to happen if the home is poorly insulated or left unoccupied for an extended period, or if the setpoint for those periods is not much lower than the IN setpoint.

HEATING CONTROLLER DATA ANALYSIS

Data for 40 weekdays in January and February 2016, from 4/1/16 to 26/2/16 were analysed from controllers from 337 homes geographically distributed across the whole of the UK. The data were anonymised and no meta-data about the buildings and resident demographics was available.

The controller data provided by PassivSystems comprised readings for the temperature setpoint, internal temperature (measured at the unit), as well as the 'call for heat' and 'call for hot water' signals generated by the controller. This data was sampled at five minute intervals. 500 homes were randomly selected from the complete list of PassivSystems installations (which are geographically dispersed across the whole of the UK). Pre-processing was carried out to remove data sets with >4,000 (6.2 %) missing data points, or where analysis showed that the PassivSystems unit was not in fact controlling the heating in the home during the period of interest. Following this pre-processing, the main analysis was carried out on data for 337 homes for 40 weekdays in January and February 2016, from 4/1/16 to 26/2/16, giving a total of 337 × 40 = 13,480 'sample days'. This period was chosen to represent part of the heating season, with no major holiday periods included. Data from weekends was excluded as the focus of the analysis was on regular routines during the week.

The timing of the IN 'occupancy' period was inferred from the temperature setpoint data. Figure 2 shows the default operating pattern programmed in the controllers when they are installed, which shows clear steps in setpoint between IN and other periods. Since the actual setpoints are very variable between homes, visual inspection was used to determine a threshold which distinguished 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'). The data were analysed to determine the time at the beginning and end of each IN period for each home on each day.

The boiler will cut in and out as required by the control system to maintain the desired temperature so it will not be running all the time during IN periods. Figure 3 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. In this example the boiler starts in the morning before the setpoint rises. This shows the operation of the (optional) 'optimum start' feature of PassivSystems controllers. The principle is to start the heating up to an hour before the beginning of an IN period, so that the home has been brought close to the desired temperature at the beginning of the period.

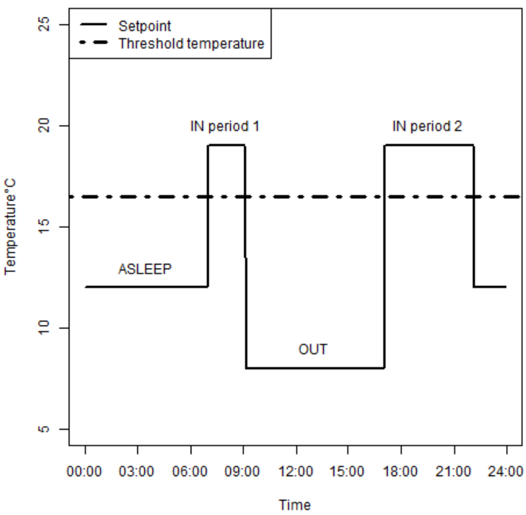

Figure 2. PassivSystems weekday default settings, showing how threshold of 16.5 °C distinguishes between IN periods and those when occupancy is set to OUT or ASLEEP.

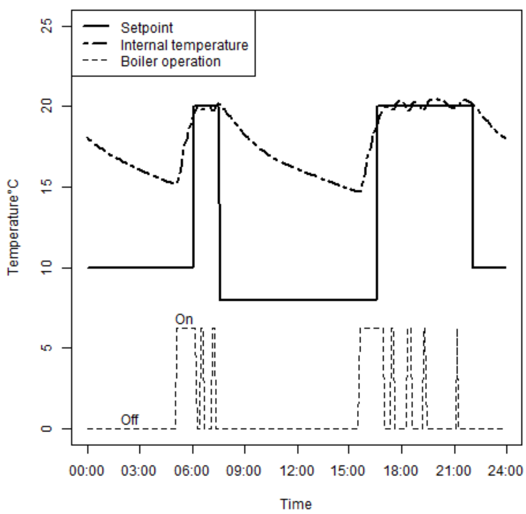

Figure 3. Typical boiler operation pattern (Home 233 19 January 2016).

PassivSystems controllers are not connected to energy meters so direct energy use data were not available. The call for heat signal from the unit was used to determine the coincidence of boiler operation as a proxy for space heating demand. A boiler coincidence factor (the proportion of homes with the boiler running at the same point in time) is calculated for each five minute period in the day. There is not a simple linear relationship between this boiler coincidence factor and the absolute level of total space heating energy demand. The boiler may modulate its heat output, and hence its fuel consumption, and may be simultaneously supplying hot water. Nevertheless, 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 power used.

INTERVIEWS

Complementing the quantitative data analysis, the study included interviews with volunteers recruited by e-mails sent out by PassivSystems to groups of customers. Semi-structured telephone interviews were carried out with seven householders with a range of house types, location and household size. The interviewees are referred to by pseudonyms in this paper. The interviews, which were carried out in March to June 2016, included open questions about how respondents decided on time and temperature settings when setting heating controls. The data were analysed under a set of headings derived from the interview questions in order to identify common themes and contrasts.

Telephone interviews were chosen in preference to surveys or face-to-face interviews, as these allowed personal interaction and open-ended questioning while being convenient and minimally intrusive for the householders.

LIMITATIONS

The results from this study are not generalisable to a wider group of homes. While the PassivSystems controllers are fitted in dwellings of a wide variety of types and ages, these are not representative of the overall UK building stock. The expectations built into the design of the PassivSystems user interface, with its 'script' (Akrich, 1992) asking for an 'occupancy schedule', may shape user interaction in a way that differs from households with less sophisticated control systems and those who operate their heating manually. The optimum start feature added complexity to the analysis as different homes had different strategies for whether or not the home was heated in advance of an IN occupancy period.

The sample for interviews was small. Volunteers who responded to the request to participate in the study may be more aware of energy use in the home than the general population. Their responses represent the point of view of only one member of each household.

Results and discussion

This section describes the findings from quantitative analysis of heating controller settings and the additional insights provided by interviews with householders. The link between daily patterns of space heating energy demand and the synchronicity of controller settings is discussed.

Table 1. Statistics for IN heating period times.

	N	median	IQR (min)	mean
First on time	12,499	07:00	90	07:23
Final on time	9,606	16:00	150	15:45
Final off time	12,478	22:00	65	21:23

HOUSEHOLD THERMAL ROUTINES AS EVIDENCED BY HEATING CONTROLLERS

The start and end times of weekday heating periods set in controllers were analysed to investigate the synchronicity of space heating operation. Table 1 shows the statistics for four time periods which are important in defining the schedule of intermittent heating operation: the start of the first IN period in the day, the start of the final IN period (for those homes with more than one operating period in the day) and the end of the final (or only) IN period in the day. The median and inter-quartile range (IQR) were used as the measures of central tendency and degree of variation for these parameters since (as can be seen from the histograms in Figures 4 and 5) the distributions are not normal, and have outliers.

The histogram of the time at which the first IN period starts Figure 4 shows a concentration of starting times around 07:00. An even more synchronous pattern is seen for the end of the final IN period in the day in Figure 5[1].

The first time the heating switches on and the last time it switches off show a clear relationship to society-wide patterns that influence when people are asleep.

Following the example of research linking energy use with time use studies (e.g. (Torriti et al., 2015) the results were compared with the 2005 UK Time Use Survey (Lader et al., 2006). This 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 'heating on time' found in this study of 07:00. 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 in this study. 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.

The median last heating on time – the beginning of the final heating period for days with two or more running periods – is 16:00. The histogram in Figure 6 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' period evident in the Time Use Survey (Lader et al., 2006).

The pattern of temperature during the day which results from this can be seen in Figure 7, which shows the mean internal temperature across all homes for all days in the sample. The mean temperature peaks in the evening, with a smaller, lower

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

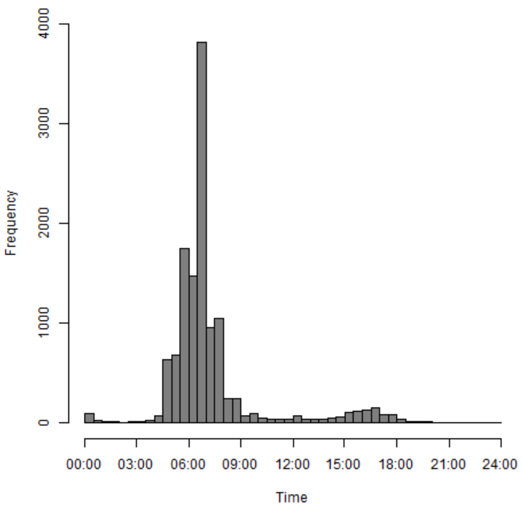

Figure 4. Start time of first IN period in day.

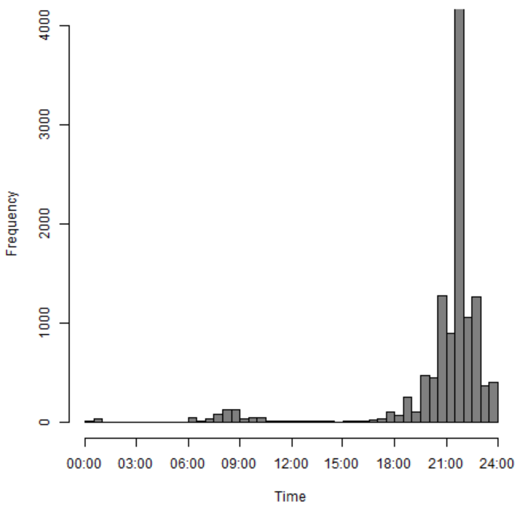

Figure 5. End time of final IN period in day.

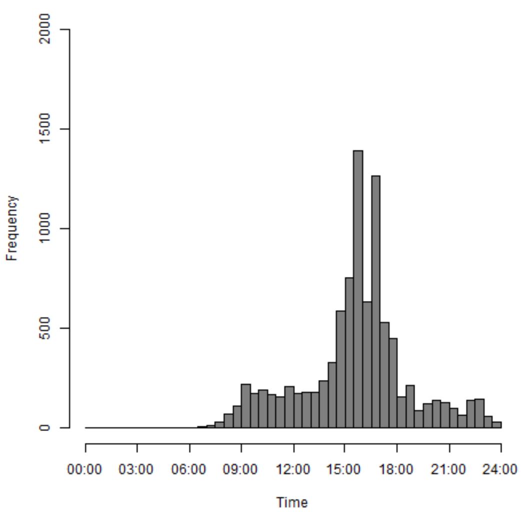

Figure 6. Start time of final IN period in day (for days with 2 or more heating periods.

peak in the morning. This profile is very similar to the profile of the largest cluster found in Huebner et al.'s (2015) analysis of data from 275 living rooms in English homes.

HOUSEHOLD THERMAL ROUTINES AS DESCRIBED BY HOUSEHOLDERS

Interviews with householders enabled 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, for some interviewees, heating schedules did not match actual times in/out/asleep. 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 when she has the controller set to OUT even though she is normally in the house. John (who works variable 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 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.

It is apparent that, at least for a proportion of this small interview sample, heating time and occupancy patterns are not the same. Their thermal routines involved heating time settings which deliver a satisfactory result for the household, even though they do not map to actual occupancy patterns of the residents. 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 energy models, which assume that heating operation coincides with times when the dwelling is occupied and the occupants are not asleep (e.g. McKenna et al (2015)). It seems that at least some users programme a two period operation schedule, 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 brought to light thermal routines not visible in the data for controller settings since they did not involve operating the heating controller. Two respondents mentioned regular use of supplementary heating. John said that he and his wife frequently use a wood burner 'when it's cold' but that they will only light this in the evening and Hugh reported using the wood burner in the living room 'every evening'. One response highlighted heating energy use which was for another purpose than thermal comfort: Catherine said she sometimes increases the thermostat temperature when she has 'emergency laundry' to dry for the next day.

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. This preference for lower temperatures when sleeping has also been noted by other researchers (Fell, 2016; Owen et al., 2012).

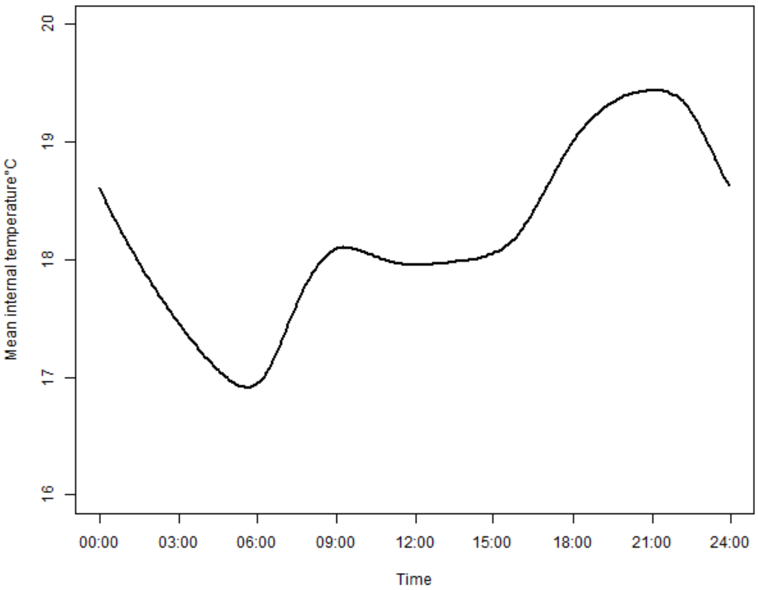

Figure 7. Variation in internal temperature measured at controller over the day (sampled at five minute intervals): mean across all days and all homes.

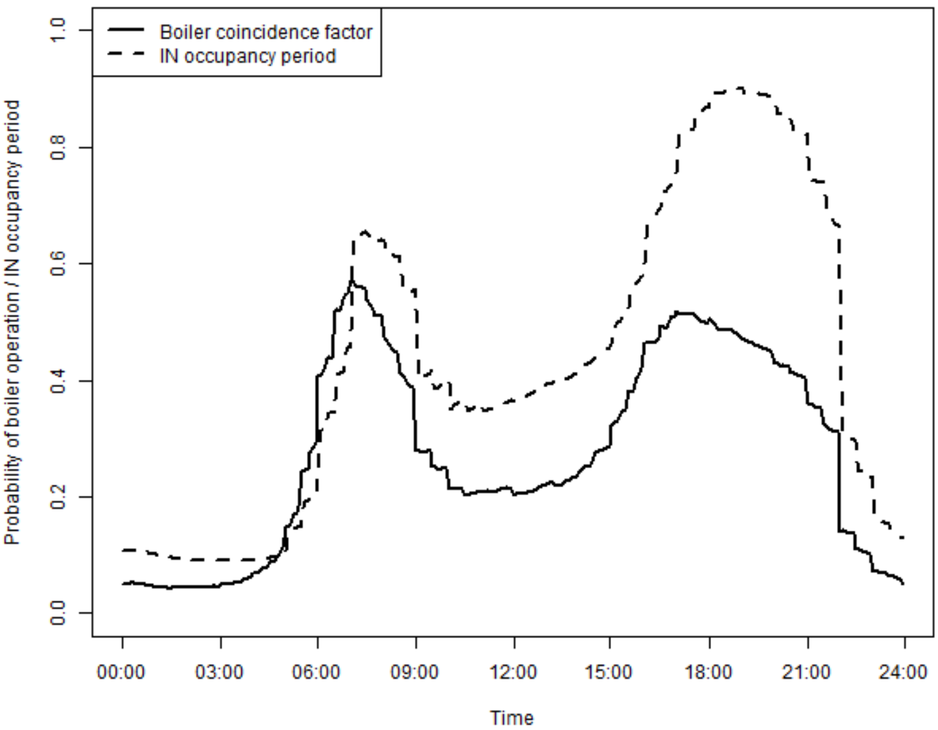

Figure 8. Daily pattern of boiler coincidence and IN occupancy period.

SOCIAL RHYTHMS AND ENERGY DEMAND

The final stage of the analysis was to examine patterns of weekday space heating demand for the whole sample, to investigate how the aggregation of individual household running patterns shapes the pattern of cumulative demand.

Figure 8 shows the mean for the 40 weekday 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. The mean proportion of homes with 'occupancy' set to IN is also plotted (as explained above, the boiler is not necessarily running continuously during IN periods). It is noticeable that both parameters have a clear pattern of morning and evening peaks[2]. However, the

2. The mean boiler coincidence factor starts to rise before the proportion of homes with occupancy set to IN because of the optimum start feature mentioned above.

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. The mean rise in internal temperature in the second half of the day (3.2 °C) is slightly higher than the mean increase in the morning period (2.8 °C) (see Figure 7), so the higher peak in the morning cannot be explained by a greater temperature increase[3]. A key factor contributing to the relative height of the morning peak is the synchronous starting of the heating at around 07:00 in many homes, which contrasts with the less synchronous starting up of heating systems in the early evening. This 'staggered start' in the evening spreads the demand for energy over a longer period and underlies the relatively lower peak[4].

Conclusion

The concept of thermal routines is proposed as a framework for examining patterns of home heating operation. It builds on the insights of thermal comfort research but focuses not on reported perceptions, but on one important action people can take to achieve the thermal conditions they require in their home, namely, changing the setting on their heating thermostat. The concept recognises that thermal expectations are linked to the routines created by regular practices in the home, which in turn are linked to wider social rhythms.

For the group of 337 UK households in the study, the link between regular practices and the time the heating is switched on in the morning drives a steep increase in heating energy demand between 06:00 and 07:00. The peak coincidence of boiler operation in the morning is higher than that in the evening peak period, which has a less synchronous starting time. This suggests that household thermal routines in the morning are a particularly important consideration for a transition to future energy systems with a high proportion of low carbon heat. Several factors that influence the current pattern of heating operation in the UK have been identified: society-wide rhythms of work and leisure; general expectations of heating schedules and a common preference for low night-time temperatures. These factors are also likely to affect patterns of heating demand from alternative heating technologies.

Heat pumps and district heating have different operating characteristics to gas boilers, and will generally be controlled differently, so the shape of demand peaks is likely to change compared to those for homes with gas boilers. Heat pumps are sized with a lower capacity than the gas boiler for the same house, for reasons of cost and efficiency of operation. This means they run for longer periods to reach the same temperature, and heat pump running is closer to continuous than the typical stop-start operation of a boiler (illustrated in Figure 3). Nevertheless there is evidence that morning demand peaks currently persist among UK heat pump users (Delta-ee, 2016; see also demand profiles for German homes with heat pumps in Fischer et al 2016).

The findings of this study are relevant to electricity network operators. The current focus of Demand Side Response load management 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 as penetration of low carbon heating from electric heat pumps increases. Morning peaks in heat demand are also an issue for district heating networks; reducing peak load reduces costs for these systems. There may be a need to change the association of practices in the home and heating operation times, particularly the expectation (very widely held in the UK) that the heating will start at, or shortly before, the time the household get up in the morning.

Policy makers and organisations wishing to promote low carbon heating should be aware that user expectations of running patterns may not align with network operator goals for demand management. Designers of heating control systems (and companies offering heating Demand Side Response services) should consider the thermal routines preferred by users. Better understanding of current household thermal routines should identify options to either work with existing routines while reducing the negative impacts on system demand peaks, or to change routines in a way that does not have a negative impact on the user.

Researchers aiming to model heating energy demand based on time use data should be aware that occupancy times and heating schedules do not always match. The interviews for this study identified some households not operating the heating in the middle of the day, even though a resident is normally present at this time.

It is important for a successful transition to low carbon heating to understand how current requirements for patterns of temperature over time relate to practices in the home, and how flexible these requirements are if the heating technology changes. Thermal routines provide a framework for examining the limits of flexibility of heating demand and exploring why users are reluctant to adopt optimum operating patterns. An area for further research is to examine how thermal routines shift when new types of heating are installed.

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3. Patterns of hot water use in the morning do not affect these results which are based on "call for heat" only: a separate signal is sent from the PassivSystems Controller to the boiler to call for hot water.

4. In addition, the evening temperature rise may be partly enabled by solar or internal gains that are more significant in the time preceding the evening peak than they are in the early morning, so reducing the load on the boiler.

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