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How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling

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ABSTRACT

Understanding heating patterns in UK homes is crucial for energy policy formulation, the design of new controls and heating systems, and for accurate stock modelling. Metrics to describe heating patterns are proposed along with methods for calculating them from measured room temperatures. The patterns of heating in 249 dwellings in Leicester, UK are derived from measured hourly temperatures and a face-to-face socio-technical survey. Of the 93% of homes that were centrally heated, 51% were heated for two periods each day and 33% were heated for only one period per day. The mean winter temperature in the rooms varied from 9.7 °C to 25.7 °C. Heating patterns varied significantly and systematically depending on the age of the householders and their employment status. Compared to younger households and those in employment, households with occupants over 60 and those unable to work, turned their heating on earlier in the year, heated for longer each day, and heated to higher temperatures. The indoor temperatures were much lower than those customarily assumed by BREDEM-based energy models and patterns of heating were quite different. Such models could seriously and systematically misrepresent the benefits of energy efficiency measures to some sectors of society.

1. Introduction

The 2008 Climate Change Act has committed the UK Government to reduce CO2 emissions by 80% of 1990 levels by 2050 [1]. In 2012 energy consumption in domestic buildings accounted for 29% of total UK energy consumption [2], of which around two thirds was used for space heating, predominantly for gas fired central heating [3]. The Low Carbon Transition Plan has set a transition budget to reduce the demand for gas to heat UK homes by 27% of the 2008 figure by 2020 [4]. In order to achieve these figures a large proportion of the UK housing stock will require thermal upgrades or more efficient heating systems and better controls. This need is reflected in UK Government energy policy, such as the Green Deal [5]. Clearly, for policies to be effective it is important to identify for which homes, occupied by which households, energy efficiency measures will be most effective.

It has been widely reported that thermal upgrades, more energy efficient heating systems and better controls do not always save as much energy as predicted [6] and can lead to unintended consequences [7]. Often such measures lead to warmer inside temperatures but lower energy savings [8] than predicted [9]; especially in homes which are operated at lower internal temperatures. A better understanding of household temperatures and thermal comfort could lead to more realistic assessments of the likely energy demands and temperatures after energy refurbishment.

In the UK, energy models based on the British Research Establishments Domestic Energy Model (BREDEM) [10] are often used to predict the energy consumption and assess policy options relating to retrofit measures [11–13]. Predictions of the energy demand for space heating are derived from the average daily temperature assuming a standardised heating temperature profile [14] (Fig. 1). However, analysis has shown that predictions are particularly sensitive to the demand temperature and the duration of heating [15,16], and top down modelling has shown significant differences in energy use between geographical areas with different household expenditure [17]. If the relationships between house type, and household composition and the demand temperature and heating pattern could be established, more realistic and reliable predictions of energy savings could be achieved.

Recent publications have called for the increased use of empirical data sets to inform the assumptions used in energy models, especially those which relate to the diversity of occupant behaviour [15,18]. The three most significant UK-based temperature monitoring studies are: the National Field Survey of Temperatures [19], which was carried out in 1981 before the increased prevalence

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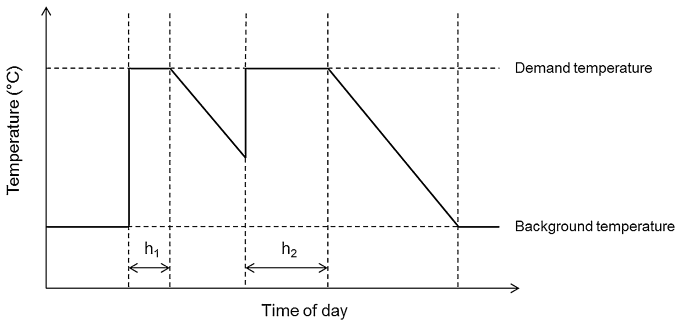

Fig. 1. Standardised temperature profile as used in BREDEM-based models. Heating durations ($h_1 + h_2$) of 9 h on weekdays and 16 h at weekends and living room and bedroom demand temperatures of 21 °C and 18 °C, respectively are generally used.

Fig. 2. Hobo data logger used to measure internal air temperature in 469 dwellings in Leicester City.

in central heating and recorded only a single spot temperature; the Warm Front Study [20], which focused solely on low income dwellings and not the full spectrum of homes and households [20,21]; and the Carbon Reduction in Buildings (CaRB) project [22–24], in which a representative sample of English houses was monitored to determine the daily heating period and thermostat settings [22] and to critique the living room temperatures [25] and heating patterns [26] assumed by BREDEM-based models. Other relevant studies include: Summerfield et al. [27] that monitored temperatures ten years apart in 14 low energy buildings; Yohanis and Mondol [28] who reported temperatures from 20 dwellings in Northern Ireland; and Martin et al. [29] in which sensors placed directly on radiators in 68 homes were used to estimate when dwellings were heated. Whilst these studies provide valuable insights into the patterns of heating in UK homes they give a far from comprehensive picture.

The work reported in this paper aims to present a more comprehensive picture of the patterns of heating in UK homes and to identify where there are significant differences in the patterns of heating depending on the house (type, age and construction), the heating system (central heated or not) and the occupancy (tenure, employment status, age and size of household).

To do this, the paper firstly defines metrics which quantify the key features of a heating pattern, including, when in the year heating is first turned on and off, the number of heating periods each day and their start and end times, the average temperatures and the achieved temperatures in living and bedrooms. Methods of calculating the metrics from measured temperatures are then proposed. It is hoped that the metrics will provide a basis for researchers to present monitoring results in a uniform way.

The metrics and calculation methods are then used to analyse the patterns of heating in 249 homes in the UK city of Leicester. Questionnaire surveys were undertaken and hourly temperatures were recorded in the living room and bedroom of each home, making this, to the authors' knowledge, the first UK city-scale socio-technical monitoring study of its type. The reasons why the calculated heating metrics vary significantly with house and household characteristics are explored and the results are compared with those obtained by others. The consequences of using the standard heating profiles within BREDEM-based energy models are discussed.

Finally, recommendations for future work that would inform those working in social, political and technical areas of energy demand reduction are presented.

2. Data collection

2.1. Household surveys

The temperature measurements were made as part of the 4M Project—measurement, modelling, mapping and management: an evidence-based methodology for understanding and shrinking the urban carbon footprint [30]. An integral part of the project was a city-wide survey carried out in Leicester, in the UK Midlands, in 2009-10. A representative sample of 1000 households was selected randomly after stratifying by percentage of detached dwellings and percentage of households with no dependent children. 575 households (approximately one in 200 homes in Leicester) agreed to take part. Face-to-face household interviews were conducted by the National Centre for Social Research (NatCen) [31] using trained surveyors that had no prior knowledge of home energy matters. As well as indoor temperatures, data was gathered about: the dwelling and its geometry, age and construction; the household and its demographics and income; the heating system; and annual energy demand. The ethnicity of occupants was not noted during the survey but 6% of surveys were not carried out in English.

2.2. Temperature monitoring

As the 4M homes were in a single urban area it was assumed that the outdoor temperature was the same across the whole sample. During the period of this study (December 2009 to February 2010) the average outdoor temperature was 2.3 °C[1]; which is much colder than usual; the 2000–2009 average temperature between December and February in Leicester was 4.6 °C.

To measure indoor temperatures, Hobo temperature sensors (Fig. 2) were placed in the living room and the main bedroom of the 469 households that consented to temperature monitoring. These recorded spot[2] values every hour between July 2009[3] and February 2010; the period being limited by the memory of the sensors. The sensors were calibrated by Tempcon Ltd. and were found to be accurate to ±0.4 °C [32]. Guidance on the placement of sensors was provided by the interviewers, specifically that the sensors should be placed away from heat sources and direct sunlight (more detail about the placement and collection of sensors is available elsewhere [33]).

Prior to analysis, to ensure that the data was error free, monthly plots of living room, bedroom and outdoor air temperature were scrutinised by eye. The data from a household was excluded from further analysis: if only one sensor was returned (31 cases); if sensors were placed in direct sunlight (3); if both sensors were placed

[1] As measured by Leicester City Council (LCC) at their central weather mast.
[2] Because the sensors record a spot temperature every hour they are more susceptible to temperature spikes than temperature sensors which report an average temperature over a logging period.
[3] The summertime temperatures are analysed and reported elsewhere [33].

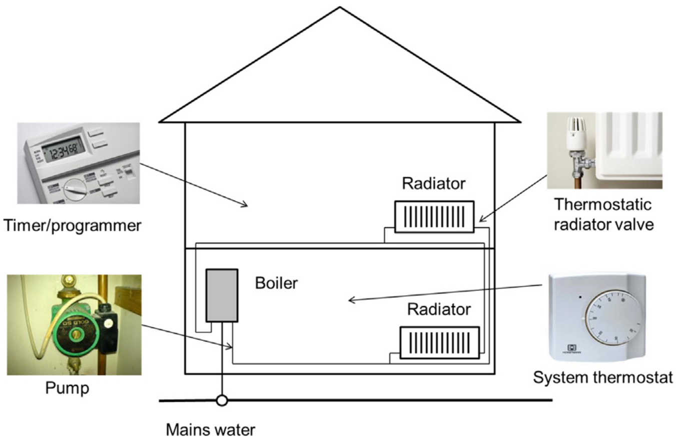

Fig. 3. Schematic of a typical UK central heating system.

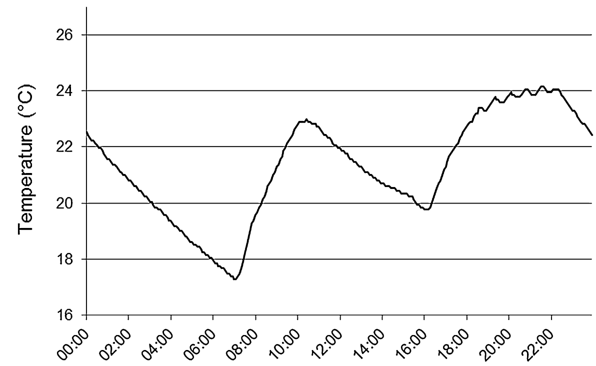

Fig. 4. Temperature measured at high resolution on a single day in a test house showing boiler cycling across two heating periods.

in the same location (not in different rooms) (5); if there was a time stamp error (5); if sensors were moved during analysis period (2); if the sensors were insulated from temperature swings (e.g. covered over) (14); or if sensors were placed in an unheated space (3). It is clear from this list, that instructions for placing sensors, were not always followed. After the exclusions there 249 homes remained in the dataset.

2.3. Comparison of sample with national census and English Housing Survey

The percentage of houses of each type in the 4M temperature sample is similar to the percentage recorded for the Leicester Unitary Authority (UA) in the 2001 census [34]. However, the percentage of detached homes in the sample, and in the 2001 Leicester UA census, is much lower than in the nation as a whole as recorded in the 2009 English Housing Survey (EHS) [35]; the percentage of semi-detached homes is correspondingly higher (Table 1). This may be because Leicester is a dense, former industrial, city and these typically have few larger, usually detached, houses, and because Leicester has a number of large estates dominated by semi-detached dwellings. The 4M temperature sample also has a lower proportion of dwellings built after 1965 than recorded in the EHS, which would be expected of an established urban area struggling with post-industrial decline.

The sizes of the households and the employment status of the occupants reflect the proportions found within the Leicester UA census, which is in turn similar to the proportions recorded for the nation as a whole[4]. The proportions renting, and either owning outright or buying with a mortgage, are also similar to the national figures but the proportion renting is much lower than reported in the 2001 census for Leicester. This may be because of the take up of the ‘right to buy’ in the intervening 8 years.

2.4. Heating systems

In the sample of 249 homes, 93% were centrally heated. In such systems a gas-fired boiler heats water, which is pumped to radiators in each room (Fig. 3). A timer/programmer enables occupants to set a heating pattern, with defined on and off times, which repeats every day. Modern timers offer more flexibility, enabling, for example, different weekday and weekend heating schedules. Thus heating systems operate automatically such that, without occupant intervention, a continuous regular on/off pattern of heating is established. Most timers enable occupants to override the set-times in order turn on or off the heating at the press of a button (for example when returning home early or leaving early). At the next programmed on or off time the system reverts to the programmed pattern of operation. Similarly, the whole system can be switched on or off relatively easily at the timer, for example at the start and end of the winter heating period or during vacations. An established regular heating pattern can therefore be disrupted by irregular, occupant-induced events that result in the heating coming on or going off for varying lengths of time.

When the timer turns the system on, the gas boiler fires and the circulating pump runs and within a few minutes, hot water is delivered to the radiators. The temperature of the supply water can usually be controlled by a dial on the boiler; although most homeowners are unlikely to use this facility. The pump runs continually until a system thermostat mounted on a wall, usually, but not always, in a hallway, senses that the demand temperature has been reached. This is the temperature set by the occupants, usually by turning the dial on the thermostat. When the demand temperature is reached, a relay will turn the boiler off, but the pump will continue to run for a while to prevent hot water stagnating in the boiler. The boiler thus cycles on and off to try and maintain the demand temperature (at the thermostat). The boiler may also turn off if the temperature of the water returning to the boiler is too high[5]. Together these modulations result in space temperatures that fluctuate over time (Fig. 4).

Individual rooms are heated by radiators that will usually be fitted with thermostatic radiator valves (TRVs). These modulate the flow to the radiator in response to the locally sensed temperature enabling different rooms to achieve different temperatures. TRVs have a rotating head, which occupants can use to change the desired room temperature.

Whilst studies of households' home heating behaviour often set great store by the demand temperatures set at the system thermostat, the TRVs mean that temperatures in individual rooms (in this paper the living room and bedroom) may be rather different. Temperatures may well be lower: because the space is not yet up to temperature, because the radiator is undersized compared to the room heat loss[6], because the system thermostat is in a space that warms up easily or because heating is curtailed by the TRV setting. Conversely, in some circumstances, room temperatures may

[4] If the ‘retired’ and ‘other’ categories of employment are combined.

[5] This can happen if, for example, the wall mounted room thermostat is calling for heat but the TRVs have curtailed flow to the radiators, or because the house is almost ‘up to temperature’ and the combined convective heat output from the radiators is thus small.

[6] And the heat loss may vary, for example due to window and door opening.

Table 1
Composition of the 249 monitored homes compared to 2001 census data for Leicester Unitary Authority and England and the 2009 English Housing Survey (EHS).

	Descriptor (n)	Percentage in sample				Percentage points difference between the temperature sample and other surveys		
		4M temperature sample (%) $n = 249$	Census Leicester UA (%) $n \approx 110{,}000$	Census England (%) $n \approx 24M$	EHS, 2009 (%) $n \approx 17{,}000$	Census Leicester UA	Census England	EHS 2009
House type	Detached (26)	10	12	23	17	−2	−13	−7
	Semi-detached (115)	46	42	32	25	4	14	21
	End terrace (24)	10	41[1]	26[1]	11	−7[1]	8[1]	−1
	Mid terrace (60)	24			19			5
	Flat (24)	10	5	19	19	5	−9	−9
	Other (bungalow) (0)				9			−9
House age	Pre-1919 (45)	18	–	–	21	–	–	−3
	1919–1944 (77)	31	–	–	17	–	–	14
	1945–1964 (58)	23	–	–	20	–	–	3
	1965–1980 (35)	14	–	–	21	–	–	−7
	Post 1980 (33)	13	–	–	21	–	–	−8
Tenure	Own outright (97)	39	24	29	67[2]	15	10	3
	Buying with Mortgage (78)	31	34	39		−3	−8	
	Rent (74)	30	40	29	33	−11	0	−4
Household size	1 (65)	26	33	30	–	−6	−4	–
	2 (91)	37	29	34	–	8	2	–
	3 (39)	16	15	15	–	1	0	–
	4 (36)	14	14	13	–	1	1	–
	5+ (18)	6	10	7		−4	0	–
Employment status[3]	Full time (102)	42	47	41	–	−5	1	–
	Part time (31)	12	4	12	–	8	0	–
	Unemployed (15)	6	6	3	–	0	3	–
	Permanently unable to work (16)	6	7	5	–	−1	1	–
	Retired (68)	27	9	14	–	18	13	–
	Other (17)	7	27	25	0	−20	−18	–

[1] The census data does not break down house type into different types of terrace property.
[2] The EHS does not distinguish between these.
[3] Data relating to employment status in the census relates to every individual in the home while in this survey employment data was only collected for the household representative person; i.e. invariably survey interviewee.

be higher than the demand temperature, for example: if the system thermostat is in a space that is hard to heat, if the radiator in the monitored room is oversized, if the TRV is on a high setting, or if there are internal heat gains (from people, appliances or the sun). Thus, in winter, room temperatures may reflect the temperatures people want, or are able to achieve (given the heating system's characteristics, the energy efficiency of the dwelling's envelope and the local weather) and not the demand temperature at the system thermostat.

Additionally and importantly, many UK homes retain some form of secondary heating in the main living rooms, often a gas fire located in the original open fireplace. Occupants may also have electric room heaters. These secondary sources may be used in preference to the central heating system or in addition, or because there is no central heating system. Measured temperatures may therefore show sharp rises in temperature at different times on different days, and bedroom and living room temperatures may not be synchronised. In the sample of homes analysed, 17 homes (7%) appeared to use secondary systems. Thus, although it is possible in principle to detect when a central heating system turns on or off using measured temperatures, there are many ways in which occupants can influence space temperatures and so detecting heating patterns from temperature measurements is not straight-forward.

2.5. Measured temperatures

The hypothetical heating profile (Fig. 1) and the test house profile (Fig. 4) show sharply defined changes in the temperature gradient indicating the times at which the central heating system turns on and off; and the temperatures achieved can be clearly identified. Temperature profiles measured in real occupied houses, using Hobo sensors are often far less well defined; inter-house profiles can be very different as can day-to-day variations in a single house (Fig. 5).

House 1 in Fig. 5 shows a typical, repeating, two-period heating pattern. The temperature reached in the evening, about 19 °C, is higher than that in the morning, which is a common occurrence; presumably because the system is unable to bring the house, which has cooled overnight, up to the demand temperature (see also Fig. 4). Over each day, the temperature range is about 5 °C, which is common for many of the houses illustrated. House 2 is not centrally heated; there is a two period pattern in the living room, whilst the bedroom remains unheated in the evenings. House 3 suggests a one-period pattern but, the bedroom is more modestly heated than the living room (perhaps the TRV is set quite low). In House 4 the heating is on continuously but the bedroom cools during the day (perhaps the living room is also heated by a secondary system). In House 5 there is a two period pattern on the first day (1st February 2010) but no heating at all on days 2 and 3; presumably due to occupant intervention. House 6 has a three period heating pattern.

Clearly, none of these plots bears any resemblance to the standardised temperature profile described in BREDEM (Fig. 1). The raw data plots indicate that a number of metrics will be needed to describe the pattern of heating, that others will be needed to describe the resulting temperatures, and that metrics will give different values for living rooms and bedrooms.

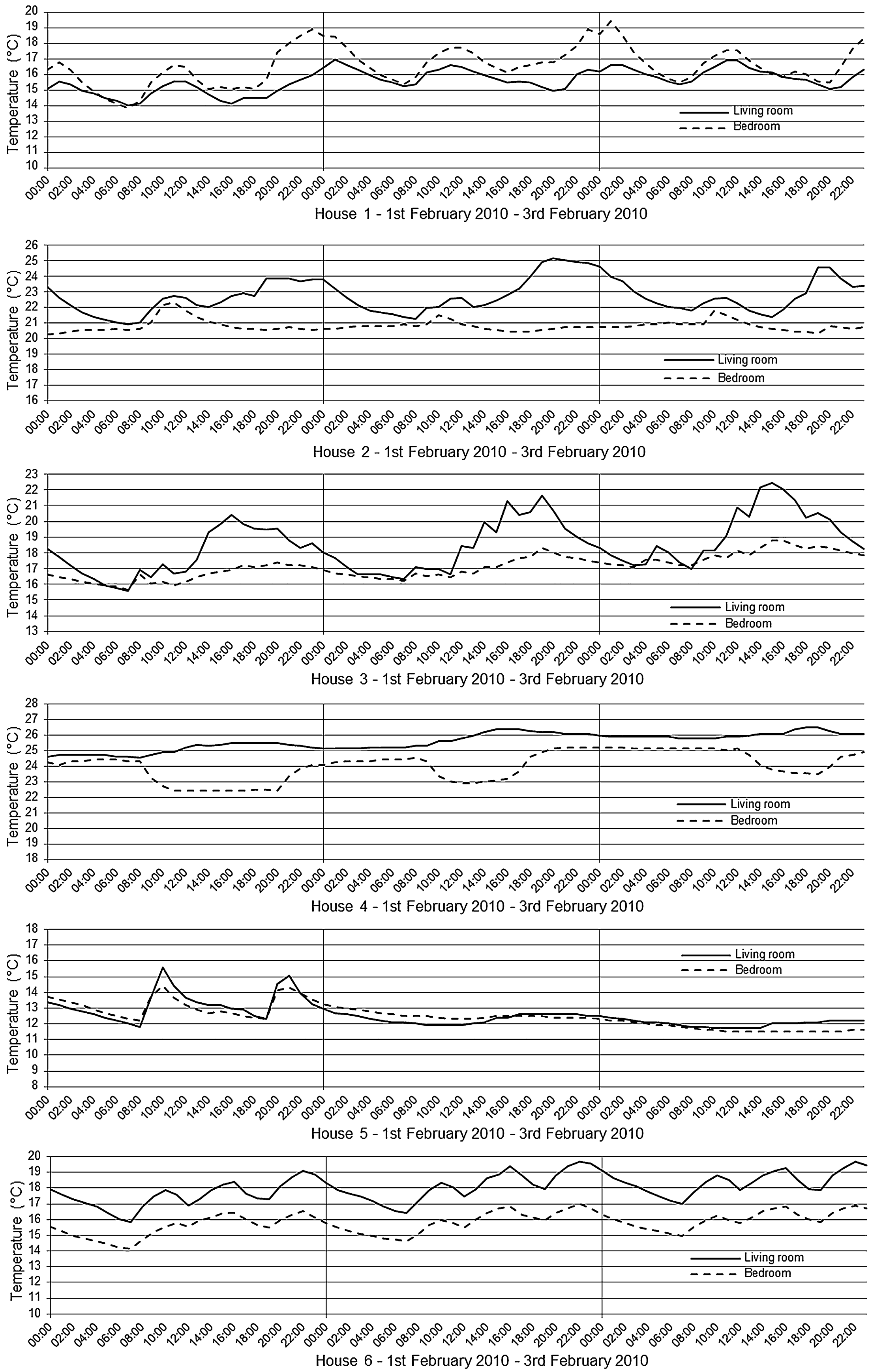

Fig. 5. Measured living room and bedroom temperatures measured in six homes on three consecutive days during February 2010.

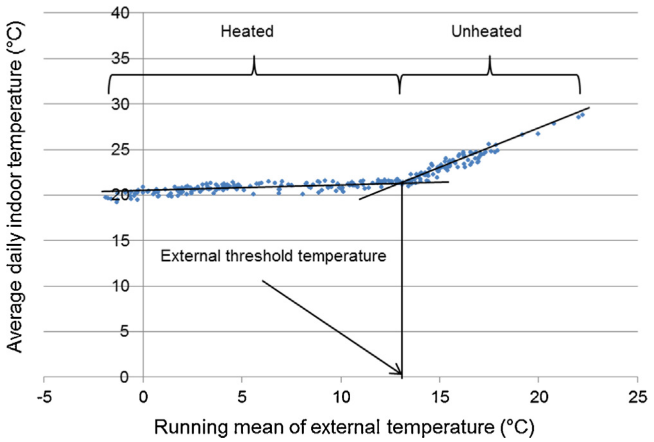

Fig. 6. Depiction of the method for calculating the external threshold temperature in one home based on data collected between July 2009 to February 2010. Results from this metric suggested that all dwellings were heated by the end of November. Consequently all of the other metrics are focused on the winter analysis period dwellings.

2.6. Derivation and calculation of heating practice metrics

For each home, nine[7] heating practice metrics were defined and a series of calculation methods developed to calculate each one. These calculation methods are described briefly here (Table 2) but more fully elsewhere [36]. Values for eight of the nine metrics were calculated from room temperatures measured in the Leicester houses during 90 days from 1st December 2009 to 28th February 2010, henceforth called the winter analysis period. This is a period when all dwellings would need to be heated to provide adequate internal temperatures[8] (Section 3.2). The metrics are divided into two groups; those that describe the heating systems' operation and those that show the resulting indoor temperatures.

Heating practice metric 1, 'external threshold temperatures', aims to identify the external temperature at which the heating system is switched on in the autumn and off in spring. Here only the 'heating on' threshold is calculated as temperature data was not recorded after February 2010. To calculate this threshold temperature the average daily indoor temperature was plotted against the running mean of the external temperature (T_{rm}) for each day of the monitoring period from July 2009 to February 2010 (Fig. 6). Heated days, when the indoor temperature remained relatively constant with T_{rm}, and unheated days, when it changed with T_{rm}, were evident for most of the dwellings[9]. Visual inspection was used to identify the T_{rm} value below which heating was used in each home.

Heating practice metric 2, 'number of heating periods per day', was identified by visual inspection of temperature traces (e.g. as in Fig. 5) recorded during the winter analysis period. It was not possible to categorise the number of heating periods in all dwellings because some had very inconsistent heating schedules, i.e. occupants regularly changed, or manually overrode, their timer settings.

An attempt to measure heating practice metric 3, 'start and end times of heating periods', which built on previous work [22], and relied on calculating the average number of hours *each day* that the indoor temperature increased, proved unsuccessful. It resulted in very inconsistent heating times due to temperature fluctuations resulting from: (1) boiler cycling during heating periods; (2) short spikes in temperature resulting from localised heat gains and; (3) occupant-induced variations in the start and end times of heating.

To overcome these complications an average heating profile was developed for each home (e.g. Fig. 7) from which the percentage of days in the winter analysis period when the heating was on at each hour was calculated using the following equation:

$$\text{Heating is in use at } T_t \quad \text{if}(T_t - T_{t-1} > 0) \text{ or } (\text{if}(T_{t-1} - T_{t-2} > 0 \text{ or } T_{t-2} - T_{t-3} > 0 \text{ and } T_{t-1} - T_t > -0.1)) \quad (1)$$

All the days in the period were considered, as this study, and work by others using a similar approach [24], has shown no significant difference between daily heating periods calculated for weekdays and weekends. The start of heating was assumed to be the first hour for which the heating was on for 10%[10] or more days than the previous hour. For example, if heating was never observed at 5:00am, observed on 8% of days at 6:00am and 29% of days at 7:00am, the start of heating was recorded as 7:00am. The end time of heating was the last hour for which the heating was on for 10% more days than the next hour.

This method was successful at identifying the heating schedule in dwellings with consistent heating patterns but in dwellings where the start and end times changed, the length of the heating pattern was overestimated and in some cases could not be identified at all (Fig. 7). Consequently, this method was only applied to those dwellings which were observed to have single (33% of dwellings) or double heating patterns (51%).

The start and end times of the heating periods for each dwelling were used to calculate heating practice metric 4, 'duration of heating per day'. As stated above, this method tended to overestimate the heating duration in dwellings with inconsistent heating patterns but the variation in duration was preserved.

Heating practice metric 5, 'number of under-heated days', was calculated by identifying the number of days during the winter analysis period that were heated for a shorter length of time than average. The number of hours heated each day was calculated using Eq. (1) and the daily figures were averaged for the winter analysis period. Where less than half the average heating hours were observed on a single day the dwelling was deemed to be under-heated. It should be noted that the heating durations used to calculate number of under-heated days are not related to metric 4.

Heating practice metric 6, 'mean winter temperature' is the mean of all the recorded temperatures during the winter analysis period whether the heating was on or not. It is calculated for both the living room and bedroom of each dwelling (metric 9 is the only other metric calculated for both rooms).

Heating practice metric 7, 'ΔT_{room}', was calculated by determining the difference between the temperatures measured in the living room and bedroom at each hour (i.e. living room minus bedroom), and then averaging these for the whole of the winter analysis period.

Heating practice metric 8, 'mean achieved temperature' was the mean of the daily maximum temperatures recorded over the winter analysis period in the living room. This method has been used in previous work [22]. The maximum daily temperatures usually occurred towards the end of the evening heating period.

Finally, heating practice metric 9, 'average temperature during heated periods' was calculated based on the start and end times of each heating period in homes with either single or double

[7] Although metrics 1, 6 and 8 yield two values and metric 3 two for each heating period.

[8] Whether or not an adequate temperature was provided depends on the occupants, the home and heating system. Sometimes the heating was not operational for a prolonged period, for example when occupants were away from home.

[9] Clear heated and unheated periods could not be identified for 30 of the dwellings (8% of the sample).

[10] This percentage appeared to work well, but other values could be used, though this may change results.

Table 2
Description of the heating practice metrics described.

		Heating practice metric	Definition
Heating pattern	(1)	External threshold temperature	The external air temperature a. below which the heating system is turned on[1] and b. above which it is turned off[2]
	(2)	Number of heating periods per day	The number heating periods that are predominantly used[3]
	(3)	Start and end times of heating periods	The median start and end times of each heating period for homes with a regular heating pattern[3]
	(4)	Duration of heating per day	The average total duration of heating per day[3]
	(5)	Number of under-heated days	The number of days during the winter analysis period which are heated for less than half of the average heating duration[3]
Resulting temperatures	(6)	Mean winter temperature	The mean of all measured temperatures a. living room and b. bedroom[3].
	(7)	ΔT_{room}	The average temperature difference between the living room and bedroom[3]
	(8)	Mean achieved temperature	The average of the daily maximum temperatures measured in the living room[3]
	(9)	Average temperature during heated periods	The average temperature calculated during each heating period a. living room and b. bedroom[3].

[1] Calculated using data measured between July 2009 and February 2010.
[2] But as the monitoring period didn't include the end of winter the second of these could not be calculated in the work presented here.
[3] Calculated for the winter analysis period between December 2009 and February 2010.

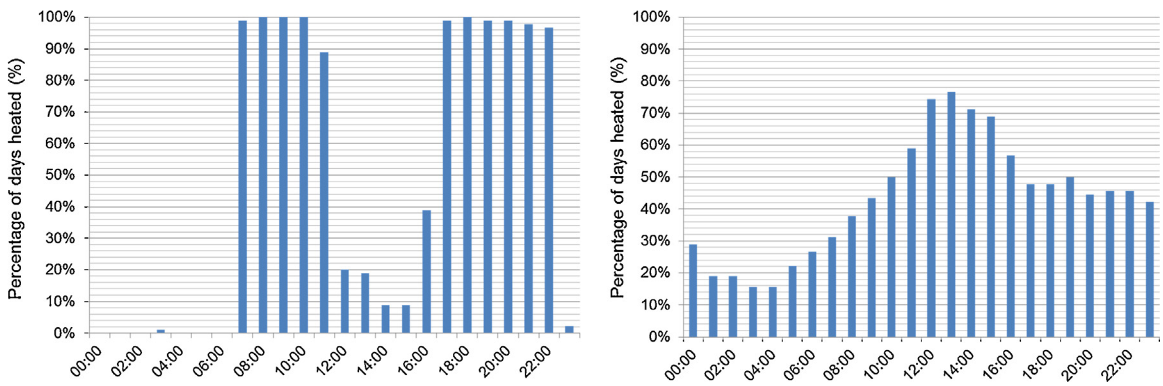

Fig. 7. Percentage of days heated at each hour during the winter analysis period (December 2009 to February 2010) in a dwelling with a consistent double heating pattern (left) and in a dwelling with an inconsistent heating pattern (right).

heating patterns (from metric 3). Hence the same start and end times were used for each day. The average temperature was calculated separately for each period and for each room[11].

Having calculated all the metrics, statistical analyses were undertaken to discover whether the values differed with house or household characteristics. For all but metrics 2 and 3, for which there was no associated standard deviation, a one way analysis of variance (ANOVA) was undertaken to establish whether differences between the mean values relating to the household characteristics were statistically different. When statistically significant results were found (i.e. $p < 0.05$), Tukey post hoc tests were undertaken to identify which characteristics led to the significantly different result ($q < 0.05$).

3. Results

3.1. External threshold temperature

During the whole monitoring period (July 2009 to February 2010) the running mean of external temperature (T_{rm}) was only over 18 °C for seven days in early July (Fig. 8). It fell steadily during the autumn but was not consistently below 8 °C until November 27th. The average external threshold temperature (metric 1) for all 249 dwellings was 13.3 °C (standard deviation 1.4 °C) (Table 3). The highest and lowest external threshold temperatures were 18 °C and 8 °C, respectively (Fig. 8). This range of external threshold temperatures suggests that some dwellings were heated for most of the year and that others were only heated during the coldest winter months.

Between 1st September and 22nd October 2009, the number of homes that had their heating on gradually increased (Fig. 8); in the subsequent warmer period (in early November) heating was switched off by some households. The external temperature dropped again at the beginning of November and all homes were heated from 9th November until the end of the analysis period.

Those living in mid-terraced houses had significantly lower ($p = 0.019$) external threshold temperatures (12.9 °C) than those living in detached dwellings (14.0 °C, $q = 0.01$). This may be because mid-terraces have less exposed wall area than other dwelling types; consequently, indoor temperatures respond slower to changes in external conditions.

It was expected therefore, that flats would also have a low external threshold temperature as they have the least exposed wall area. However, flats had a higher external threshold temperature (13.3 °C) than mid-terraces (12.9 °C). This result may however be because there was a relatively low number of flats in the sample ($n = 26$) compared to mid terraces ($n = 62$), or because flats have less well-insulated facades, for example they may well have a higher proportion of facade glazing.

Some interesting trends were observed that were not statistically significant. The lowest external threshold temperature was observed in the dwellings where the oldest occupants are between 20 and 30 years old (12.5 °C). This may suggest that younger occupants turn on their heating systems later in the year, or choose

[11] Metrics 8 and 9 were calculated with the under-heated days included. This provided uniformity across all homes. Estimates indicate that had the under-heated days been excluded, the tabulated values for these metrics (Table 4) would have increased by at most about 0.1K.

Table 3
Mean external threshold temperature, heating patterns, start and end times of heating, duration of heating period and under-heated days between December 2009 and February 2010 as calculated for different groups of dwellings and household types in 249 dwellings. Statistically significant results ($q < 0.05$) shown in bold.

Characteristic	Metric 1	Metric 2		Metric 3						Metric 4	Metric 5	
	Mean external threshold temp[1] (°C)	Heating pattern[2]		Median start and end times of heating[2]						Duration of heating per day[1,3] (h)	Number of under-heated days[1] (Days)	
		Single	Double	Single pattern		Double heating pattern						
	(Mean, SD)	No. of dwellings		On	Off	On	Off	On	Off	(Mean, SD)	(Mean, SD)	
	All dwellings	13.3, 1.4	83	126	07:00	23:00	06:00	09:00	15:00	22:00	12.6, 3.5	2.9, 4.4
House type	Detached	**14.0, 1.3**	8	15	07:00	23:00	07:00	09:30	15:00	22:00	12.0, 3.9	2.3, 2.6
	Semi-detached	13.3, 1.3	46	56	07:00	23:00	06:00	09:00	15:00	22:00	13.1, 3.6	2.4, 4.7
	End terrace	13.6, 1.1	5	16	09:00	23:00	06:00	09:00	14:00	21:00	11.9, 3.8	3.0, 4.6
	Mid terrace	**12.9, 1.4**	15	29	08:00	21:00	06:00	10:00	15:00	22:00	12.1, 3.1	3.4, 4.1
	Flats	13.3, 1.7	9	10	08:00	23:00	06:00	11:00	16:00	23:00	12.6, 3.1	4.5, 4.2
House age	Pre 1919	13.4, 1.5	11	28	07:00	23:00	07:00	09:00	15:00	23:00	12.5, 3.7	3.3, 4.2
	1920–1943	13.4, 1.2	30	34	07:00	22:00	06:00	09:00	13:30	22:00	13.4, 3.4	2.0, 3.2
	1944–1965	13.2, 1.4	22	31	07:00	22:00	06:00	10:00	15:00	22:00	12.7, 3.3	3.2, 5.9
	1966–1980	13.2, 1.3	10	17	08:00	23:00	06:00	09:00	16:00	22:00	11.5, 3.4	2.7, 3.5
	Post 1980	13.1, 1.8	10	16	08:00	23:00	06:00	09:00	16:00	23:00	11.7, 3.8	3.8, 4.4
Wall type	Solid wall	13.3, 1.3	33	58	07:00	23:00	06:00	09:00	15:00	22:00	13.0, 3.6	2.5, 3.8
	Unfilled cavity wall	13.2, 1.3	20	31	08:00	00:00	06:00	09:00	16:00	22:00	12.2, 3.0	3.3, 3.8
	Filled cavity walls	13.3, 1.4	30	37	08:00	22:30	06:00	10:00	15:00	21:00	12.4, 3.6	3.0, 5.3
Central heating	Yes	13.3, 1.3	75	121	07:00	23:00	06:00	09:00	15:00	22:00	12.4, 3.4	2.8, 4.3
	No	13.1, 1.9	8	5	06:30	22:30	07:00	10:00	16:00	00:00	14.3, 3.4	4.3, 4.6
Tenure	Own outright	13.5, 1.1	36	49	07:00	23:00	07:00	09:00	15:00	22:00	13.3, 3.5	2.9, 5.2
	Buying with mortgage	13.1, 1.2	17	47	08:00	22:30	06:00	09:00	15:00	22:00	11.4, 3.6	2.7, 3.5
	Rent	13.2, 1.7	30	30	07:00	23:00	06:00	10:00	15:00	22:00	13.0, 3.6	3.0, 4.0
Employment status	Employed	13.2, 1.4	25	82	08:00	23:00	06:00	09:00	15:00	22:00	**11.7, 3.5**	3.0, 3.8
	Retired	13.3, 1.2	37	26	07:00	22:00	07:00	10:00	14:00	22:00	13.7, 3.2	2.7, 5.7
	Unable to work	13.4, 1.6	11	6	06:00	23:00	06:00	09:00	14:30	22:30	**14.0, 3.7**	2.4, 3.6
	Unemployed	12.8, 1.5	5	8	08:00	23:00	05:30	10:30	15:30	21:30	12.3, 2.9	2.7, 3.3
	Other	13.8, 1.5	5	4	07:00	23:00	05:30	11:00	15:00	00:00	14.6, 2.4	3.3, 4.3
Age oldest occupant	20–29	12.5, 1.8	0	7	N/a	N/a	07:00	10:30	15:00	21:30	12.1, 3.3	4.6, 4.6
	30–39	13.0, 1.6	12	23	07:00	23:00	06:00	09:00	15:00	23:00	12.0, 4.4	3.3, 4.2
	40–49	13.2, 1.3	13	31	08:00	23:30	06:00	09:00	16:00	22:00	**11.6, 3.4**	2.9, 3.3
	50–59	13.1, 1.0	10	23	07:30	23:00	06:00	09:00	15:00	22:00	**11.6, 2.5**	2.5, 4.0
	60–69	13.5, 1.4	23	22	08:00	22:00	06:00	10:00	15:00	22:00	**14.0, 3.0**	2.2, 3.5
	70+	13.6, 1.2	25	20	07:00	23:00	07:00	10:00	13:00	22:00	13.6, 3.3	2.9, 6.3
Household size	1	13.2, 1.2	25	31	08:00	22:00	07:00	09:00	15:00	22:00	12.5, 2.5	**5.0, 6.3**
	2	13.3, 1.3	31	47	07:00	23:00	06:00	09:00	16:00	22:00	12.9, 4.1	1.9, 3.0
	3	13.4, 1.2	11	19	08:00	23:00	06:00	09:00	13:30	22:00	12.2, 3.0	2.3, 3.6
	4	13.1, 1.9	11	18	07:00	22:30	06:00	09:00	15:00	21:00	12.3, 4.0	2.7, 3.4
	5+	13.6, 1.4	5	11	06:30	23:30	05:30	10:00	15:00	22:00	12.9, 3.3	**1.7, 1.8**

[1] 229 Dwellings.
[2] Excludes the 40 dwellings (16%) that had multiple or irregular heating periods.
[3] The method of calculation used here may overstate the heating period in homes with irregular heating patterns.

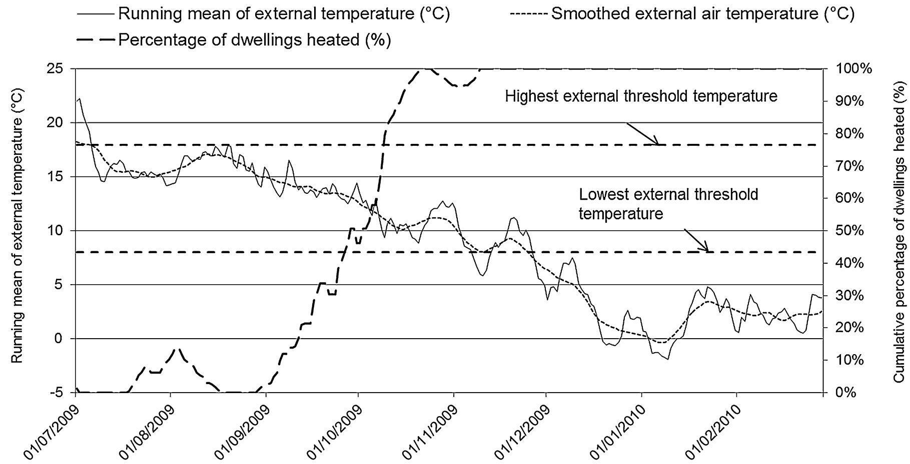

Fig. 8. Running mean temperature (T_{rm}) during the monitoring period and the percentage of the 249 dwellings heated, with indication of the highest and lowest external threshold temperature.

lower demand temperatures and therefore have shorter heating seasons than older occupants.

Although all homes in this study were in one geographical location, they switched their heating on gradually over a two month period. One might imagine that a nationally distributed sample would reveal an even greater temporal variation; with those in colder locations switching on earlier and those in warmer location later.

3.2. Number of heating periods per day

Although double heating patterns were the most common (n = 126, 51%) other heating patterns such as single (n = 83, 33%) and multiple (n = 13, 5%) were also frequently observed (Table 3). There was no discernible difference in heating patterns between weekends and week days. Single heating patterns were found to be as common as double heating patterns in dwellings occupied by people over 60 and in flats, but much more common in the homes of those retired or unable to work.

The heating patterns used in 11% of dwellings (n = 27) were too inconsistent to categorise. This suggests that in at least 11% of dwellings the heating is turned on and off manually, or the timer is overridden, on a regular basis.

3.3. Start and end times of heating

Within the 209 homes with either single or double heating periods, the median heating times were 07:00–23:00 (15 h) for single heating periods and 06:00–09:00 and 15:00–22:00 (10 h in total) for double heating periods (Table 3). Across all house characteristics the median start time of heating was relatively consistent, 07:00–08:00 for homes with a single heating pattern and 06:00–07:00 in homes with a double pattern. However, dwellings with five or more occupants seem to turn their heating on early 06:30 (single period) or 05:30 (double period). Likewise, those that were unable to work tended to turn their heating on earlier (06:00, single pattern) as did those that were unemployed or in the 'other' category (05:30, double pattern). The earliest median start of heating time for the second heating period was found in dwellings where the occupants were over 70 (13:00), the latest afternoon start time was 16:00 in dwellings occupied by two occupants and in homes with occupants in the 40–49 age group.

3.4. Duration of heating per day

The average daily heating duration was 12.6 h (standard deviation 3.5 h) with daily heating durations in individual homes ranging from 4 h to 22 h (Fig. 9). This is longer than calculated by previous research, Shipworth et al. estimated heating to be active for 8.2 h on weekdays and 8.4 h on weekends [22]. This may be partially because the method used in this paper overestimates the start time and so the duration of heating period, especially in dwellings with inconsistent heating patterns.

No statistically significant differences were found between the durations of heating in houses of different type, age or construction. However, the characteristics of the occupants did have an effect. Employment status and age of oldest occupant showed statistically significant differences (p < 0.04). Those unable to work, or in the 60–69 age band, heated for significantly longer (14.0 h) presumably because they were at home longer than those where the oldest person was aged between 40 and 59 (11.6 h, q = 0.02), probably because the occupants were at work. Dwellings that were heated for longer (metric 4) were found to have a statistically higher mean winter temperature (metric 1) (p = 0.062).

3.5. Under-heated days

In the whole sample over the whole 90 day winter period, 39% of the dwellings had no under-heated days, 17% had only one under-heated day, 22% had between two and four under-heated days and

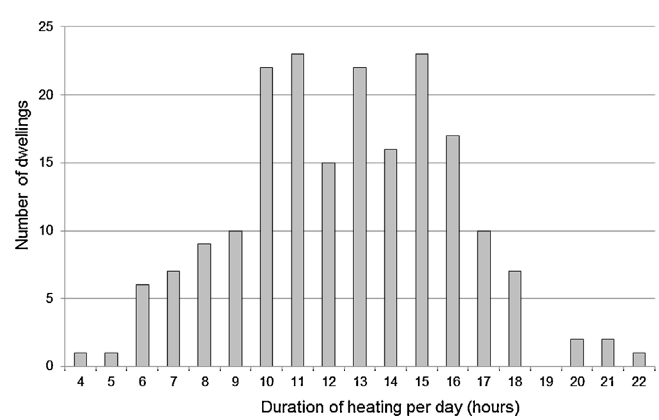

Fig. 9. Duration of heating per day in the 209 dwellings with single and double heating patterns.

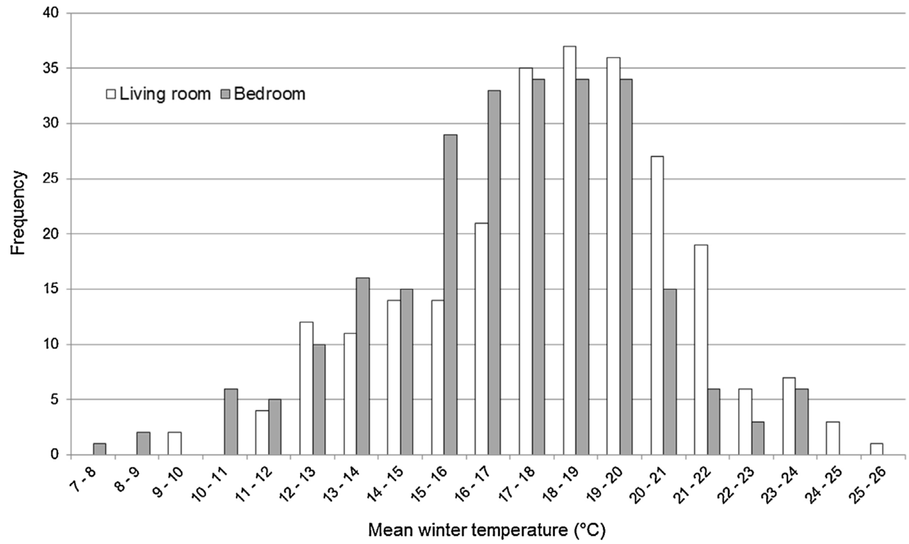

Fig. 10. Mean winter temperature in living room and bedrooms in 249 dwellings in Leicester between December 2009 and February 2010.

8% had more than ten under-heated days. The most under-heated days (38 days) was found in a dwelling with a single occupant in the 70 years or older category, which may be related to an extended stay away from home.

The analyses indicated that dwellings occupied by only one person had significantly more under-heated days (an average of five than homes with five or more occupants 1.7 days (2%) ($q = 0.066$). Dwellings where the oldest occupant was between 20 and 30 had more under-heated days (4.6) than other households. No statistically significant relationship was established between number of under-heated days and the technical house descriptors.

3.6. Mean winter temperature

Mean winter temperatures measured in the individual homes ranged from 9.7 °C to 25.7 °C in living rooms and 7.6 °C to 24.2 °C in bedrooms (Fig. 10). The averages for the sample as a whole were 18.5 °C (standard deviation 3.0 °C) in the living rooms and 17.4 °C (standard deviation 2.9 °C) in the bedrooms.

Significant differences ($p < 0.05$) were found between the mean winter temperatures in living rooms between houses of different type and construction; terraces (17.9 °C) were significantly cooler than flats (20.0 °C, $q = 0.037$), solid wall properties (18.0 °C) were significantly cooler than those with insulated (filled) cavities (19.2 °C), ($q = 0.025$). Both results are consistent with the differences in heat loss between the dwelling types, solid walls being less well insulated than filled cavity walls.

More interesting perhaps are the significant differences between households of different size, age of oldest occupant, tenure and employment status ($p < 0.05$). Single person households were particularly cool (17.7 °C), significantly cooler than homes with two occupants (19.0 °C, $q = 0.046$). The high number of under-heated days (metric 5, Table 3) in single person households will partly explain this. The homes of the over 60's (19.3 °C and 19.2 °C) are significantly warmer than those occupied by under 20's (16.4 °C, $q < 0.05$), perhaps partly because they are heated for significantly longer (metric 5, Table 3). Rented homes (19.1 °C) are warmer than owner occupied homes (17.7 °C, $q = 0.011$), perhaps because some that rent are not directly responsible for paying fuels bills. Households where the occupants are unable to work (20.6 °C) are significantly warmer than those where the occupants are employed (17.9 °C, $q = 0.001$), which can also be explained, in part, by the significantly different heating durations (metric 5, Table 3).

The only statistically significant difference observed in bedrooms was between dwellings with (17.5 °C) and without (16.1 °C) central heating ($p = 0.044$). This is to be expected as these dwellings are likely to be heated with secondary heating in the living spaces downstairs.

One sample *t*-tests were applied to assess whether the mean living room and mean bedroom temperatures were significantly different. Statistically significant differences ($p < 0.05$) between the living room and bedroom temperatures were found for dwellings where the oldest occupant was over 60 but not for any other age groups. The next metric explores this matter further.

3.7. ΔT_{room}

Over the whole winter period, 68% of living rooms there warmer on average than bedrooms (Fig. 11); the highest average temperature difference was 8.8 °C, which occurred in a semi-detached dwelling with central heating built between 1944 and 1965 with four occupants. In the homes where the bedroom was warmer the largest average temperature difference was 6.1 °C. This occurred in a detached dwelling built since 1980 with three occupants.

The difference between the mean living room temperature and the mean bedroom temperature was significantly smaller in centrally heated homes than in other homes ($p = 0.003$). This would be expected if secondary heating located in the living room was used in non-centrally heated homes. The temperature difference was also significantly smaller in the homes of those in employment (0.4 °C) compared to those unable to work (2.0 °C, $q = 0.059$), and in homes of those aged 20 to 29 (0.0 °C) compared to those aged over 70 (2.0 °C, $q = 0.104$) (Table 4).

This suggests that younger people and those in work have a more uniform temperature throughout the rooms of their home than older people and those unable to work. This may be a result of the use of secondary heating; people who are retired or not working may heat their living spaces using secondary heating during the day when the central heating is off. It also reflects the fact, even when homes have central heating, the unemployed may have it on for longer than those in work (metric 5, Table 3). When central heating is turned off, the temperatures fall and ultimately the whole house will achieve roughly the same (low) temperature.

Table 4
Mean winter temperature, ΔT_{room}, mean achieved temperature, and average temperature during heated periods as calculated for all 249 dwellings in Leicester between December 2009 and February 2010. Statistically significant results ($q < 0.05$) are shown in bold.

Characteristic	Metric 6[1]		Metric 7[1]	Metric 8[1]	Metric 9[2]						
	Mean winter temperature (°C)		ΔT_{room} (°C)	Mean achieved temp[3] (°C)	Average temperature during heated periods (living room) (°C)			Average temperature during heated periods (bedroom) (°C)			
	(Mean, SD)	(Mean, SD)	(Mean, SD)	(Mean, SD)	(Mean, SD)			(Mean, SD)			
	Living room	Bed		Living room	Single	First	Second	Single	First	Second	
	All dwellings	18.5, 3.0	17.4, 2.9	1.0, 2.5	20.9, 3.2	18.8, 3.2	17.5, 2.8	19.0, 3.0	17.2, 3.4	17.0, 2.7	17.8, 2.8
House type	Detached	17.8, 3.2	17.4, 2.9	0.3, 2.6	20.4, 3.9	18.3, 4.3	15.7, 2.3	17.6, 2.4	17.0, 4.2	16.3, 2.4	17.4, 2.1
	Semi-detached	18.7, 2.8	17.2, 3.0	1.5, 2.5	21.1, 3.0	19.0, 2.9	17.6, 2.6	19.3, 2.9	16.7, 3.6	17.0, 2.5	17.8, 2.5
	End terrace	18.2, 3.3	17.5, 3.4	0.7, 2.5	21.0, 3.4	17.4, 2.6	17.8, 3.4	19.5, 3.8	17.4, 2.9	17.1, 3.4	17.8, 3.6
	Mid terrace	**17.9, 2.9**	17.4, 2.5	0.5, 2.5	20.2, 3.1	17.9, 3.8	17.1, 2.4	18.3, 2.6	17.6, 3.3	17.0, 2.5	17.5, 2.7
	Flats	**20.0, 3.1**	18.5, 3.0	1.5, 1.8	22.3, 3.5	20.5, 3.2	19.2, 3.1	20.3, 3.5	18.6, 2.5	18.2, 3.5	18.9, 4.0
House age	Pre 1919	17.2, 3.3	16.6, 3.2	0.6, 2.8	**19.6, 3.7**	16.9, 3.5	16.5, 3.2	17.9, 3.5	16.0, 3.8	16.5, 3.2	17.1, 3.4
	1920–1943	18.4, 2.8	17.3, 2.9	1.0, 2.4	20.7, 3.0	18.7, 3.1	17.5, 2.4	19.0, 2.4	16.6, 3.7	17.3, 2.1	18.2, 2.1
	1944–1965	19.0, 3.2	17.4, 3.0	1.5, 2.6	**21.5, 3.5**	20.1, 3.3	17.5, 2.9	19.3, 3.3	18.2, 3.0	16.3, 2.9	17.2, 3.1
	1966–1980	19.4, 2.3	18.2, 2.4	1.2, 2.2	**21.9, 2.6**	18.9, 1.5	18.9, 2.5	20.4, 2.6	17.3, 2.8	18.1, 2.5	19.0, 2.5
	Post 1980	18.8, 2.8	18.2, 2.7	0.7, 2.2	21.0, 2.7	18.4, 3.5	17.5, 2.2	19.0, 2.6	17.7, 3.5	17.6, 2.1	18.0, 2.0
Wall type	Solid wall	**18.0, 3.0**	17.4, 2.7	0.6, 2.5	20.4, 3.2	17.9, 3.1	17.1, 2.9	18.5, 2.9	16.6, 3.2	17.2, 2.5	17.9, 2.7
	Unfilled cavity wall	18.4, 3.3	17.3, 3.6	1.2, 2.5	20.8, 3.6	19.5, 4.0	17.5, 3.1	19.0, 3.4	17.7, 4.2	16.3, 3.2	17.3, 3.5
	Filled cavity walls	**19.2, 2.7**	17.7, 2.7	1.5, 2.4	21.6, 2.9	19.4, 2.7	18.1, 2.2	19.9, 2.7	17.4, 3.2	17.3, 2.4	17.9, 2.4
Central heating	Yes	18.5, 3.0	**17.5, 2.8**	**0.9, 2.4**	20.9, 3.3	18.7, 3.3	17.5, 2.7	19, 3	17.3, 3.4	**17.1, 2.5**	**17.9, 2.6**
	No	18.8, 2.9	**16.1, 3.9**	**2.8, 3.4**	20.9, 2.4	19.8, 2.0	16.1, 3.4	17.9, 3.2	15.8, 3.9	**14.8, 4.7**	**14.8, 4.9**
Tenure	Own outright	18.7, 2.8	17.3, 3.2	**1.3, 2.7**	21.1, 3.0	17.5, 3.0	17.0, 2.7	18.5, 2.9	17.0, 3.2	17.0, 2.7	17.8, 2.8
	Buying with mortgage	**17.7, 3.2**	17.4, 2.8	**0.3, 2.2**	**20.1, 3.4**	19.0, 3.3	18.5, 2.7	20.1, 3.0	17.2, 3.9	16.6, 2.9	17.1, 3.2
	Rent	**19.1, 2.9**	17.6, 2.7	**1.4, 2.3**	**21.6, 3.2**	20.7, 2.6	20.4, 2.6	22.1, 3.5	18.2, 3.4	19.1, 1.9	19.9, 1.9
Employment status	Employed	**17.9, 2.9**	17.5, 2.7	**0.4, 2.4**	**20.4, 3.2**	17.5, 3.0	**17.0, 2.7**	**18.5, 2.9**	17.0, 3.2	17.0, 2.7	17.8, 2.8
	Retired	19.0, 3.0	17.1, 3.5	1.9, 2.3	21.4, 3.2	19.0, 3.3	18.5, 2.7	20.1, 3.0	17.2, 3.9	16.6, 2.9	17.1, 3.2
	Unable to work	**20.6, 2.6**	18.6, 2.8	**2.0, 2.9**	**22.7, 2.8**	20.7, 2.6	**20.4, 2.6**	**22.1, 3.5**	18.2, 3.4	19.1, 1.9	19.9, 1.9
	Unemployed	17.9, 2.9	16.7, 2.2	1.3, 2.9	20.6, 3.5	19.6, 3.4	17.1, 2.6	18.4, 2.8	15.7, 1.6	17.2, 2.2	18.0, 2.0
	Other	18.9, 2.6	17.8, 1.7	1.0, 2.0	20.9, 2.5	18.4, 3.0	18.0, 2.8	19.3, 2.7	17.2, 1.8	17.7, 1.4	18.6, 1.5
Age of oldest occupant	20–29	**16.4, 3.4**	16.4, 3.4	**0.0, 1.7**	**18.3, 3.5**	n/a, n/a,	**13.9, 2.6**	**14.8, 2.6**	n/a, n/a	13.7, 2.6	14.5, 2.5
	30–39	18.3, 2.8	17.7, 2.2	0.6, 2.3	20.6, 3.5	18.3, 3.3	17.5, 2.4	18.9, 2.6	17.7, 1.7	17.2, 2.5	17.8, 2.7
	40–49	18.0, 2.9	17.5, 2.7	0.5, 2.5	20.6, 3.1	18.2, 3.1	16.9, 2.7	18.5, 3.1	16.0, 3.3	17.6, 2.3	18.5, 2.4
	50–59	18.1, 3.1	17.2, 2.9	0.9, 2.6	20.7, 3.1	18.2, 4.0	17.5, 2.6	19.1, 2.4	16.1, 2.9	17.2, 2.8	18.1, 2.8
	60–69	**19.3, 2.6**	17.8, 3.1	1.5, 2.4	**21.7, 2.7**	19.2, 3.0	**18.8, 2.1**	**20.3, 2.2**	17.5, 3.8	17.4, 2.3	18.1, 2.5
	70+	**19.2, 3.2**	17.2, 3.5	**2.0, 2.5**	**21.6, 3.4**	19.3, 3.2	**18.4, 3.1**	**20.3, 3.5**	17.6, 3.9	16.4, 3.0	17.0, 3.3
Household size	1	**17.7, 3.5**	16.6, 3.7	1.1, 2.3	20.2, 3.8	**17.3, 4.0**	16.9, 3.2	18.3, 3.6	**15.8, 4.0**	15.9, 3.3	16.5, 3.6
	2	**19.0, 2.6**	17.9, 2.6	1.1, 2.4	21.3, 2.8	19.9, 2.2	17.8, 2.8	19.3, 3.0	**18.7, 3.1**	17.2, 2.3	17.8, 2.2
	3	18.1, 3.0	17.1, 2.5	1.0, 2.9	20.8, 3.3	18.2, 3.6	17.2, 2.1	18.9, 2.4	15.7, 1.7	17.2, 2.6	18.3, 2.8
	4	18.9, 2.7	17.8, 2.6	1.1, 2.8	21.2, 2.7	**20.0, 2.6**	18.2, 2.5	19.7, 2.7	17.7, 3.1	17.8, 2.1	18.4, 2.2
	5+	18.7, 2.9	18.2, 2.5	0.5, 2.1	21.2, 3.6	18.6, 1.6	16.6, 2.9	18.6, 3.1	16.9, 1.9	17.7, 2.9	18.8, 2.7

[1] All 249 dwellings.
[2] Excludes the 40 dwellings (16%) that had multiple or irregular heating periods.
[3] In the living room.

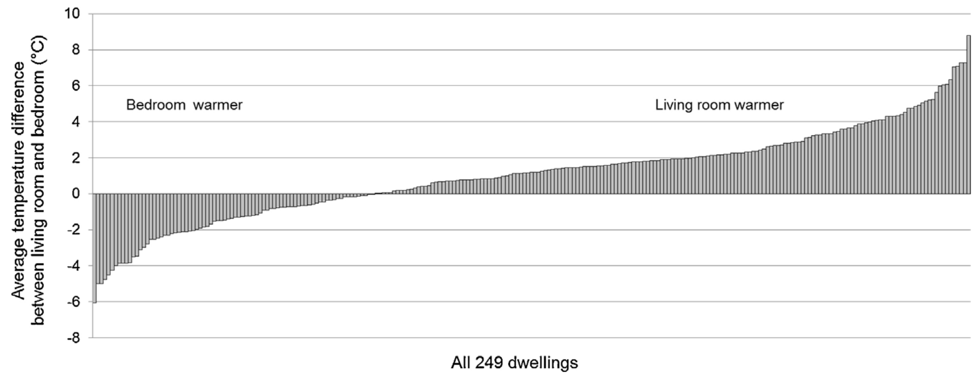

Fig. 11. Average difference between living room and bedroom temperature measured in 249 dwellings between December 2009 and February 2010.

3.8. Mean achieved temperature

A large variation in mean achieved temperature across the sample was evident; the highest value for an individual home was 30.5 °C while the lowest was 11.0 °C. The mean achieved temperatures were highly correlated with the mean winter temperature (metric 6) in both living rooms ($R^2 = 0.87$) and bedrooms ($R^2 = 0.91$). The average mean achieved temperature across all 249 homes was 20.9 °C (standard deviation 3.2 °C) (Table 4).

Considering house type, the highest mean achieved temperature was found in flats (22.3 °C) and the lowest in mid-terraced dwellings (20.2 °C), but this difference was not statistically significant ($p > 0.05$). A clear significant trend can be observed for house age ($p = 0.02$), the oldest dwellings, i.e. built before 1919 had the lowest mean achieved temperature (19.6 °C) and dwellings built between 1966 and 1980 the highest (21.9 °C, $q = 0.06$)). The mean achieved temperature was slightly lower in the newest dwellings, i.e. built since 1980 (21.0 °C). These trends mirror those found for the mean winter temperatures in the living room (metric 6, Table 4).

The mean achieved temperature differed significantly with the age of oldest occupant ($p = 0.015$). Dwellings where the oldest occupant was in their twenties had significantly lower mean achieved temperature (18.3 °C) than homes occupied by those aged 60–69 (21.7 °C, $q = 0.013$) or over 70 (21.6 °C, $q = 0.019$). This is partially because dwellings of twenty year olds had the highest number of under-heated days. The highest mean achieved temperature was found in dwellings where the household representative person was permanently unable to work (22.7 °C); this was significantly higher than the mean achieved temperature in dwellings of those in employment (20.4 °C, $q = 0.017$). The homes of those renting had a significantly higher mean achieved temperatures (21.6 °C) than homes owned with the aid of a mortgage (20.1 °C, $q = 0.011$). The trends and the significance of the results for tenure, employment, age of occupants and household size, mirror those found for the mean winter temperature in the living room (metric 6, Table 4).

3.9. Average temperature during heated periods

The average temperature during single heating periods was 18.8 °C in living rooms and 17.2 °C in bedrooms (Table 4). In dwellings with a double heating pattern, the average living room temperatures were 17.5 °C in the first period and 19.0 °C in second, the corresponding bedroom temperatures were 17.0 °C and 17.8 °C. Average temperatures in dwellings with a double heating pattern were always higher in the second heating period, which is a result of the second heating period being, on average, longer than the first. The living room temperatures are lower than the standard BREDEM assumptions used in energy models (21 °C during heated periods [14]) and the 18 to 21 °C suggested as comfortable by the World Health Organisation [37]. This might suggest that occupants are heating their homes for longer to try and achieve adequate temperatures later in the day.

Significant differences in the average temperatures during heated periods were not found for the technical household descriptors, but household characteristics were influential. The age of the oldest occupant was strongly related to the average living room temperature during both heating periods. Homes occupied by young people (aged 20–30) had particularly low average temperatures (13.9 °C first period and 14.8 °C second period). The average temperatures increased with occupant age such that temperatures in homes of those over 60 were significantly warmer ($q < 0.05$), being 18.8 °C for 60–69 year olds and 18.4 °C for 70 years plus in the first period, and 20.3 °C for both groups in the second period.

Household size was significantly related to the average temperature for homes heated using a single heating period ($p = 0.025$) but not for those using double period heating ($p > 0.3$). Conversely, employment status was significant in dwellings with a double heating patterns ($p < 0.05$) but not for those with a single heating pattern ($p = 0.079$); those in employment had significantly cooler homes (first period 17.0 °C, second period 18.5 °C) than those unable to work (first period 20.4 °C, second period 22.1 °C) ($q = 0.048$). Low average temperatures for both single and double patterns were found in dwellings with only one occupant.

4. Discussion

4.1. Reflections on home energy surveys

Before discussing the results and their implications it is useful to consider the strengths and weaknesses of the monitoring undertaken.

Large-scale monitoring campaigns in diverse homes must use low cost, easy to install, robust sensors. Here Hobo sensors that log every hour were used successfully, but their sensitivity to small temperature changes is poor and memory capacity is limited. More expensive logging devices with greater accuracy and memory would have enabled better resolution of heating on and off times[12]. In this regard, a small self-contained temperature logger such as an ibutton [38] attached to a radiator or the boiler casing might be a useful addition, an approach used by Martin et al. [29].

In this work, and that of others [20,22], temperatures were only measured in two rooms. This choice was influenced by the use of two 'zones' in BREDEM-based models. By measuring temperatures

[12] Because, with hourly logging, if a temperature rise is observed in the 7:00am reading it was impossible to know whether the heating was turned on at 6:00am or 6:50am.

in all rooms the spatial distribution of temperatures could be explored, and the two-zone concept evaluated. The results of such a study by the present authors will shortly be published.

Sensor technology is advancing quickly through the use of wireless communication and broadband networks, and soon the UK will begin a role out of smart meters that can record gas and electricity use at half hour intervals. These developments are creating a market for smart, digital, remotely accessible, home heating controls [39]. These will enable the real time capture, as shorter time intervals, of actual gas use, (thus indicating when boilers are firing), and feed-back from smart controllers will identify whether heat or hot water is being generated. In some systems occupants' use of heating controls can also be logged. It will be some years before large-scale surveys can make use of the full potential of such technology, but in the meantime much better equipment for understanding how homes are heated will gradually emerge. The approach used in this work will soon seem crude.

The nine metrics developed here proved very useful for describing heating patterns; however, the methods of calculating them could be improved. The most challenging aspect of the analysis was estimating when spaces were being heated. A simple profile approach was ultimately adopted which was similar to an approach used by others [24]. Other more rigorous strategies might be developed aided by the emergence of new monitoring technology. The idea of a standard set of metrics, calculated by well-documents methods, to quantify key features of home heating behaviours is though valuable. It is an area which would benefit from collaboration between interested researchers.

This paper has, like others [30], underscored the value of associating questionnaire surveys with monitoring, i.e. socio-technical studies. The 4M survey questionnaire drew on the one developed in the CaRB project [22] but, because questionnaire also explored other non-energy matters, the heating questions were reduced in scope. The questionnaire did not explore whether occupants felt comfortable, despite the cool temperatures recorded, or whether they were struggling to heat their home, for example because the heating system was inadequate or due to fuel costs [40]. Questions that probe this would be valuable additions. The gradual convergence of the research community to a core set of standard questions would be very valuable, as it will enable the pooling of data from different studies.

4.2. Comparison with the results of others

There are strong similarities between the results reported here and those recently reported by others, most notably Huebner et al. [25,26]. In their work, living room temperatures recorded in a nationally dispersed sample of 275 homes, of which 93% had central heating, were monitored for 92 days during the winter of 2007/08, as part of the CaRB project. Their papers note, as reported here: that there is a high degree of variability in the heating patterns and temperatures achieved in centrally heated homes; that the weekend and week day temperature patterns and the temperatures reached are similar; that the temperatures reached in the first, morning, heating period are lower than those reached in the second, evening, heating period; that in some homes, on some days, the heating is turned off; and that the temperatures are invariably lower than 21 °C.

Huebner et al. [25] quoted a mean daily living room temperature of 19.0 °C, whilst Oreszczyn et al. [20] reported a median standardized daytime temperatures in living rooms and bedrooms of 19.1 °C and 17.0 °C[13]; the corresponding values reported here (metric 6) are 18.5 °C and 17.5 °C for living rooms and bedrooms, respectively. Huebner et al. [26] quote average temperatures during the first and second heating periods of 18.3 °C and 19.9 °C, respectively, cf. 17.5 °C and 19.0 °C (metric 9) reported here. In their companion paper [26], they quote an average demand temperature of 20.6 °C, whilst Shipworth et al. [22] estimated the average thermostat setting in their sample to be 21.1 °C, cf. the mean achieved temperature reported here (metric 7) of 20.9 °C. Finally, in [26], 16% of homes are reported as having five or more under-heated days, cf. 22% with five or more under-heated days herein.

Overall, the high level of agreement between the findings of these different studies, both with regard to the heating patterns and the temperatures achieved, is rather remarkable; especially given the different samples, monitoring equipment used, periods of measurement, parameter definitions and methods of calculation. Specifically, all the temperatures quoted here are within 0.6 K, except for the average temperature during the first heating period; which might be explained by the much colder winter during this study (2009/10), than during the study reported by Huebner et al. [25,26][14].

4.3. How different households heat their homes

As a whole, the work here and by others, shows that heating patterns and temperatures in UK homes vary substantially: even when only centrally heated homes are considered. But this work has shown that patterns of heating do not vary randomly; rather, there are clear, systematic differences which depended on the characteristics of the household: the age of the oldest occupant and employment status.

Concerning the age of the occupants, three broad groupings have been identified. First, young people, aged 20–29, tended to have their heating system on later in the year (when it is colder, metric 1) and turn their heating off more frequently (under-heated days, metric 5). The living room temperatures that result are also low (mean achieved temperature, metric 8, temperature during the heating periods, metric 9 and the overall mean winter temperature, metric 6).

The second group, those over 60, heat their homes in a very different way. The heating comes on earlier in the year, the afternoon heating period begins earlier (metric 1), spaces are heated for longer (metric 4) and there are fewer under-heated days. Secondary heating may be used more often in living rooms. Consequently, the living room temperatures (metrics 6, 8 and 9) are all significantly higher, for example, the overall mean winter temperatures were 19.2 °C for over 60's (and 19.3 °C for over 70 s), compared with 16.4 °C for twenty year olds.

The third broad group, 30 to 59 year olds, heated their homes in a similar way, with patterns and temperatures midway between those observed for the other two groups.

These results are not surprising. Younger people are more likely to be in work or otherwise engaged and so spend longer outside the home. They are also likely to be healthier, more active and so more accommodating of cool conditions. Older people are likely to spend longer at home, be more sedentary and more sensitive to cold conditions. Health concerns may also precipitate a desire for warmth.

Employment status also had a significant effect on how homes were heated. Those in work (employed) heated their homes for a significantly shorter time and experienced significantly lower temperatures (metrics 6, 8, 9) than those unable to work. This group

[13] Average from 08:00 to 20:00 for the living room and 20:00 to 08:00 for the bedroom, and standardised to an external temperature of 5 °C.

[14] Temperatures in the first heating period will be especially susceptible to external temperature differences as the heating system labours to bring the house up to temperatures following the cold night.

heated their home the longest (14 h, metric 4) and achieved the highest temperature (22.7 °C, metric 8) of any grouping. (There may, of course, be a significant numbers of households common to the over 60 and unable to work categories.) Households signifying that they were retired had heating patterns and temperatures intermediate to these two groups. Interestingly, those that classified themselves as unemployed had heating patterns and temperatures similar to those in employment; although they may spend more time at home.

4.4. Implications for housing stock modelling

The results have clear implications for energy stock models and it is pertinent to consider these, especially the appropriateness of BREDEM-based modelling, which is the prevailing paradigm in the UK. Such models suffer from three problems, firstly, the inherent failure to capture correctly the thermal physics and engineering of the way heating systems and the house fabric interact, secondly the incorrect assumption about patterns of heating and the temperatures achieved, and thirdly the use of fixed heating patterns and temperatures for all houses and households[15].

First, regarding the engineering and physics, in BREDEM-based models the idealised temperature profile (Fig. 1) is a device to enable the mean internal temperature, from which energy demands are calculated, to be determined. Actual temperatures profiles are very different, even in homes that are centrally heated for two periods, as the detailed measurements (Fig. 4) and the monitored profiles (Fig. 5) illustrate. Fundamentally, and ignoring occupant effects for the present, the space temperatures result from the interplay between the heating system and the built geometry and fabric of the dwelling. This affects both the way homes warm as well as how they cool: the BREDEM profile only admits to effects during cooling.

Correct modelling of house warming is important. In the shorter, morning, heating period the measured temperatures were *always* much lower than in the longer afternoon/evening period[16] (Table 4). This is partly because the rate of heat output is limited by the size of radiators, and/or the operation of any TRVs, meaning that hot water returns to the boiler causing it to modulate, especially so as the 'demand' temperature is approached. It is also because some of the delivered heat flows into the thermal mass of the building, especially so after the house has cooled overnight. This cold mass must be 'charged' before the air temperatures stabilise; BREDEM-based models essentially ignore thermal mass effects. Thus, in real buildings, achieved temperatures will be dependent on the characteristics of the heating system and the fabric and not, as BREDEM-based models assume, independent of them[17].

Second, the standard heating profiles used in most BREDEM-based models[18] make incorrect assumptions about occupants' patterns of heating and the temperatures that they desire. First, the model assumes *all* homes are heated to a two period pattern during week day. Again, this isn't so. In the sample studied here, only half of the homes (51%) were heated in this way and, importantly, the heating pattern depended on occupancy; here employment status was shown to be particularly important. Second, the model assumes that homes are heated for longer at weekends than during the week; the work here and by others [25,26] has demonstrated that there is, in fact, little differences between weekday and weekend patterns[19]. Third, the model assumes that demand temperatures of 21 °C and 18 °C are reached in living spaces and bedrooms and that these are maintained throughout the heating periods. In fact these two zones had rather similar temperatures, and whilst centrally heated bedrooms were close to 18 °C (being 17.1 °C and 17.9 °C in the morning and evening heating periods, respectively, metric 9), living rooms were much cooler than 21 °C, (17.5 °C and 19.0 °C in the two periods). In 32% of homes the bedrooms were, in fact, warmer than the living rooms.

Third, whilst it is possible to change heating schedules and demand temperatures in BREDEM-based models the lack of empirical data about how homes are heated has meant that most models have used standard assumptions [13]. Other differences in heating patterns such as under-heated days, earlier or later switching (on or off) at the start and end of winter and variations in temperature throughout the homes (unused rooms may be unheated) are not modelled in BREDEM-based models. Some of these factors vary systematically with the house, heating system or occupant characteristics.

It is difficult to deduce what the effect of all these modelling errors on predicted energy demands is likely to be; there are many different and counteracting affects at work. Nevertheless, one might speculate that because living area temperatures are assumed by BREDEM-based models to be higher than they are in reality, the steady-state heat loss will be over predicted and so the predicted heating energy demand will also be too high. There is useful work to be done to understand the energy prediction consequences of using BREDEM for stock modelling.

What does seem clear is that the uniformity of the assumptions that BREDEM makes *will* lead to systematic errors that could have unfortunate consequences for energy policy making, and the targeting of energy efficiency measures, such as those planned via the UK Green Deal[20]. Based on the evidence generated here, those over 60 and those unable to work, are likely to use more energy and have the highest heating bills, and so energy efficiency measures could benefit them most. They are also a sector of the population which might experience most difficulty in paying fuel bills, yet benefit most from maintaining a relatively high indoor temperature over the whole day. In contrast, households of younger people will benefit less, because their homes are much less frequently heated and to lower temperatures. Targeting energy efficiency measures at the elderly is not new idea of course. Random mistakes when targeting of energy efficiency measures are inevitable, but not critical, however policies, driven by model predictions, which systematically disadvantage some sectors of society could have serious political consequences.

Much has changed in the 25 or so years since the BREDEM modelling framework was created, both in the way we use our homes and the availability of useable energy models. (We no longer expect to be able to understand the mathematics behind models or be able to complete calculations by hand; arguments that have been used in support of simple BREDEM-like modelling). Others [41,42] have modelled stocks using state of the art simulation programmes. Is it not time to adopt a more realistic approach to understanding the energy demands of our national housing stock and to targeting energy efficiency measures?

[15] Which isn't surprising given that they were devised for rating the efficiency of the house.

[16] During which the average achieved living room temperature in centrally heated homes, 20.9 °C, was similar to the assumed BREDEM value of 21 °C

[17] The significant difference in achieved temperature with house type (metric 8, Table 4) might be evidence of this.

[18] One model does not use all of the standard assumptions but varies heating patterns based on employment status [15].

[19] BREDEM-like modelling was initiated around 1986, which was prior to the Sunday trading act of 1996, and so weekend heating patterns may well have been rather different then than they are today.

[20] The Green Deal assessment is based on BREDEM and uses standard heating assumptions.

5. Conclusions

Indoor temperature measurements were made at hourly intervals in the living room and main bedroom of 249 dwellings in the city of Leicester, in the UK Midlands between July 2009 and February 2010. These were supported by a face-to-face questionnaire survey. This is thought to be the largest city-scale study of this type undertaken in the UK.

Conclusions are drawn about the analysis methods used, the patterns of indoor temperature in the homes, and the standard UK approach to home energy modelling. This work has implications for large-scale UK home energy efficiency schemes.

- Although central heating was used in 93% of the homes, the heating patterns and the temperatures achieved were diverse and hard to define. The basic pattern of temperatures generated by the heating system was punctuated by occupant interventions and other temperature-affecting events: the use of secondary heating, switching the system on and off manually, opening windows, etc. A set of metrics with associated methods of calculation have been defined to capture this complexity.
- The nine metrics define: (1) the external threshold temperature that triggers the start of winter heating, (2) the underlying heating pattern, (3) the beginning and end of the heating periods, (4) the duration of heating, (5) the number of days when homes are 'under-heated', (6) the average temperature over the winter as whole, (7) the difference between living room and bedroom temperatures and (8) the average temperatures achieved over the winter as a whole and (9) during each heating period. A method for calculating each metric was developed, but the start and end of each heating period was particularly hard to define. A common set of metrics with agreed calculation methods, which are standardised across the home energy research community, would be a useful advance.
- At the start of the winter, central heating systems in some homes switched on up to two months before it did in others; thus some dwellings were heated for most of the year whilst others were only heated during the coldest winter months. The heating switched on significantly earlier in homes heated to a higher temperature than it did in homes in homes heated to a lower temperature.
- A double heating pattern, morning and afternoon/evening, was found in 51% of the dwellings and single heating patterns in 33%; others had multiple or inconsistent patterns of heating. There was no discernable difference in the heating pattern between weekdays and weekends. Single heating patterns were much more common (60%) in the homes of those that were retired or unable to work.
- In 32% of homes, the bedroom was warmer on average than the living room. Homes without central heating had significantly cooler bedrooms, but not living rooms, than homes with central heating and those over 60 had bedrooms that were significantly cooler than the living room. Secondary heating in the living room may be the main source of daytime warmth in many of these homes.
- The dwelling type, age and construction had much less impact on the measured temperatures than did the characteristics of the occupants. However, heating systems came on at a significantly lower external temperature, i.e. later in the year, in mid-terraced homes than in detached houses. The average living room winter temperatures and/or the temperatures achieved during the whole heating season were however lower, often significantly so, in pre-1919, solid wall, or mid-terrace homes than in modern homes, with insulated cavities and flats.
- The temperatures within homes differed significantly and systematically with the age of the household. Households where the oldest person was just 20 to 29 tended to have the heating on later in the year and to turn their heating off more frequently. Those over 60 had their heating on earlier in the year and heated for longer each day. The achieved living room temperature and the average winter temperatures were significantly higher in the homes of the elderly than in those of the under 30s' (average winter temperature 19.2 °C cf. 16.4 °C). Households in the 30 to 59 age group heated their homes in a similar way, with patterns and temperatures midway between the other two groups.
- Those in employment heated their homes for a significantly shorter time and experienced significantly lower internal temperatures than those unable to work.
- The results suggest that homes occupied by older people and those permanently unable to work should be targeted for energy efficiency improvements as they are heated for longer and to higher temperatures and therefore have greater potential for energy savings.
- The patterns of heating were quite different from the pattern assumed by BREDEM-based models that are often used for energy demand assessments in the UK. First, none of the homes had daily profiles akin to those assumed by the model, which fail to capture correctly the interplay between the heating system and the form and fabric of the house. Second, homes are invariably heated to lower temperatures and often using a different on/off pattern than assumed by the model. And thirdly, the model offers no ready way to fully capture the diverse and systematic ways in which heating patterns differ between households.
- It is argued that the prevailing BREDEM-based approach to UK home energy use prediction could seriously and systematically misrepresent the energy demands of some sections of society; which risks systematic miss-targeting of energy efficiency measures in large-scale refurbishment programmes.

More generally, it is hoped that the work reported here will bolster socio-technical approaches to studying home energy use and that it makes a valuable contribution to the evolution of a set of common 'standard' metrics and methods of calculation that can be used across the domestic energy research and policy communities.

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