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The reality of English living rooms – A comparison of internal temperatures against common model assumptions☆

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ABSTRACT

Objective: This study examines the extent that temperatures in English living rooms correspond to standard assumptions made in established UK building stock models.
Methods: Spot temperature measurements taken every 45 min over 92 winter days in 248 homes in England were analyzed and compared to the assumed thermostat setting of 21 °C inside and outside the assumed heating periods.
Results: Homes on average displayed lower internal temperatures during assumed heating periods and significantly shorter durations of heating to 21 °C than common models assume, with about 20% of homes never reaching the assumed demand temperature of 21 °C. Data showed a difference of only about 45 min in the duration of temperatures at or above the demand temperature for weekdays and weekends, contrary to the assumed difference of 7 h. Variability between homes was large.
Conclusion: These findings suggest that currently used standard assumptions of heating demand and heating duration do not accurately reflect the living room temperatures of dwellings in England.
Practice implications: Standard assumptions might have to be revised, in particular regarding the weekday–weekend differentiation. The prediction of internal temperature for a given home contains potential large error when using standard assumptions.
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1. Introduction

In order to meet climate change and energy policy goals, the United Kingdom must reduce greenhouse gas emissions by 80% by 2050 from 1990 base line levels [1]. Since home energy use accounts for 23% of these emissions [2], the UK Government established a goal of reducing emissions from homes by 29% by 2020 [3]. Reducing energy consumption and emissions from residential homes requires understanding of both the buildings and the way they are used, since it is the two together that results in energy consumption. One common approach is to use models to predict home energy use, and then make recommendations for energy saving based on the outputs of the models. However, scarce empirical evidence is available to support the assumptions used in these models regarding occupant demand temperatures in UK dwellings.

Residential energy consumption models are largely grouped into either top-down models, which estimate consumption based on aggregated input parameters, or bottom-up models, which calculate consumption based on household-level variables and can then be extrapolated to a larger scale, such as the whole building stock for a country [4]. Bottom-up models can be useful for identifying specific energy-efficient and cost-effective measures for emissions reductions [5]. A widely used bottom-up model on which many housing stock models are based in the UK is the Building Research Establishment Domestic Energy Model (BREDEM). This is a data-driven building physics model which uses “heat balance equations and empirical relationships” to estimate energy demand, though the distinction between modelled parameters and the basis for empirical relationships remains uncertain [5, p. 1685]. This model was developed in the 1980s and has undergone a number of revisions of fine-tuning, particularly as it moved from a paper-based to computer-based tool [6]. The current versions estimate annual energy demand (BREDEM 12) and monthly energy demand

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(BREDEM 8) of homes, and a modified version (BREDEM 9) forms the basis the Standard Assessment Procedure (SAP), the UK government's primary assessment mechanism for determining the energy efficiency of homes. The results of SAP inform, inter alia, the UK Building Regulations which instruct the building industry and set the expected standard for energy efficiency in homes. Many UK housing stock models use BREDEM as the foundation for calculating energy consumption of the domestic stock including BREHOMES, The Cambridge Housing Model, DeCARB, UKDCM and CDEM [5].

The BREDEM family of models serves a variety of purposes. As part of regulatory instruments, like the SAP, they set standards for energy use against which individual dwelling design proposals are evaluated for compliance. In doing this they serve a normative function representing how the fabric and heating technology in dwellings should perform; they standardize occupant influences in order to assess the building performance independently of occupant effects. When used as the basis for building stock modelling however, their purpose is to indicate how homes (i.e. occupied houses) actually perform. In this function they should correctly represent occupant influences in order to correctly estimate national energy demand from the nation's homes.

BREDEM (and SAP) include a wide array of input parameters, including building materials, size and type of dwelling, heat loss, ventilation, lighting and appliance use, and water and space heating. Overall energy use is estimated from four main areas: space heating, water heating, cooking and lights and appliances. Of those four, space heating is the largest contributor to energy consumption; on average, it accounts for 57% of energy use in a home [3]. In BREDEM, space heating calculations are based on "heat losses, heat gains and the internal temperatures" in dwellings [7, p. 52]. Heat losses can occur due to the nature of building materials as well as through ventilation. Heat gains are calculated from heating systems, as well as other sources such as cooking, water heating, solar gains, gains from electronic devices, and metabolic gains. Internal temperatures are calculated in two zones: the living area (or living room) and the rest of the dwelling. The default assumption in the model is that the living area is heated to a higher temperature (usually 3 °C) than the rest of a home and only heated during specific time periods, specifically:

- Heating demand temperature (i.e. the thermostat setting): 21 °C
- Heating pattern:
  - o Weekday: 7:00–9:00, 16:00–23:00 (9 hours)
  - o Weekend: 7:00–23:00 (16 hours)

Outside this specified time periods, the heating system is assumed to be off. BREDEM based models assume that the demand temperature is reached immediately when the heating is on.

Heating systems and heating controls are also taken into account regarding these estimations. BREDEM assumes that the average temperature demanded in a living room is 21 °C only if it has central heating and a room thermostat; otherwise, the living room demand temperature is assumed to be slightly higher. A sensitivity analysis on a BREDEM-informed model, CDEM, found that heating demand temperature was the most important input variable, followed by heating pattern [8]. Hence, in order to predict energy consumption and carbon emissions correctly as energy efficiency measures are applied in the building stock, detailed estimates are needed from empirical measurements of heating demand temperatures and patterns.

The input parameters to BREDEM are based on empirical data and can be altered to include actual data from a given building. However, the default values which are commonly used for occupant-related variables, such as heating patterns or internal temperatures, have questionable validity: Oreszczyn and Lowe [9] indicate that more data is needed to validate the BREDEM model and capture the observed variations in occupant behaviour known to occur in the stock (see also [5,10]). In addition, Kelly demonstrated that estimates of energy demand made using SAP have been shown to be poor predictors of actual energy consumption [11], and more specifically, of the fuel consumption related to space heating [12].

Whilst Shipworth et al. found that the average maximum internal temperature for three winter months, used as a proxy for thermostat settings, was 21.1 °C, in line with the heating demand temperatures as assumed by BREDEM based models, the analysis revealed large variability in the heating demand temperature [10]. Also, for weekends, the estimated heating duration was only 8.4 h, almost half of the BREDEM assumption of 16 h. For weekdays, the estimate was about in line with the length of time that BREDEM assumes for weekdays, i.e. 9 h. However, the authors did not analyze *when* the heating was on over the course of a day.

The aim of this paper is to test if the BREDEM default values for heating demand temperatures and heating duration accurately reflect living room temperatures in English homes. The data consists of living room temperatures recorded in 2007–2008 in 248 dwellings across the UK. The measured temperatures are compared to the BREDEM demand heating temperature of 21 °C and according to the default BREDEM heating pattern for weekdays and weekends. The investigation specifically examines the extent that the measured temperatures correspond with the assumed heating (and non-heating) periods in BREDEM, i.e. the temporal distribution of temperatures of 21 °C over the course of a day are examined. It is important to note that this approach only compares realized temperatures against assumed temperatures; the findings should not be interpreted as an indication of alternative heating durations and demand temperatures to be used in BREDEM models. This is because BREDEM assumes that the heating system can elevate internal temperatures to 21 °C the instant that temperature is demanded, and thus the duration of heating demand temperature being reached, and the duration of the heating being on, are identical. In reality, homes do not reach the demand temperature instantly, and so the duration of heating demand temperature being reached, and the duration of the heating being on, are not identical.

2. Methods

2.1. Survey and temperature measurements

This study draws on living room temperature data from the Carbon Reduction in Buildings Home Energy Survey (CaRB HES), the first national survey to exclusively focus on energy use in English homes, that commenced in early 2007 (for details, see [10]). Households were selected by stratified random sample drawn from the Postcode Address file. Sampling and face-to-face interviews in 427 homes were carried out by the National Centre for Social Research (NatCen). During the interview, householders answered questions on the building characteristics of their home, heating practices, and socio-demographics. For a subset of homes, temperatures were monitored in the bedroom and living room from mid July 2007 to early February 2008. HOBO UA 001-08 sensors were used; these are self-contained data loggers that were programmed to record spot temperature every 45 min, resulting in 32 measurements per day. These were placed in the home by the interviewer and/or the homeowner with instructions on correct placement, i.e. between knee and head height, away from any heat sources or direct sunlight. The sensors have a manufacturer reported accuracy of ±0.47 °C, however calibration measurements were taken for each logger before placement in the home and used to correct subsequent readings after the recorded data had been extracted.

Table 1
Comparing the CaRB HES with temperature data with national estimates.

Characteristic	CaRB HES survey (%)	EHCS 2007 (%)
Tenure type		
Owner occupied	82.7	71.2
Privately rented	5.2	11.6
Local authority	6.0	8.8
Housing association/registered social landlord in EHCS 2007	5.6	8.4
Dwelling type		
Terraced	22.2	27.9
Semi-detached	25.0	27.8
Bungalow or detached houses	41.1	27.8
Flats	10.1	16.6
Other	1.6	
Dwelling age		
Pre 1919	13.4	21.1
1919–1944	17.4	17.5
1945–1964	23.0	19.7
1965–1980	26.2	21.8
Post 1980	19.8	19.9
Total number of households in survey	248	21,380

2.2. Sample characteristics

Of the 275 dwellings with data on living room temperatures, 11 used night-storage heaters, and 16 used other types of non-central heating technology; these were excluded from the following analysis as BREDEM assumptions differ for those technologies [7]. Of the remaining 248 homes, 93.5% had central heating with gas or LPG, and the other 6.5% had some other sort of central heating. Table 1 provides a brief overview of key characteristics of the sample in comparison to national averages [13].

As Table 1 shows, the CaRB sample had an over-representation of owner-occupied and detached homes and bungalows, and under-representation of privately rented accommodation and flats.

2.3. Temperature data and data cleaning

Living room data was recorded for the winter months, defined as a 92-day period between November 2007 and January 2008, after which point the temperature loggers were withdrawn. A variable expressing average daily external temperature was created based on minimum and maximum temperature at local weather stations within the respondent's Government Office Region [14]. For no day or region in the data analyses did the average maximum external temperature exceed 15.5 °C; this is the temperature above which it is assumed that no heating is necessary [15]. The recorded internal temperature data was screened for outliers, i.e. for recorded temperatures below 10 °C or above 35 °C, and for changes of more than 10 °C in 45 min (indicating, e.g., possible placement close to a heating source or in direct exposure to sunlight). Those potentially erroneous data points occurred on less than 0.2% of days and were excluded from further analysis. The dataset was managed and analyzed using SAS 9.2, MS Access, SPSS, STATA, and MatLab.

2.4. Analysing the data

The measured temperatures over the 92 days of winter formed the basic unit of analysis. As the BREDEM models assume differences in heating demand depending on weekday versus weekend, the data were divided into weekdays (66 days) and weekends (26 days). During the cold months of winter, when external temperatures were not exceeding 15.5 °C, BREDEM assumes heating systems must bring the living room to the comfort temperature of 21 °C. In Section 3.1, the average temperatures for weekdays and weekends are indicated. Then, the measured temperatures during the assumed heating periods are compared to the assumed heating demand temperature. Section 3.2 examines the probability that homes were heated to below 21 °C, to 21 °C, and above 21 °C. For each home and measurement point, the number of occurrences of temperatures equal to or below 20.5 °C (below BREDEM), above 20.5 °C and below 21.5 °C (matching BREDEM), and equal to and above 21.5 °C (above BREDEM) was counted. For each home at each of the 32 measurement points, the frequencies were divided by the number of data points (i.e. 66 for weekdays and 26 for weekends) to arrive at a probability value for each of those three categories for each measurement point. The temperatures 20.5 and 21.5 °C were chosen as the dividing point following the standard convention of rounding to the nearest integer. This way of representing temperature data is similar to showing actual temperature, but has one key advantage: it disregards absolute deviation from the assumed heating demand temperature, allowing a classification of how many homes meet the assumed demand temperature, how many homes are below, and how many are above. Given that the aim of the paper is to compare to what extent BREDEM assumptions are met, the absolute magnitude of difference is not the main focus. When averaging across measurement points within one home, it is possible to calculate an estimate of the number of hours that a home would fall into each of the three categories.

2.5. Definition of heating time periods

A perfect mapping on the heating times as assumed by BREDEM was not possible as temperatures were taken at 45 min intervals. To coincide with these, the weekday morning time window was defined as ranging from 7:30 to 9:00, and the evening window as 16:30–22:30. The weekend[5] time window ranged from 7:30 to again 22:30. Though these times underestimated very slightly the BREDEM-defined heating periods, they allowed more time for heating up the dwelling, and therefore the potential for higher temperatures in the time frames, and therefore offered a conservative assessment of BREDEM assumptions.

3. Results

3.1. Average heating temperatures and patterns

In order to examine average temperatures of the CaRB HES sample, the mean temperature over the 92 days of winter at each measurement point was calculated for each home. The mean values were then averaged across all homes.

Fig. 1 shows the average mean temperatures for weekdays (solid line) and weekends (dashed line) for all dwellings across the winter measurement period. The vertical lines indicate the times when BREDEM assumes the heating demand temperature would reach 21 °C during weekdays and weekends. As can be seen, average temperatures never reached 21 °C during the assumed heating periods, or at any point during the day, whether weekend or weekday.

BREDEM assumes a demand temperature and an achieved temperature of 21 °C for 16 h on weekends and 9 h on weekdays. Mean temperature, therefore, would be expected to be higher on the weekends. In the CaRB HES dataset, the mean temperatures over the course of a day were $M_{weekday} = 18.96$ °C ($SD_{weekday} = 2.46$) and $M_{weekend} = 19.11$ °C ($SD_{weekend} = 2.44$). As data did not violate the assumption of normal distributions, as checked with

[5] The term 'weekend' indicates one day of the weekend (i.e. 24 h). For brevity, the term 'weekend' is used in this meaning throughout the paper instead of writing 'one weekend day'.

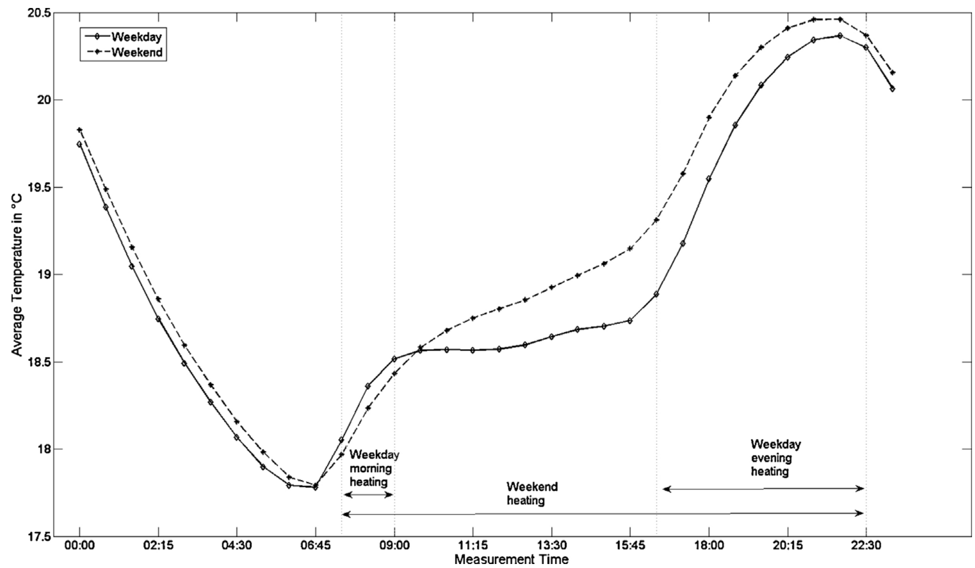

Fig. 1. Average temperatures across all homes for weekdays (solid) and weekends (dashed). The dashed vertical lines indicate approximate heating times according to BREDEM.

the Kolmogorov-Smirnov test, parametric tests were used to compare temperatures; a paired *t*-test showed that weekend temperatures were significantly higher than weekday temperatures, $t(247) = 6.72$, $p < .001$. However, the difference was only $M_{\text{difference}} = 0.16\,^\circ\text{C}$, indicating that despite seven more hours of assumed heating for weekends by BREDEM, the average temperature was barely higher than for weekdays.

To test the BREDEM assumption of a heating demand temperature of 21 °C for certain heating periods, the averages of each heating period were compared against a value of 21 °C. Analysis was done with one-sample *t*-tests. As seen in Table 2, the measured temperature for each heating period was significantly lower than 21 °C.

Though BREDEM assumes that both morning and evening heating periods attempt to achieve a similar temperature in the living room, the CaRB HES data indicates that mornings are cooler. In order to examine this in more detail, the morning and evening heating periods of weekdays were compared with the *between heating* period, i.e. from 9:45 to 15:45. The mean temperature *between* the two assumed heating periods was $M_{\text{between\_heating\_weekday}} = 18.62\,^\circ\text{C}$ ($SD_{\text{between\_heating\_weekday}} = 2.49$). A repeated measures ANOVA was used to test whether the means of three groups (i.e. *weekday_morning*, *weekday_between*, and *weekday_evening*) were equal. Temperatures differed significantly across the three periods, $F(2,494) = 299.96$, $p < .001$. In order to test which of the temperature values differed significantly from each other, post hoc pairwise comparisons with Bonferroni correction were calculated. Each of the three pairwise comparisons were significant (all $p < .001$), indicating that weekday morning temperatures were significantly lower than both the period between heating windows and weekday evening temperatures, and that weekday evening temperatures were significantly higher than the 'between' temperatures. Hence, a decline in temperature from assumed weekday morning heating hours to subsequent hours was not observed, contrary to what would be expected in the BREDEM model. Even when considering only the middle measurement point of the 'between' period, i.e. at 12:45 ($M_{12:45} = 18.60\,^\circ\text{C}$, $SD_{12:45} = 2.50$), to allow a longer time for the building to cool down in the assumed non-heating time, the results are the same, with higher temperatures in the *between_heating* than the morning heating hours contrary to BREDEM assumptions of a clear two-peak heating pattern.

For weekends, roughly the same temperatures would be expected under BREDEM from 7:00 to 23:00. However, as seen in Fig. 1, average temperatures in the CaRB HES sample continue to increase during the heating hours. In fact, the temperature pattern that emerged here is similar for weekdays and weekends; the main difference is the steeper increase on weekend days from about 9:00 to 15:45, i.e. the 'between' heating period on weekdays.

The empirical data hence showed significant deviations from BREDEM model default values. Homes were, on average, not heated to 21 °C during the assumed heating periods. However, the standard deviations of a magnitude of about 2.5 °C in all of the temperature averages as calculated up to now indicate a large variability in the individual temperature data. For example, the weekday evening heating period has an average temperature of 19.87 °C with a *SD* of 2.63 °C. This means that about 34% of all homes have an average temperature between 17.24 and 19.87 °C, and another 34% between 19.87 and 22.50 °C. Yet another 16% will have even colder temperatures than 17.24 °C on average, and 16% warmer temperatures than 22.50 °C. This large variability of data is exemplified by Fig. 2, which shows the individual average data for the 248 homes.

Fig. 2 indicates that heating demand temperatures and heating durations do not follow a standard pattern, but vary widely between homes.

Table 2
Average temperatures during BREDEM heating periods, compared to 21 °C.

CaRB HES heating period	Mean temperature (°C)	Standard deviation	One-sample *t*-test against 21 °C		
			t	*df*	*p*
Weekday morning heating period, 7:30–9:00 ($M_{\text{weekday\_morning}}$)	18.31	2.57	−16.46	247	<.001
Weekday evening heating period, 16:30–22:30 ($M_{\text{weekday\_evening}}$)	19.87	2.63	−6.78	247	<.001
Weekend heating period, 7:30–22:30 (M_{weekend})	19.30	2.48	−10.80	247	<.001

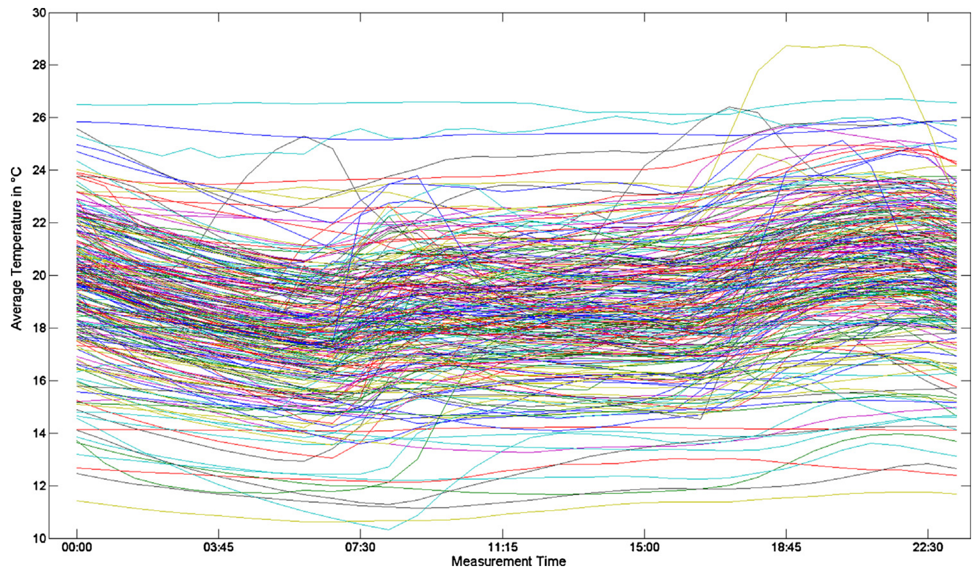

Fig. 2. The individual lines correspond to average weekday winter temperature data for the $N = 248$ individual homes.

Taken together, analysis of temperature revealed:

- Average temperatures were below the assumed heating demand temperature of 21 °C during the assumed heating periods both for weekdays and weekends.
- The two-peak heating pattern for weekdays (i.e. morning and evening) assumed by BREDEM was not evident in the data. In fact, the morning period was significantly cooler than both the evening heating period and the period of time between morning and evening.
- Average temperatures increased from early morning to late evening both for weekdays and weekends.
- The difference in daily average temperatures between weekdays and weekends was 0.16 °C. While this is statistically significant, it is of little practical significance in the context of between home variability in temperatures.

3.2. *Probability of temperatures being below, within, or above BREDEM assumptions*

The results of translating average temperatures into probabilities of temperatures below, at, and above the assumed demand temperature are reported in this section. The probabilities were calculated for each home at each measurement point and then averaged across homes at each measurement point. Given that the probability estimates were not normally distributed, both the mean and median would be biased estimators of central tendency. The Hodges–Lehmann estimator is a robust estimator of central tendency recommended for use with non-normally distributed data [16].[6] The resulting values are much more suited for expression of central tendency but lose the property that the average probability values for the three categories add up to exactly 1 at each measurement point. Fig. 3 shows the probability of temperatures falling into each of the three categories at each measurement point, for weekdays (a) and weekends (b).

The average probability – either over the course of a day or at any given measurement point or time period – can be interpreted in two ways: (1) it indicates the percentage of homes with temperatures in the respective categories at the time period or point under consideration and (2) it represents the likelihood of a home drawn at random from the dataset falling into the category over the period indicated.

The graphs indicate that throughout the day, including BREDEM assumed heating periods, more than half the homes did not reach the assumed demand temperature. On the other hand, both within and outside assumed heating periods, some homes showed temperatures above 21 °C. For each of the BREDEM assumed heating periods the percentage of homes falling into the three categories was calculated (Table 3). If BREDEM assumptions were reflected in living room temperatures, then 100% of homes should fall into the middle column, i.e. corresponding to BREDEM assumptions.

Table 3 shows that for all three of the assumed heating periods and hence expected temperatures of 21 °C, the majority of homes had lower temperatures. Only between 7% and 12% of homes matched the assumed temperature of 21 °C. During weekday morning heating periods almost nine out of ten (88%) failed to reach 21 °C, and in the evenings more than one in four homes (29%) reached temperatures above 21 °C in the assumed heating periods. It is not the case that the same proportion of homes are below and above 21 °C in the heating periods which would indicate that on *average* homes would reach 21 °C. The results indicate that homes have lower temperatures than assumed in BREDEM in assumed heating periods.

In the next step, the distribution of the three categories over the course of the day was examined to test if temperatures of 21 °C are reached in homes for 9 and 16 h when considering the whole day. If so, this would indicate that the patterns are shifted with regard to the assumed periods of heating but that

Table 3
Percentage of homes falling into each of the three categories during assumed heating periods.

	Percentage of homes		
	Below 21 °C	At 21 °C	Above 21 °C
Morning weekday heating	88%	7%	3%
Evening weekday heating	57%	12%	29%
Weekend heating	67%	10%	19%

Given the usage of the Hodges–Lehmann estimator, percentages do not add up to 100% in all cases.

[6] It is calculated as the Cartesian product of the dataset with itself, i.e. for this dataset with $n = 248$ measurements, it has $248(248 + 1)/2$ pairs. For each such pair, the mean is computed. Finally, the median of these $n(n + 1)/2$ averages is defined to be the Hodges–Lehmann estimator of location.

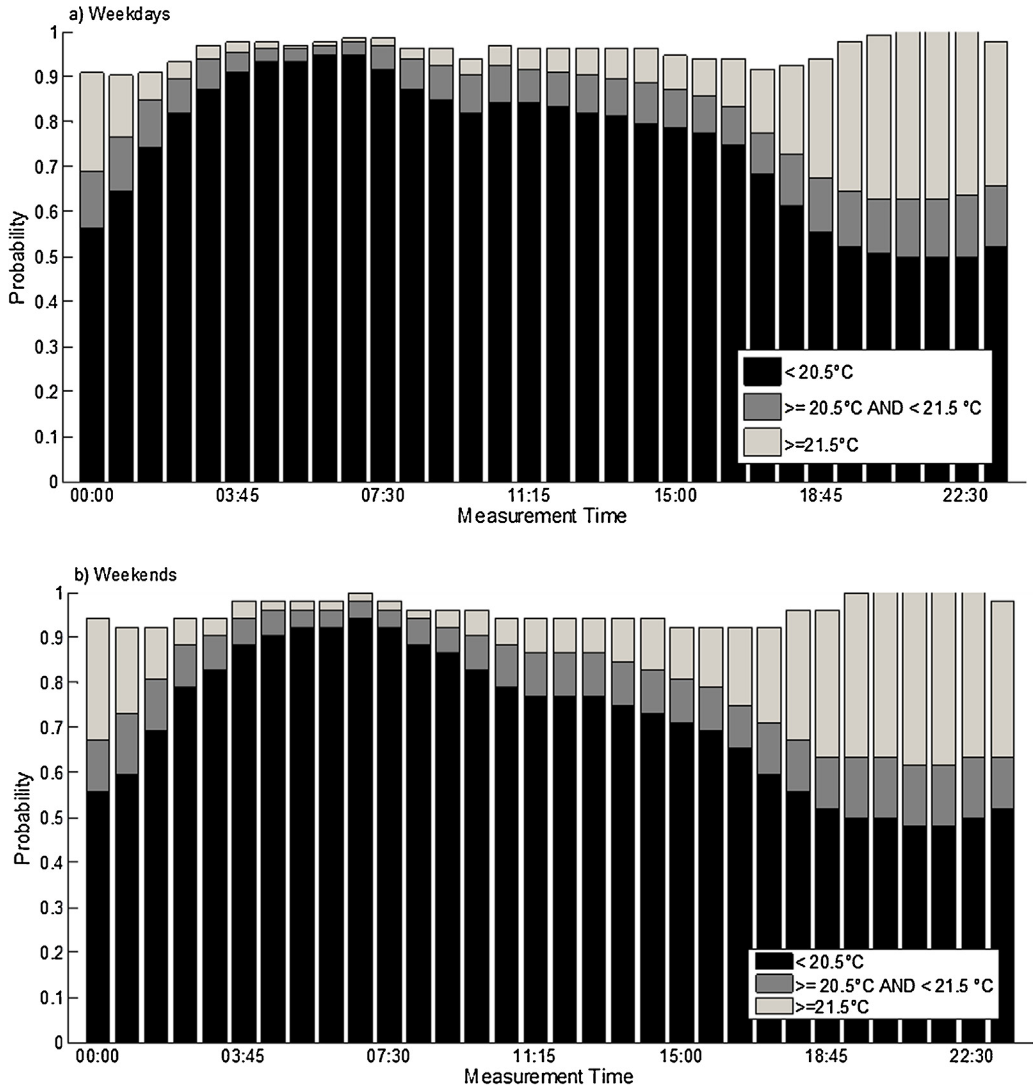

Fig. 3. Probability of temperatures falling into three categories of being below, within, or above BREDEM assumptions for weekdays (a) and weekends (b).

the duration per se corresponds to recorded temperatures. The probability estimates were averaged over the 32 measurement points, and the resulting average was multiplied by 24 (i.e. the number of hours per day) to get an estimate of the number of hours homes fall into the respective categories over the course of a day (Table 4).

The data showed that also when considering the whole day, the numbers of hours of temperatures of 21 °C were much lower than assumed. Dwellings reached temperatures of 21 °C or more for only about 5 to 5 h 45 min per day. The estimates for weekdays and weekends are very similar, with only about 45 additional minutes of temperatures of 21 °C or more on weekends.

Taken together, this part of analysis showed that:

- The majority of homes did not reach 21 °C during the assumed heating periods. This effect was particularly striking in the assumed morning heating periods where 88% of homes had temperatures lower than 21 °C.
- Homes on average reached 21 °C only for about 2 h per day; above 21 °C for about 3 h, and hence temperatures below 21 °C for about 18 h.
- Weekends and weekdays showed a very similar distribution across the three categories.

3.3. *Variability between homes on the durations of temperatures above 20.5 °C*

In a final step, the reasons that these findings differ from BREDEM default values were examined. There were two possible hypotheses: (1) all homes differ in a similar manner from the BREDEM assumptions (i.e. having a longer-than-expected duration of temperatures below the assumed demand temperature) or (2)

Table 4
Probability for each of the three categories and numbers of hours of in the three categories.

	Probability of temperatures			Number of hours over the day		
	Below 21 °C	At 21 °C	Above 21 °C	Below 21 °C	At 21 °C	Above 21 °C
Weekday	.74	.09	.13	18 h 10 min	2 h	3 h
Weekend	.71	.09	.16	17 h 20	2 h 11 min	3 h 38 min

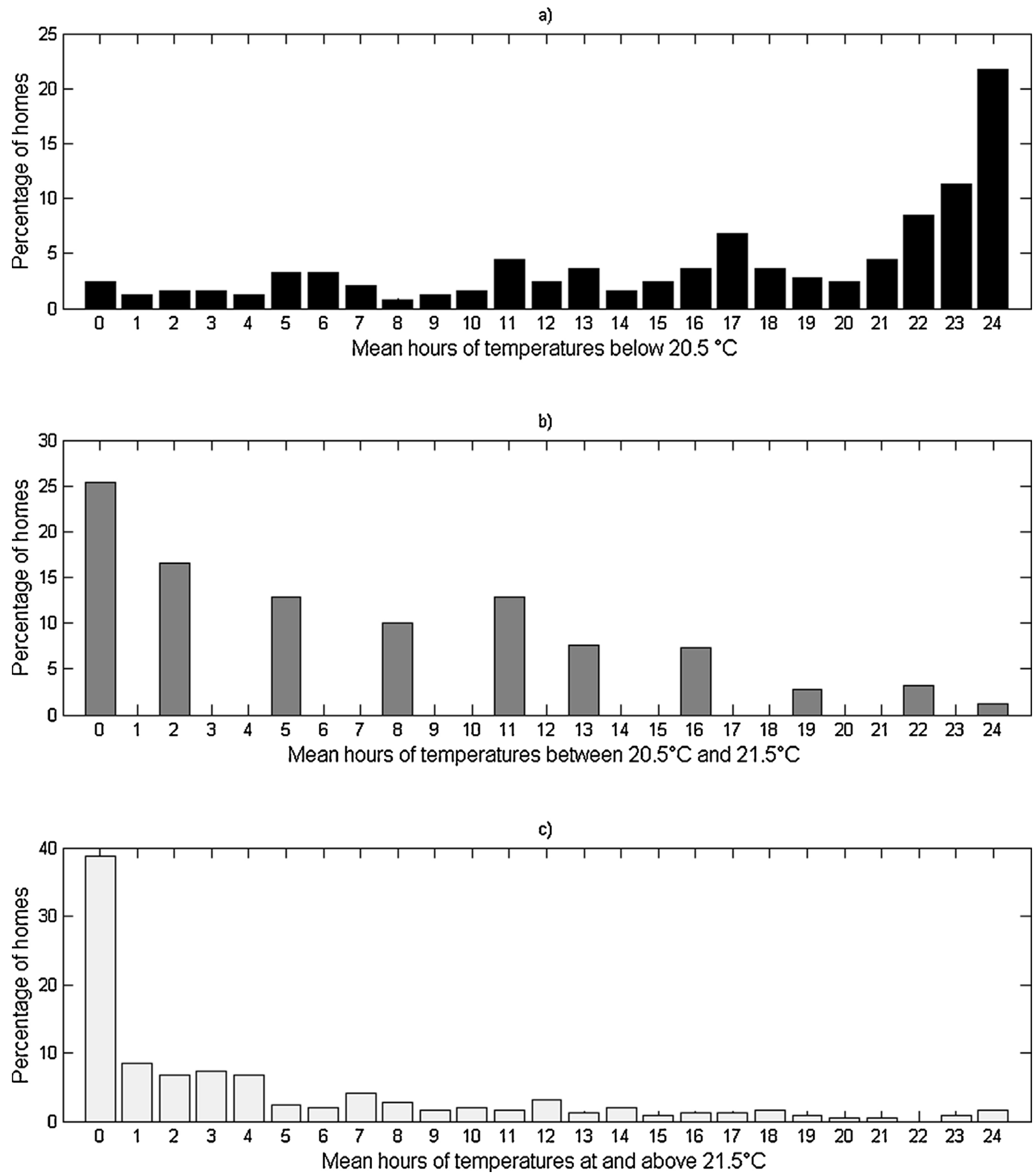

Fig. 4. Histograms of observed hours of temperatures below (a), at (b), and above (c) the assumed demand temperature.

there is a great variability between homes in being below, at or above the assumed demand temperature. As indicated by the large variability in the average temperatures (see Fig. 2), the latter is more plausible. A differentiation between the two is of importance when predicting heating demand of an individual home (instead of a large sample) because the error of prediction for an individual home could be large if homes differ substantially. Fig. 4 shows a histogram of the daily hours homes displayed temperatures below, at, or above the commonly modelled demand temperature. The distribution within a category is shown as the percentage of homes that have a given value of number of hours of fulfilling the criteria of the respective category.

Given the large similarity between weekdays and weekends, only data for weekdays is presented.

Fig. 4 indicates the wide variation in average hours spent in the respective temperature categories. About 22% of homes always had temperatures below the assumed heating demand temperature, and another 11% for 23 h (Fig. 4a). All possible values were present; homes varied from zero to 24 h of temperatures below 20.5 °C. BREDEM would expect 15 h of temperatures below the demand temperature on weekdays; however, 65% homes had even more hours, and 32% of homes less hours of temperatures below the demand temperature. No home showed temperatures of 21 °C for exactly 9 h as assumed under BREDEM for weekdays (Fig. 4b); 65% had fewer hours at the assumed demand temperature and 35% more hours. About 40% of homes never reached temperatures above the assumed demand temperature but data is again widely dispersed (Fig. 4c).

These findings indicate that homes differ strongly in the number of hours in which they reach temperatures below, at, or above the demand temperature. The distribution is not uniform across all possible numbers (i.e. from 0 to 24 h) though, with a larger proportion of homes located at one end of the underlying scale. The variability indicates that prediction of heating demand for one particular home will very likely be incorrect when based on the average of a sample or standard assumptions.

In summary, analysis of the variability of homes showed:

- There was a large variability in the number of hours that dwellings reached temperatures below, at, and above the assumed demand temperature.

- On weekdays, about 65% of homes had less than the assumed 9 h of heating to 21 °C.
- On weekends, about 82% of homes did not reach the assumed 16 h of heating to 21 °C (data not shown).

4. Discussion and conclusion

As far as the authors are aware, this is the first published study to compare measured living room temperatures with the assumed heating periods used in BREDEM. The results suggest that the default heating values in many BREDEM based UK housing stock models are far from an accurate representation of the temperatures people actually achieve in their homes. This has significant implications for understanding home heating, building models and national energy policy. The BREDEM default values of two occupant-related variables, i.e. living room heating temperature and time periods of heating, were compared to recently collected data from 248 UK households in an attempt to answer if homes are heated to 21 °C during the assumed heating periods and for how many hours homes are heated to 21 °C (i.e. not considering if within the assumed time periods). The analysis indicated that a large share of homes had lower temperatures than the assumed heating demand temperature during assumed heating periods, from about 57% during the weekday evening heating, about 88% during the assumed morning heating, and about two-thirds during the assumed weekend heating periods. Also uncoupled from the assumed period of heating, on average the estimated durations of heating to 21 °C were much shorter than the BREDEM assumption of 9 and 16 h, for weekdays and weekends, respectively, of heating to 21 °C. Up to 29% of homes showed temperatures above the assumed demand temperature in assumed periods of heating; however, this did not balance out the large proportion of homes with below-assumed temperatures or actual temperatures. In addition, the findings indicated that weekdays and weekends have much more similar heating patterns than assumed in BREDEM, and that a large variability between homes exist, challenging the assumption that one pattern fits all.

Beyond establishing that BREDEM default values do not reflect temperatures of living rooms in England, the results are of particular importance in relation to the following four aspects:

1. Predictions of energy demand for an individual home contain a high degree of uncertainty.

The large variability between homes – irrespective of BREDEM assumptions – indicates that homes do not follow a standard pattern. This accords with previous findings: Hunt and Gidman [17] found a standard deviation of 3.0C in living room temperatures; Palmborg [18] found wide variations in their small study in Stockholm; as did Rathouse and Young [19] in their qualitative study in England. Hence, prediction of heating durations or heating demand temperatures for an individual dwelling based on a group average could lead to substantial prediction errors. If average values are used for predicting energy savings and hence financial savings through refurbishment, then this could lead to the predicted savings not materializing. For example, in the UK, the Government launched the “Green Deal” scheme which gives loans for energy efficiency measures which are paid back through the energy bills [20]. The intention is that savings on energy bills will outweigh the cost of repayments, the so called “Golden Rule”. In order for this to work out, predictions need to be as accurate as possible so that households will not be left with much higher bills than expected to repay the loans. Just as temperatures have previously been shown to be influenced by social and building demographic variables [21], linking heating durations and temperatures to certain building- or socio-demographic segments, for example, could increase prediction accuracy, and additionally help in targeting subgroups for energy saving interventions much more precisely.

2. Weekends and weekdays are much more similar than assumed, leading to an overestimation of energy used.

The difference between weekends and weekends, both in average temperatures and heating to 21 °C, was very small. This is in line with previous findings of similar hours of heating duration of weekends and weekdays [10]. BREDEM based models, on the other hand, assume that heating duration is 7 h longer on weekends than weekdays. This means that the assumed energy demand is most likely overestimated. A revision of default assumptions would be in order. Given the comparatively small difference between weekdays and weekends, adaption of a single heating duration for all seven days of the week seems a prudent simplifying assumption.

3. BREDEM based models which function as building stock models need to accurately represent how homes actually perform, correctly representing occupant influences, if a correct allocation of energy demand to space heating is to be achieved.

The findings are not as important for models which are designed to compare the potential of building fabrics and technologies, such as SAP. However, the findings are critical for representing the spectrum of occupant-driven heating patterns and temperatures. In turn, these will heavily influence actual energy consumption and greenhouse gas emissions in models attempting to represent a nation’s homes. BREDEM and similar building stock models have become benchmarks for assessing energy use and subsequent energy efficiency measures. Policy and regulations often rely on the outcomes of such models for setting standards and assessing future energy and climate change scenarios. It is therefore important that they draw upon empirically based evidence as closely as possible. As stock models are already lacking in socio-technical variables [5], they should therefore make the best use of the few occupant-related variables which are already incorporated by rigorously examining accuracy and variability, particularly as new data become available. Given the expected demographic changes of an older population and more, but smaller, households [22], a detailed representation of typical values for subgroups of the population would be needed in order to predict future energy demand correctly. This would allow a segmentation of the housing stock on socio-demographic variables as well as building-demographic variables currently supported by those models. Given the large variability in the data and the findings that homes do not correspond to BREDEM assumptions, this challenges the validity of current estimation of energy demand which might be substantially flawed.

4. The calculation of the heat-loss of a building could be incorrect when using standard assumptions.

BREDEM models assume that the demand temperature is achieved throughout the assumed heating periods, and calculations of the heat-loss from the home during these periods assume constant internal temperatures of 21 °C. If the actual temperature was lower than this, the use of 21 °C in fabric heat loss calculations would result in overestimating losses. Conversely, if the actual temperature was higher than assumed, the fabric heat loss using 21 °C would result in an underestimation. Hence, using the current standard 21 °C values might lead to incorrect estimation of heat-loss.

4.1. Limitations of the current study

For a more accurate comparison to the time windows used in BREDEM based models, recordings at smaller time intervals than 45 min would have been desirable. Ideally, the HOBO data loggers would have recorded temperatures every 30 min (or less), but as they are only able to record a limited amount of events, this would have shortened the number of months they could have recorded temperatures in respondents’ homes, which would have excluded the summer temperature monitoring that was included. This paper was based on evaluating heating patterns of the demand temperature that BREDEM assigned: 21 °C. The demand temperature is the temperature which people 'demand' or want for their home. The data indicated that the realized temperatures are much lower than the assumed demand temperature but do not indicate the heating demand temperature per se. Likewise, for the assumed heating periods, temperatures were compared against the assumed demand temperature of 21 °C, but not for the heating system being on as such. Also, the current study does not allow differentiating if temperatures were below the assumed demand temperature because people chose lower temperatures or because the heating system was not able to heat the home to the desired demand temperature which could be 21 °C.

Whilst the data presented is from the years 2007/08, to the authors' knowledge it is the most recent temperature data from a large *probability sample* of English households. As Rudge pointed out in 2004, there has been no national domestic temperature data collected since the 1996 English House Condition Survey [23]. Moreover, this study includes only dwellings with gas-central heating and the market share of this technology has increased since 2007 [24]. Furthermore, the construction and demolition rates of dwellings are very low [24], so the domestic building stock would have changed very little since 2007.

4.2. Outlook on future research

Subsequent work needs to explicitly address the heating demand temperature and the heating pattern instead of only looking at recorded temperatures. Also, linking temperatures and/or heating patterns to socio-demographic and buildings variables would then allow for the identification of sub-segments of the population characterized by particular patterns of heating. This would then enable the tailoring of interventions as needed and permit prediction of energy consumption much more accurately, both on an individual home-basis and across homes. Irrespective of the need for future work, this study clearly established that the assumptions of BREDEM models do not correspond to measured temperatures in living rooms in England and constitutes a basis for further research.

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