Department for
Energy Security
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The effect of energy efficiency measures on summertime overheating in English homes: temperature sensitivity analysis

Overheating in Homes: Further Analysis of EFUS Data

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Introduction

Internal dwelling temperatures in unheated dwellings are strongly driven by outdoor ambient air temperatures. In the context of overheating, it would be valuable to understand: (i) how sensitive indoor temperatures are to changes in outdoor ambient air temperature (in particular, how rapidly indoor temperatures rise in response to increasing outdoor temperatures); and (ii) at what outdoor ambient temperatures one can expect indoor ambient air temperatures to exceed overheating thresholds.

Dwellings in which the indoor temperature is particularly sensitive to outdoor temperature increases might be a target for measures to mitigate overheating risk. Prediction of the prevalence of overheating at given outdoor temperatures is of potential value for determining conditions under which occupants may be notified of overheating risk. With more work, it may also be possible to predict the prevalence of overheating in stocks of homes under different (future) weather conditions.

For the 591 main bedrooms[1] and 616 living rooms in the EFUS2017 sample that produced reliable data for the five-month study period (May–September 2018 inclusive), sensitivity of indoor temperatures to outdoor temperatures was characterised by comparing daily mean indoor temperatures against 2-day mean maximum outdoor temperatures (2DMM) calculated for the two preceding days[2]. The idea is based on the as-yet unpublished PhD work of Paul Drury (2023).

The relationship between daily mean indoor temperature and 2DMM outdoor temperature was first visually assessed via creation of per-room scatter plots (*Visualising temperature sensitivity: overheating signatures*). Observation of approximately linear relationships motivated subsequent fitting of linear mixed-effects models of daily mean indoor temperature as a function of 2DMM outdoor temperature, for both living rooms and main bedrooms (*Characterisation of temperature sensitivity*). Finally, these models were used to predict daily mean indoor temperatures for living rooms and main bedrooms for given 2DMM outdoor temperatures (*Prediction of indoor temperatures*).

While the living room and main bedroom samples were analysed separately, neither sample was subdivided (such as into those in houses and flats). Although national weightings were not applied in constructing the models, subsequent predictions of the proportion of living rooms and bedrooms exceeding given threshold temperatures did use national weightings; thus, any proportions stated in the results (*Prediction of indoor temperatures*) are relative to the national stock.

[1] Throughout this report, any reference to a bedroom means the main bedroom.

[2] The relationship between mean daily/nightly indoor temperature and mean daily/nightly outdoor temperature was also considered; however, linear mixed-effects models of mean daily/nightly indoor temperature against 2DMM air temperatures were found to be more strongly correlated (having greater marginal and conditional R^2 values).

Visualising temperature sensitivity: overheating signatures

To visualize the sensitivity of indoor temperatures to outdoor temperatures, scatter plots were created for each room in the sample (591 main bedrooms, 616 living rooms), plotting indoor daily (or nightly) mean temperature for each day (or night) against the 2-day mean maximum temperature for the previous two days[3].

For each living room (N=616), the daily mean indoor temperature $\overline{\theta}_{in}(d)$ during occupied hours (0700–2200) for each day d was calculated as:

$$\overline{\theta_{in}}(d) = \frac{1}{30}\sum_{i=15}^{44} \theta_{in}(d,i) \qquad (1)$$

where $\theta_{in}(d,n)$ is the indoor temperature logged at the start of the i^{th} half-hour of day d[4].

For each main bedroom (N=591), the nightly mean indoor temperature $\overline{\theta}_{in}(d)$ during occupied hours (2200–0700) for the night ending on each day d was calculated as:

$$\overline{\theta_{in}}(d) = \frac{1}{18}\left\{\sum_{i=45}^{48} \theta_{in}(d-1,i) + \sum_{i=1}^{14} \theta_{in}(d,i)\right\} \qquad (2)$$

where $\theta_{in}(d,n)$ is the indoor temperature logged at the start of the i^{th} half-hour of day d[4].

For both living rooms and bedrooms, the 2DMM outdoor temperature $2DMM_{out}(d)$ for the two days before day d was calculated as:

$$2DMM_{out}(d) = \frac{1}{2}\{\theta_{out,max}(d-1) + \theta_{out,max}(d-2)\} \qquad (3)$$

where $\theta_{out,max}(d-1)$, $\theta_{out,max}(d-2)$ are the maximum outdoor temperatures logged on each of the two previous days $d-1$ and $d-2$.

Equations 1–3 are formulated such that:

- For living rooms, plotting $\overline{\theta}_{in}(d)$ against $2DMM_{out}(d)$ compares daily mean indoor temperature for each day d (for occupied hours, 0700–2200) with the mean of the maximum temperatures logged on each of $d-1$ and $d-2$.
- For bedrooms, plotting $\overline{\theta}_{in}(d)$ against $2DMM_{out}(d)$ compares mean nightly temperature for the night ending on day d (for occupied hours, 2200 on day $d-1$ to 0700 on day d) with the mean of the maximum temperatures logged on each of $d-1$ and $d-2$.

The purpose of comparing $\overline{\theta}_{in}(d)$ against $2DMM_{out}(d)$ was to determine whether there was a linear relationship (and thus potential for a linear predictive model) between mean indoor air temperature on a given day (or night) and the outdoor temperatures experienced over the preceding two days. Each individual scatter plot can be thought of an overheating signature for

[3] Successive day peak temperatures are used to indicate the occurrence of heatwaves by the UK Met. Office.
[4] So 00:00 for $i = 1$, 00:30 for $i = 2$, … , 23:30 for $i = 48$.

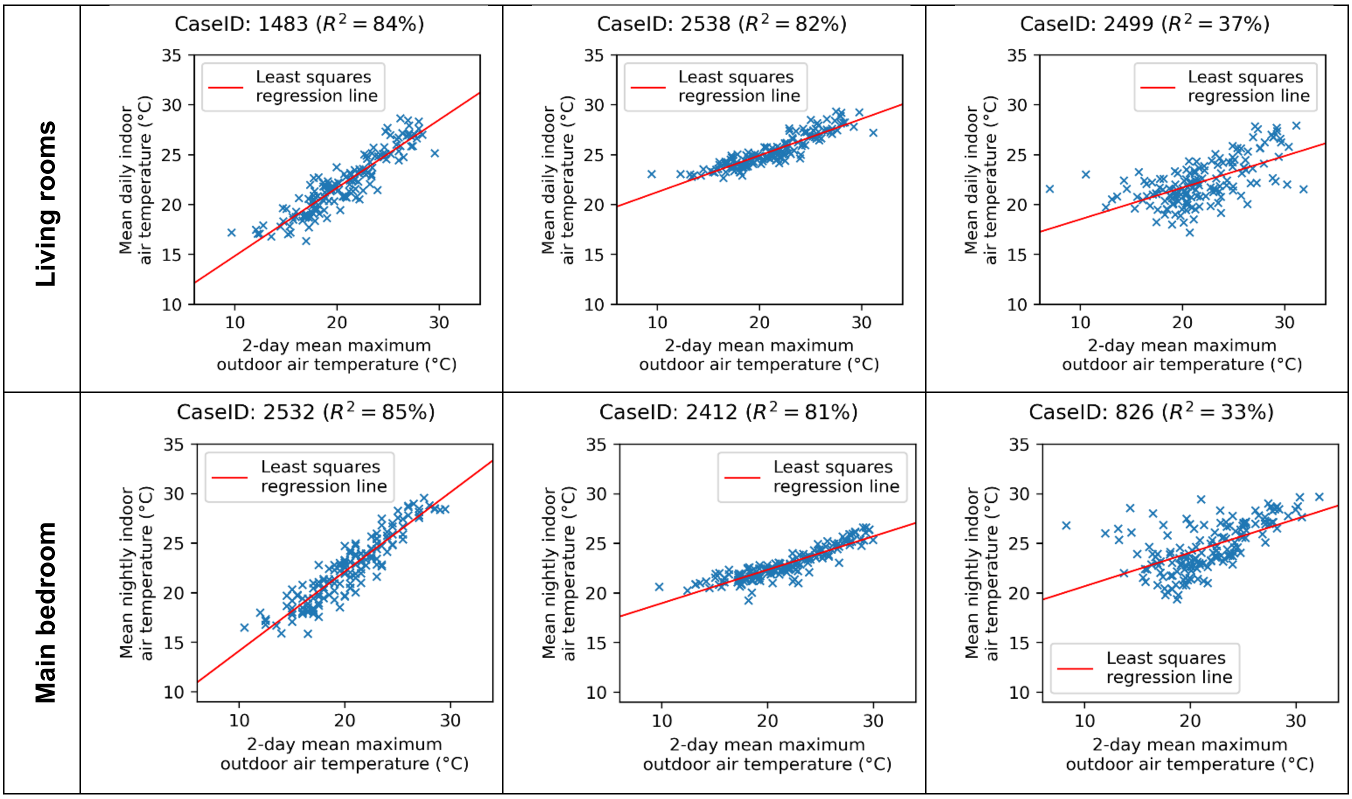
the room represented, which indicates the rate of change of daily internal temperature with external temperature.

For each individual room, an ordinary least squares linear regression model of mean daily (or nightly) indoor temperature was fitted against the 2DMM outdoor temperature. This was done to assess the strength of linear correlations between indoor and outdoor temperatures on a per-dwelling basis.

A selection of “temperature signature” scatter plots is presented in Figure 1. Some rooms (e.g., living room ID1483 & bedroom ID2532, leftmost in Figure 1) exhibit strong positive correlations, with mean daily (or nightly) indoor air temperature increasing with 2DMM outdoor temperature. Other rooms (e.g., living room 2538 & bedroom 2412, centre in Figure 1) exhibit similarly strong positive correlations, but with shallower slopes, suggesting lower rates of indoor temperature increase in response to each increment of outdoor temperature. Meanwhile, some rooms (e.g., living room ID2499 & bedroom ID826, rightmost in Figure 1) exhibit comparatively weak correlations, suggesting that a linear model is a relatively poor fit to the data.

In general, identification of non-linearity in a signature plot may offer a means of identifying occupant behavioural and operational responses to temperature changes, such as ventilating at higher temperatures, or heating during cooler periods. For example, in bedroom ID826, the relatively low coefficient of determination (R^2 = 33%) is partly informed by a subset of indoor temperatures exceeding 25°C logged for 2DMM outdoor temperatures below 15°C: it is possible that these represent use of heating during the shoulder season.

Figure 1: Selected temperature signature scatter plots for living rooms and bedrooms (EFUS2017 data, May–Sep 2018)



Descriptive statistics for linear regression parameters obtained from per-room models are presented in Table 1. For both living rooms and bedrooms, the majority of dwellings exhibit strong positive linear correlations between daily (or nightly) indoor air temperature and 2DMM outdoor temperature, as evidenced by lower quartiles of $r = 0.79$ and $r = 0.84$ for correlation coefficients for living rooms and bedrooms, respectively. Linear models are therefore considered to be generally appropriate for characterising sensitivity of daily (nightly) mean indoor temperature to changes in 2DMM outdoor temperature in living rooms (bedrooms) of the EFUS2017 sample.

Table 1: Descriptive statistics for per-dwelling ordinary least squares linear regression models of daily mean indoor temperature against preceding 2DMM outdoor temperature (EFUS2017 living rooms and main bedrooms, May–Sep 2018)

Room type	Parameter	Descriptive statistics						
		Mean	**SD**	**Min**	**Q1**	**Median**	**Q3**	**Max**
Living room (N = 616)	**Intercept**	13.86	3.18	5.08	11.73	13.50	15.51	26.80
	Slope	0.40	0.12	-0.24	0.34	0.41	0.48	0.81
	Correlation coefficient	0.81	0.14	-0.47	0.79	0.85	0.88	0.95
	R^2	68%	16%	0%	63%	72%	78%	90%
Bedroom (N = 591)	**Intercept**	12.63	3.23	4.76	10.43	12.28	14.55	27.17
	Slope	0.48	0.13	-0.07	0.39	0.48	0.57	0.85
	Correlation coefficient	0.86	0.11	-0.15	0.84	0.89	0.92	0.96
	R^2	75%	14%	2%	70%	79%	84%	93%

Characterisation of temperature sensitivity

For each of the living room and main bedroom samples, separately, daily (or nightly) mean indoor and 2DMM outdoor temperature data were used to fit a linear mixed-effects model of daily mean indoor temperature $\overline{\theta_{in}}(d)$ as a function of the preceding 2DMM outdoor temperature $2DMM_{out}(d)$ (as a fixed effect predictor) and dwelling CaseID (as a random effect predictor). In contrast with the individual per-room linear regression models of the previous section, these linear mixed-effects models are combined models, fitted using data from the full samples of living rooms and bedrooms.

For the model-fitting process, $2DMM_{out}(d)$ values were rescaled by subtracting the sample-wide mean value and dividing by the sample standard deviation (Table 2). Each model was fitted with random slope and random intercept.

Table 2: Descriptive statistics for s for living room and main bedroom samples, as used in rescaling for linear mixed-effects modelling

Sample	Descriptive statistics for 2DMM outdoor temperature (°C)							
	Number of readings	**Mean**	**Standard deviation**	**Min**	**Q1**	**Median**	**Q3**	**Max**
Living rooms	94 179	20.611	4.127	6.2	17.8	20.45	23.35	33.4
Main bedrooms	90 423	20.591	4.123	6.2	17.8	20.45	23.30	33.4

Results from the model-fitting processes are summarised in Table 3 (living rooms) and Table 4 (main bedrooms). Both models had conditional R^2 values exceeding 80%: 82% for living rooms; 84% for main bedrooms.

For living rooms (Table 3), the mean estimate of the intercept corresponds to a predicted next-day daily mean indoor temperature of 22.1°C for a 2DMM outdoor temperature of 20.6°C. The mean estimate of the coefficient of re-scaled 2DMM outdoor temperature corresponds to a mean 0.4°C increase in predicted next-day daily mean indoor temperature for each 1°C increase in 2DMM outdoor temperature[5].

For main bedrooms (Table 4), the mean estimate of the intercept corresponds to a predicted upcoming nightly mean indoor temperature of 22.4°C for a 2DMM outdoor temperature of 20.6°C. The mean estimate of the coefficient of re-scaled 2DMM outdoor temperature corresponds to a mean 0.5°C increase in predicted upcoming nightly mean indoor temperature for each 1°C increase in 2DMM outdoor temperature[6].

Table 3: Linear mixed-effects model-fitting results for daily mean indoor temperature of living rooms

Fixed effects				
	Estimate	**Standard error**	**95% confidence interval**	p
Intercept	22.147	0.059	[22.031, 22.264]	<0.0005
$2DMM_{out}(d)$ (scaled)	1.660	0.019	[1.622, 1.697]	<0.0005
Random effects				
	Variance	**Standard deviation**		
CaseID	2.161	0.116		
Observations	94 179			
Groups	616			
R^2 **(marginal / conditional)**	43.8% / 81.8%			

[5] [slope for unscaled variable] = [slope for scaled variable] / [unscaled standard deviation] = 1.660 / 4.127 = 0.402.
[6] [slope for unscaled variable] = [slope for scaled variable] / [unscaled standard deviation] = 1.964 / 4.123 = 0.476.

Table 4: Linear mixed-effects model fitting-results for nightly mean indoor temperature of main bedrooms

Fixed effects				
	Estimate	**Standard error**	**95% confidence interval**	p
Intercept	22.435	0.056	[22.325, 22.546]	<0.0005
$2DMM_{out}(d)$ (scaled)	1.964	0.022	[1.922, 2.006]	<0.0005
Random effects				
	Variance	**Standard deviation**		
CaseID	1.878	0.105		
Observations	90 423			
Groups	591			
R^2 **(marginal / conditional)**	54.3% / 84.4%			

Prediction of indoor temperatures

The linear mixed-effects models of the previous section were used to predict mean daily (nightly) indoor temperatures $\overline{\theta_{in}}(d)$ of living rooms (main bedrooms), for a range of preceding 2DMM outdoor temperatures, $2DMM_{out}(d) \in \{20°C, 22°C, 24°C, 26°C, 28°C, 30°C, 32°C\}$. The model-predicted temperatures were then analysed to determine, for each 2DMM outdoor temperature $2DMM_{out}(d)$, the proportion of living rooms (main bedrooms) whose predicted mean daily (nightly) indoor temperature $\overline{\theta_{in}}(d)$ for the following day (night) exceeded a selection of threshold temperatures $\boldsymbol{T} \in \{16°C, 17°C, \ldots, 32°C\}$. Results of these analyses are presented in Figure 2 (living rooms) and Figure 3 (main bedrooms); proportions were calculated using statistical weightings and are therefore relative to the English national stock.

For a chosen temperature threshold $\boldsymbol{T}$°C, one can use Figure 2 and Figure 3 to obtain proportions of living rooms and main bedrooms whose daily or nightly mean indoor temperature is expected to exceed $\boldsymbol{T}$ following a given 2DMM outdoor temperature. For example, the proportion of living rooms whose next-day daily mean indoor air temperature (for 0700–2200) is predicted to exceed $\boldsymbol{T}$ = 27°C is:

- 0.3% for 2DMM outdoor temperature 20°C.
- 0.8% for 2DMM outdoor temperature 22°C.
- 1.7% for 2DMM outdoor temperature 24°C.
- 4.6% for 2DMM outdoor temperature 26°C.
- 11.6% for 2DMM outdoor temperature 28°C.
- 27.1% for 2DMM outdoor temperature 30°C.
- 46.9% for 2DMM outdoor temperature 32°C.

Figure 2: Proportions of English living rooms with predicted next-day daily mean temperature exceeding given thresholds *T* for given 2DMM outdoor temperatures

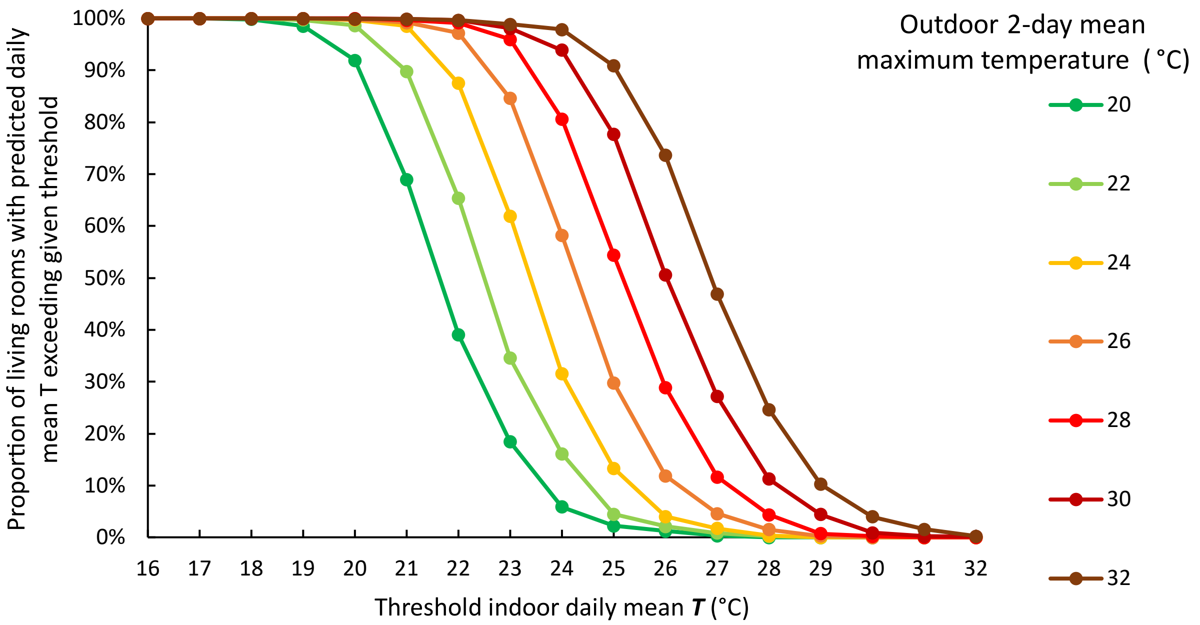
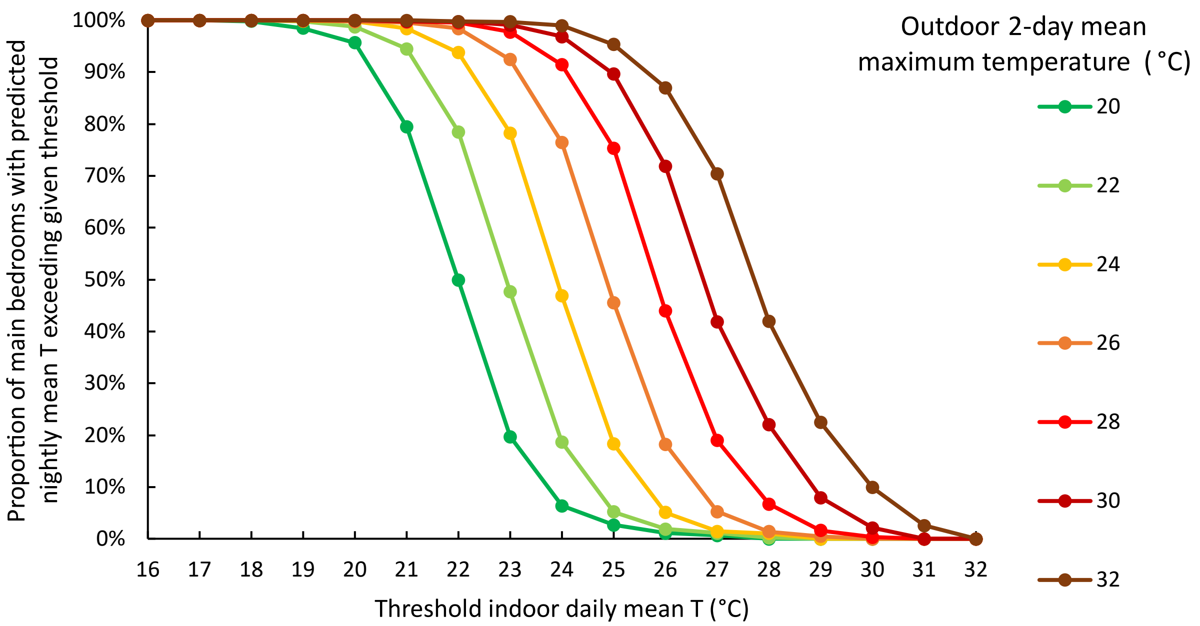


Figure 3: Proportions of English main bedrooms with predicted upcoming nightly mean temperature exceeding given thresholds *T* for given 2DMM outdoor temperatures



Meanwhile, the proportion of main bedrooms whose upcoming nightly mean indoor air temperature (for 2200–0700) is predicted to exceed $\boldsymbol{T}$ = 27°C is:

- 0.6% for 2DMM outdoor temperature 20°C.
- 1.1% for 2DMM outdoor temperature 22°C.
- 1.5% for 2DMM outdoor temperature 24°C.
- 5.3% for 2DMM outdoor temperature 26°C.
- 19.0% for 2DMM outdoor temperature 28°C.
- 41.9% for 2DMM outdoor temperature 30°C.
- 70.4% for 2DMM outdoor temperature 32°C.

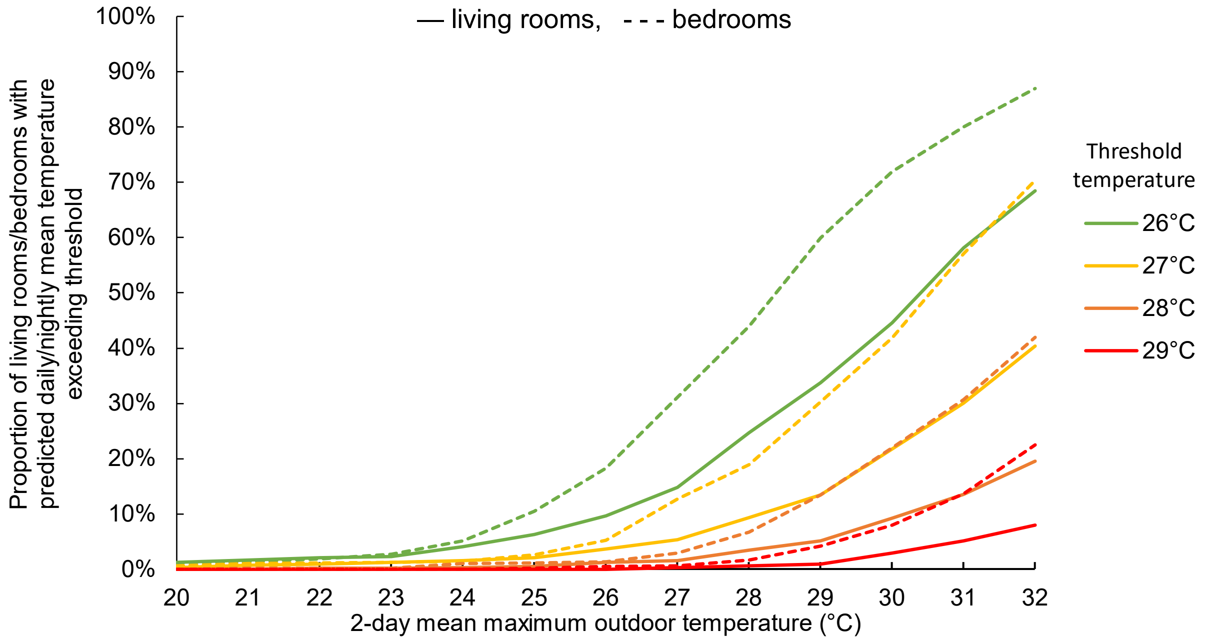
Comparing Figure 2 and Figure 3, the proportion of main bedrooms predicted to overheat (i.e., have nightly mean temperature exceeding 27°C)[7] is greater than that of living rooms for any 2DMM outdoor temperature. Because bedrooms have a greater sensitivity to outside temperature rises than living rooms (0.5°C per 1°C increase in 2DMM outdoor temperature compared to 0.4°C), the proportion of overheated bedrooms, when compared to living rooms, increases more rapidly as the outdoor temperature increases.

“Overheating sensitivity” plots provide an approach to visualising the relationship between overheating temperature threshold exceedance and outdoor temperatures. In such plots the threshold exceedance (%) is on the vertical axis and the 2-day mean maximum temperature (°C) on the horizontal axis, with curves shown for each overheating threshold. Figure 4, for example, visualises the rates at which proportions of living rooms and bedrooms in the English stock are predicted to exceed overheating thresholds as the 2-day mean maximum temperature increases. The rate of increase in living room overheating is generally lower than that for bedrooms at all the thresholds depicted (26°C, 27°C, 28°C, 29°C), indicating comparatively lower sensitivity of living rooms to outdoor temperatures.

“Overheating sensitivity” plots can be used to explore possible changes in overheating prevalence as the English climate warms. For example, 41.9% of main bedrooms are predicted to exceed 27°C when the 2-day mean maximum temperature exceeds 30°C and the number of such days is predicted to rise from an average of 0.20 occurrences per year to 4.1 by 2070 (Met Office, 2022). This is a fruitful area for further analysis using the EFUS2017 data.

[7] At a mean nightly temperature of 27°C, the quality of sleep begins to degrade for some people, above 29°C sleeping is difficult for all persons (Lomas and Li, 2023)

Figure 4: Overheating sensitivity plot for EFUS2017 living rooms and bedrooms, showing proportions with predicted daily/nightly mean temperature threshold exceedance at given 2DMM outdoor temperatures



Discussion

Production of temperature signature plots for each living room and main bedroom (see *Visualising temperature sensitivity: overheating signatures*) revealed that the response of indoor room temperatures to changes in outdoor temperatures varies between different dwellings. The adopted linear mixed-effects modelling approach (see *Characterisation of temperature sensitivity*) produces an individual linear model for each room, which subsequently allow generation of overheating sensitivity plots to predict the prevalence of overheating threshold exceedance (see *Prediction of indoor temperatures*). Overheating sensitivity plots have been presented for the full sample of EFUS2017 living rooms and main bedrooms, scaled to the English stock as a whole.

Exploiting overheating sensitivity analysis

Overheating sensitivity plots offer a means of quantifying the potential impacts of different energy efficiency and overheating mitigation measures on internal temperature. This potential is exploited in a summary report to this project (Lomas et al., 2023).

Overheating sensitivity analysis also enables the effect of climate change on the prevalence of overheating in stocks of English homes to be examined. It would be possible to explore the regional changes in overheating, the effects of dwelling type, and whether occupant characteristics affect the sensitivity of indoor temperatures to outdoor temperature. Might the more disadvantaged in society suffer more than others from the changing climate?

Another analysis approach may be to apply clustering techniques to the temperature signatures followed by analysis of the likelihood of different dwelling types exhibiting each of the identified signature types. Such analysis would provide insight regarding which dwelling, and occupancy characteristics may be associated with elevated (or reduced) overheating risk.

It is reasonable to expect that the temperature signature of any given room will be influenced by whether and what ventilation and/or cooling strategies are used by the dwelling's occupants. Without knowing how rooms in the EFUS2017 sample were ventilated and/or cooled, there is therefore a degree of uncertainty regarding the extent to which the obtained temperature signatures describe the fabric thermal performance of the dwellings studied. Understanding the ventilation and cooling behaviours typically enacted by a room's occupants during hot weather would be a useful avenue for further work.

Temperatures in bedrooms were found to be, on average, more sensitive to outdoor temperature increases than temperatures in living rooms; however, the potential influence of confounding factors has not been examined. Further work could explore whether there is a systematic difference between the living room and main bedroom temperature signatures in individual dwellings, or whether the result is driven by other factors, such as differences in the dwelling characteristics of the living room and bedroom samples.

Analysis for both living rooms and bedrooms has been conducted using static overheating thresholds for mean indoor temperatures. However, while (static) mean night-time temperatures are proposed as a useful metric for identifying overheating risk in bedrooms when people are sleeping (Lomas and Li, 2023), daytime and night-time overheating when people are awake is typically assessed using adaptive overheating criteria, in which threshold temperatures are defined relative to the running mean outdoor temperature. A similar approach to that taken here could perhaps be applied to analysis of the relationship between daily hours above adaptive thresholds and running mean outdoor temperatures.

Conclusions

The development of temperature signatures for living rooms and main bedrooms revealed that an assumption of an increasing linear relationship between daily (or nightly) mean indoor temperature and 2-day mean maximum outdoor temperature for the preceding two days is appropriate for the majority of the EFUS2017 living rooms and main bedrooms.

Successful fitting of linear mixed-effects models demonstrated the feasibility of predicting daily (or nightly) mean indoor temperatures based on preceding 2-day mean maximum temperatures. The resulting overheating sensitivity models permit prediction of the proportion of a stock of dwellings that can be expected to exceed different static overheating threshold temperatures given the outdoor temperatures in the previous two days.

With further work, the overheating sensitivity models could be used to explore the prevalence of overheating in the English homes with different dwelling and occupancy characteristics as the UK climate warms.

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