Department for
Energy Security
& Net Zero

The effect of energy efficiency measures on summertime overheating in English homes: Summary

Overheating in Homes: Further Analysis of EFUS Data

Contract ref. PS22100

February 2024

Acknowledgements

The work was undertaken by Dr Matthew Li, Mr Paul Drury, Dr Stephen Watson and Prof K J Lomas who authored this report. All are members of the Building Energy Research Group in the School of Architecture Building and Civil Engineering at Loughborough University. This report summarises and expands on three other related reports delivered as part of this contract.

The research would not have been possible without the previous analysis of the EFUS2017 dataset funded by the Department of Business Energy and Industrial Strategy and funding from the Engineering and Physical Sciences Research Council, grant ref. EP/L01517X/1.

Any enquiries regarding this publication should be sent to us at: EnergyResearch@energysecurity.gov.uk

Contents

Summary 4
Introduction 5
Analysis Methods 6
  Systematic Evidence Review 7
  Re-analysis of the EFUS2017 dataset 8
    Overheating Prevalence 9
    Temperature threshold exceedance 10
    Temperature Signatures **Error! Bookmark not defined.**
Results 15
  Prevalence of overheating in English homes 16
  Temperatures in living rooms & bedrooms 17
  The influence of flat level on room temperatures 17
  Effect of overall energy efficiency rating on room temperatures 19
  Effect of individual energy efficiency measures on room temperatures 22
  Matters for further investigation 25
Conclusions 26
  Principal observations 26
  English homes and overheating 27
  Effect of overall energy efficiency rating 28
  Effect of individual energy efficiency measures 28
  Opportunities for further investigations 29
References 30

Summary

The project sought to answer the following question ‘*Do measures which reduce home energy demand in the winter increase the risk of overheating in the summer.*’? The research involved a review of the high-quality evidence relevant to UK homes published in peer-reviewed literature. The EFUS2017 data set was also re-analysed to calculate the prevalence of overheating and the frequency and intensity of exceedance of temperature thresholds ranging from those signifying cold discomfort to those indicating overheating. The sensitivity of overheating prevalence to changes in outdoor temperatures was also explored using a new analysis method, temperature signatures.

The EFUS dataset includes temperatures measured in 616 living rooms and 591 main bedrooms between May and September 2018. Meta data enabled comparisons to be made for houses and for flats which had: a high or low energy efficiency rating; cavity or solid walls; reasonable loft insulation; insulated walls; and full double glazing. The results of analyses were weighted to be representative of the whole stock of English homes.

As context, the prevalence of overheating in the living rooms of flats was three or more times greater than in houses. Thus, around 16% of flats would be classed as overheated by current definitions. The top floor flats exceeded overheating thresholds far more frequently, and were more sensitive to outdoor temperature increases, than other flats. Ground floor flats were cooler and less sensitive than other flats. Bedrooms[1] of houses were hotter at night than living rooms were during the day, they were also more sensitive to outdoor temperature increases.

The principal finding was that the overall energy efficiency rating of English houses and flats did not significantly increase the risk of summertime overheating in either living rooms or main bedrooms, neither did the installation of individual energy efficiency measures installed in the EFUS sample. There is evidence that increased loft insulation and wall insulation may significantly reduce the risk of serious overheating in the bedrooms of houses. The evidence review supported these findings.

The work provides evidence that energy efficiency measures are effective at raising internal temperatures in the heating season. Consequently, the occurrence of temperatures associated with cold discomfort was significantly lower in the living rooms of houses with a better energy efficiency rating, full double-glazing (with cavity[2], rather than solid walls). Double glazing kept flats warmer without increasing overheating risk. No other energy efficiency measure had any significant effect on the exceedance of any of the temperature thresholds.

The review produced evidence of an increased risk of overheating in houses retrofitted with internal wall insulation (not a prevalent measure in the EFUS sample) - but that this may be readily mitigated with pre-existing ventilation and shading provision. More work is needed to

---

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

[2] The cavities may or may not have been insulated.

understand the risk for overheating, and the effectiveness of mitigation measures, in dwellings built to energy efficiency standards beyond those found in the EFUS2017 homes.

Introduction

The central question addressed by this research is '*Do measures which reduce home energy demand in the winter increase the risk of overheating in the summer.*'? Reduction of wintertime heating energy demand is key to climate change mitigation, energy security, reducing household energy costs, and the alleviation of fuel poverty. Adaptation to climate change requires homes that are comfortable and healthy in summer, both for living and sleeping. The question seeks to understand whether mitigation and adaptation of new and existing homes can be addressed independently, or whether mitigation measures provoke a need for additional adaptive measures.

The question has been addressed through three strands of research, a systematic evidence review (Overheating in Homes: an evidence review DESNZ - Drury, 2024a) and re-analysis of temperatures measured in English homes during the summer of 2018 (Prevalence, frequency and intensity analysis DESNZ - Li, 2024a; Temperature sensitivity analysis DESNZ - Li, 2024b). The evidence review provides insights for homes with lower energy efficiency levels (e.g. uninsulated walls, partial double glazing, low levels of loft insulation) as well as homes with much higher insulation levels (e.g. double glazing, higher levels of loft insulation, insulated walls). The data analysis provides a clear, consistent and detailed picture of the impact of installed efficiency measures on the summertime temperatures in the living rooms and main bedrooms of English flats and houses, but only for one summer, albeit a summer that was the joint warmest on record (with 2006) at the time and could be typical of those expected in the 2050's according to Met Office projections (Madge, 2019).

The international academic literature reports numerous studies into summertime overheating in dwellings. However, the emerging picture is confusing with different authors drawing, apparently, diametrically opposite conclusions about the influence of some energy efficiency measures. The systematic, critical evidence review sought to identify and synthesise the good quality evidence relevant to the UK housing stock. The review identified the potential overheating risks associated with both current and future energy efficiency standards and climatic conditions (Overheating in Homes: an evidence review DESNZ - Drury, 2024a).

The re-analysis of the summertime temperature data from the 2017 Energy Follow-up Survey (EFUS2017) to the English housing Survey (EHS) constitutes the core of the work. This builds on earlier work (BEIS, 2021a; Lomas et al., 2021) which concluded that: "*there was no significant difference in the measured overheating of living rooms or bedrooms with changes in any fabric energy efficiency measures*" and that, whilst the living rooms of more energy efficient homes had a higher prevalence of overheating, the result was significant at the 5%, rather than the 1% level (as in the original EFUS2017 analysis). The re-analysis reported here re-examines these conclusions in more detail. Further clarity is brought by separating the analysis of flats and houses[3].

The re-analysis calculates the prevalence of overheating, as indicated by established and emerging overheating criteria. Also calculated is the frequency and intensity with which room temperatures exceed a range of temperature thresholds (Prevalence, frequency and intensity analysis DESNZ - Li, 2024a).

Energy efficiency measures may also affect the rate at which dwellings heat up and cool down in hot weather. For example, some dwellings might heat up slowly but also cool down slowly and so, perhaps, have lower indoor peak temperatures than other dwellings. Some dwellings might be hot because of high internal heat gains rather than external environmental conditions. The EFUS2017 re-analysis therefore explored the relationship between room temperatures and external temperatures (Temperature sensitivity analysis DESNZ - Li, 2024b). The work was somewhat experimental, exploiting, for the first time, the recently developed concept of 'temperature signatures' (the relationship between the 2day mean outdoor temperature and the daily mean internal temperature) (Drury, 2024b) to understand the sensitivity of overheating prevalence to external temperature.

Each area of work addressed one of the three research questions posed by DESNZ at the outset of this project. These were:

- Is there existing evidence that energy efficiency measures affect the propensity of UK homes to overheat?
- Do energy efficiency measures affect the prevalence, frequency and intensity of overheating in English houses and flats?
- Do energy efficiency measures affect how quickly the internal temperatures in English homes increase as the outdoor temperature rises?

This Summary report briefly describes the three methods of research, then, the results of the analyses are presented followed by the overall conclusions and some suggestions for further work. For details of the methods see Drury (Overheating in Homes: an evidence review DESNZ - Drury, 2024a) and Li (2024a, 2024b).

Analysis Methods

The three methods used to investigate how flat floor level, individual energy efficiency measures, and the overall energy efficiency rating of a dwelling, affects indoor temperatures are described. The findings specific to each method are reported.

---

[3] The previous analysis combined flats and houses and so the result may be due to the tendency of flats to have a higher energy rating and to overheat more readily than houses.

Systematic evidence review

The evidence review (Overheating in Homes: an evidence review DESNZ - Drury, 2024a) was conducted as a Rapid Evidence Assessment (REA), and sought "*to provide an informed conclusion on the volume and characteristics of an evidence base, a synthesis of what that evidence indicates and a critical appraisal of that evidence*" (Collins et al., 2015). The purpose was to identify: the energy efficiency measures which result in a higher summertime indoor temperature; the energy efficiency measures that do not result in higher temperatures; if there are measures that may result in lower summertime temperatures; and whether very high energy efficiency standards might lead to elevated summertime temperatures.

The review was conducted in four stages following the approach adopted in previous work for BEIS (Lomas et al, 2018).

Firstly, **identification of relevant documents** was undertaken by searching two databases of peer-reviewed literature: Scopus, which gathers content from 7,000 publishers across a range of academic disciplines and EI Compendex, which is engineering focussed. Additional evidence was sought by searching Google Scholar, the Construction Information Services database and UK Government websites. After duplicate articles were excluded, 311 unique documents were uncovered.

Secondly, **document screening** was undertaken to isolate articles that could be assimilated within the available time: written in English, accessible online, relevant to the UK housing and climatic context, and pertinent to internal temperatures and energy efficiency measures. Articles related to non-domestic buildings were excluded. Relevant documents were selected for full text screening based on titles and abstracts. This screening identified 41 documents addressing UK dwellings. A further 21 documents that passed the screening but were about overseas dwellings were archived to enable future analysis; 15 of these related to locations with weather similar to the UK.

Thirdly, **research and reporting quality assessment** was undertaken using the scoring system which was previously provided by BEIS (see Lomas et al, 2018). The system considers the track record of the publishing organisation, the rationale for the article, the research methodology, the peer-review status of the article, and the veracity of the conclusions; 39 articles remained after this process. These covered a range of dwelling types, locations and individual energy efficiency measures.

Most of the evidence was provided by modelling studies, 26 articles. Modelling has the benefit of isolating the effects of individual energy efficiency measures, providing an insight into internal temperatures under future climatic conditions, and testing the influence of different *assumed* occupant behaviours. However, the inherent reliability of models' predictions of overheating is questioned (e.g., Roberts et al, 2019), and modellers must make assumptions about the way occupants behave in response to higher indoor temperatures, opening windows (or not), closing curtains (or not), etc . Other evidence came from five large-scale field trials, four meta studies, one small scale field trial, and one field experiments, and two other methods. Analysis of the literature is complicated because different overheating definitions and metrics of measurement are used and different weather conditions prevail, either actual weather in the field trials or current, future and/or synthetic weather in modelling studies.

Finally, **classification of the quality of the evidence** was undertaken by carefully reading each article and applying a modified version of the Grading of Recommendations Assessment, Development and Evaluation (GRADE) system, for reviews of medical research (Wiley, nd). Evidence is *high quality* if further research is very unlikely to change confidence in the result, in particular, several high-quality studies report consistent findings. Evidence is *moderate quality* if further research is likely to have an important impact on confidence in the result.

In the review reported here, evidence was classed as high quality when quality research based on both modelled studies and field trials produced the same result. Such results were also often corroborated by the re-analyses of the EFUS2017 data (see below). It is these results that form the backbone of the results and conclusions section in this Summary report.

The review also uncovered high quality evidence indicating that modelling results are very sensitive to the choice of overheating criterion and modellers’ assumptions about occupant behaviour. These matters need careful consideration in guidance documents and standards concerned with overheating assessment in new or refurbished dwellings.

Re-analysis of the EFUS2017 dataset

The influence of energy efficiency measures on indoor temperatures in the English housing stock was determined primarily by a re-analysis of the EFUS2017 dataset (Prevalence, frequency and intensity analysis DESNZ – Li, 2024a; Li 2024b). This is a subset of 750 households taken from the 13,300 or so that completed questionnaires in the 2014/15 to 2016/17 English Housing Surveys. Around 6,200 of these dwellings were physically surveyed. For the EFUS homes, additional questionnaires were delivered and temperatures measured in up to five rooms. The methodology is described in detail elsewhere (BEIS, 2021b).

Table 1: Dwelling characteristics analysed

For houses and flats:

Energy efficiency rating band

Whether solid or cavity wall

Whether fully double-glazed

Whether walls were insulated

Loft insulation thickness

For flats only:

Flat floor level

Flat entry level

After cleaning and organising the EFUS2017 data, half-hourly indoor temperatures, hourly outdoor temperatures, and descriptions of the household and dwelling were available for 616 living rooms and 591 main bedrooms (Lomas et al. 2021). For these homes, the overall energy efficiency rating of the dwelling was available as well as the predominant wall type and the presence, or otherwise of three different energy efficiency measures (Table 1). The floor level and entry level of all flats was also extracted from the English Housing Survey dataset.

The analyses in this section, and those that follow, focus on the temperatures measured between May and September 2018, which, at the time of writing, was England's joint hottest ever summer (McCarthy et al. 2019).

Flats and houses can have very different thermal behaviour and top floor flats are particularly prone to overheating, so the analysis of the houses was separated from the analysis of the flats and their floor level.

Throughout this report, the results obtained by analysing the EFUS samples of living rooms and bedrooms with a particular (energy efficiency) characteristic were weighted to provide insights pertinent for the whole stock of English living rooms and bedrooms with that characteristic (see BEIS, 2021b).

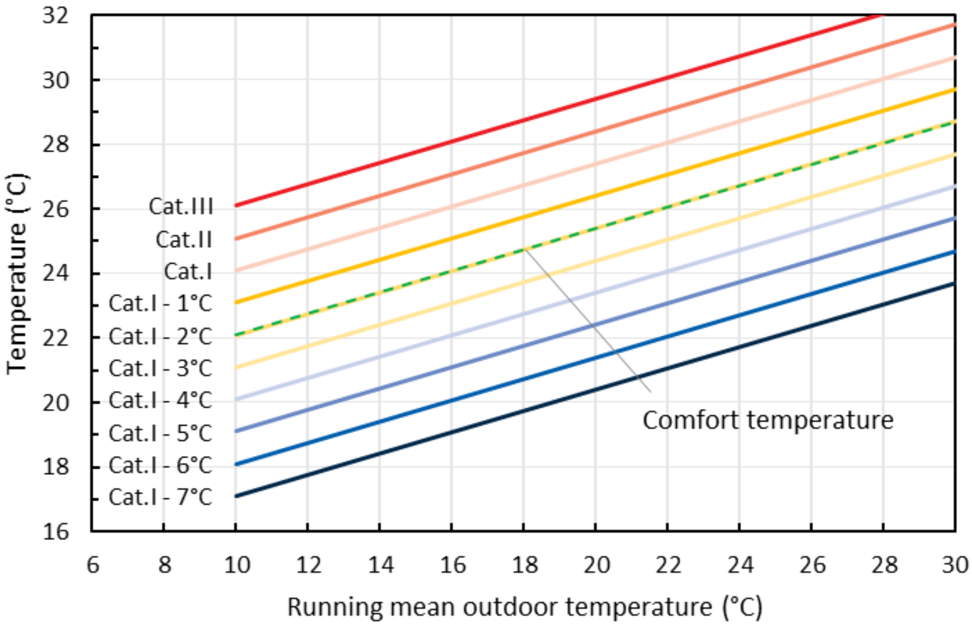
Prevalence of overheating

The prevalence of overheating was defined as *the proportion of rooms with a chosen characteristic that fail existing UK overheating criteria.*

For living rooms, overheating was identified using an approach similar to that which was used in the previous analysis of the EFUS2017 dataset (BEIS, 2021a; Lomas et al., 2021). But in this re-analysis, the prevalence of overheating as judged by three *adaptive* temperature thresholds associated with warm discomfort was calculated.

The three overheating threshold temperatures, Cat.I, Cat.II and Cat.III, are defined in BSEN16798 (BSI, 2019). These signify, respectively, the upper temperature thresholds for spaces meeting high, medium or moderate expectations of thermal comfort in warm conditions. Each threshold is 1°C warmer than the previous, and each increases with the running mean of outdoor daily mean temperature, which accounts for people's adaptation to warmer weather (Figure 1).

Figure 1: The adaptive temperature thresholds for living rooms: based on BSEN16798.



The Cat.II and Cat. I thresholds are adopted by CIBSE Technical Manual TM59 (CIBSE, 2019), which supports the current building regulations controlling the risk of overheating in new homes, Approved Document, Part O (HMG, 2021). In TM59, a living room is deemed to overheat if there are *more than 3% of occupied hours between May and September that exceed the threshold temperature by 1 degree (°C) or more*. In TM59, the previous EFUS analysis work, and this work, the occupied hours were assumed to be 07:00 to 22:00, i.e., 15 hours.

For bedrooms, when people are asleep, *fixed* threshold temperatures were used, as proposed following more recent analysis of the EFUS2017 data (Lomas and Li, 2023). A bedroom is deemed to overheat if there are *more than seven nights between May and September with a mean temperature that exceeds the threshold temperature.* The night was assumed to last from 22:00 to 07:00, i.e., 9 hours.

Mean night-time temperature thresholds of 27°C, 28°C and 29°C are proposed to represent high, medium or moderate expectations of comfort when people are asleep (Lomas and Li, 2023). 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). In this work, exceedance of all three thresholds, and a threshold of 26°C[4], was examined.

Temperature threshold exceedance

The frequency with which living rooms and bedrooms in English homes exceed chosen temperature thresholds, as well as the intensity of exceedance, were calculated (Prevalence, frequency and intensity analysis DESNZ – Li, 2024a). For these calculations, ten threshold

---

[4] A threshold temperature of 26°C is widely used in bedroom overheating criteria (e.g., CIBSE, 2017).

temperatures were considered, which ranged from those associated with overheating to those signifying cold discomfort.

The frequency of exceedance was defined as the *mean daily/nightly hours between May and September for which the living room/bedroom temperature exceeded a chosen threshold temperature during occupied hours* (Prevalence, frequency and intensity analysis DESNZ – Li, 2024a). For any single living room, the maximum frequency of exceedance is therefore 15 hours, and for a bedroom 9 hours: i.e., the rooms exceed the chosen threshold for every occupied hour for the whole May to September period.

If an energy efficiency measure, such as insulation, is effective at keeping dwellings warm, then compared to dwellings without the measure, there should be a significantly higher frequency of room temperatures above thresholds that represent cold thermal discomfort. Therefore, for living rooms, a range of ten adaptive temperature thresholds were used (Figure 1). The three lowest thresholds define temperatures at which cold thermal discomfort will be experienced (Cat.-I, Cat.-II and Cat.-III) and the three warmest represent overheating (Cat.I, Cat.II and Cat.III), all six are given in BSEN16798 (BSI, 2019). Four further thresholds between Cat.-I and Cat.I were also used. These represent different levels of thermal comfort: Cat.0, the ideal thermal comfort temperature (BSI, 2019), Cat.0-2, Cat.0-1 and Cat.0+1).

For bedrooms, a set of ten fixed mean threshold temperatures were also adopted, ranging from 20°C up to 29°C, in increments of 1°C. Whilst thresholds above about 27°C may cause warm discomfort when people are sleeping, the use of duvets and other bedding avoids cold discomfort at the lower temperature thresholds.

The intensity of exceedance combined the frequency of threshold exceedance with the degree of exceedance, so was measured as the *mean daily/nightly °C.hours between May and September for which the living room/bedroom temperature exceeded a chosen threshold temperature during occupied hours*[5] (Li,2024a). The same ten adaptive or fixed thresholds, as used for the frequency of exceedance calculations, were used.

Statistical analysis

To identify any significant differences in the prevalence of overheating or the frequency and intensity of exceedance, each energy efficiency category (Table 1) was split into two possibilities. For example, to analyse the influence of Energy Performance Certificate (EPC), energy efficiency rating, homes were characterised as more energy efficient (bands A, B or C) or less energy efficient (bands D to G)[6]. For the homes in each group the mean frequency and intensity of threshold exceedance was then calculated.

Chi-square tests were used to identify any significant difference in the prevalence of overheating, and pair-wise independent t-tests were used to identify any significant difference in the mean frequency and intensity of threshold exceedance. The distributions of the

---

[5] Thus, if room temperatures exceed the threshold by 2°C, then 3°C then 4°C in successive hours, the frequency of exceedance is 3 hours and the intensity 9°C.hours.

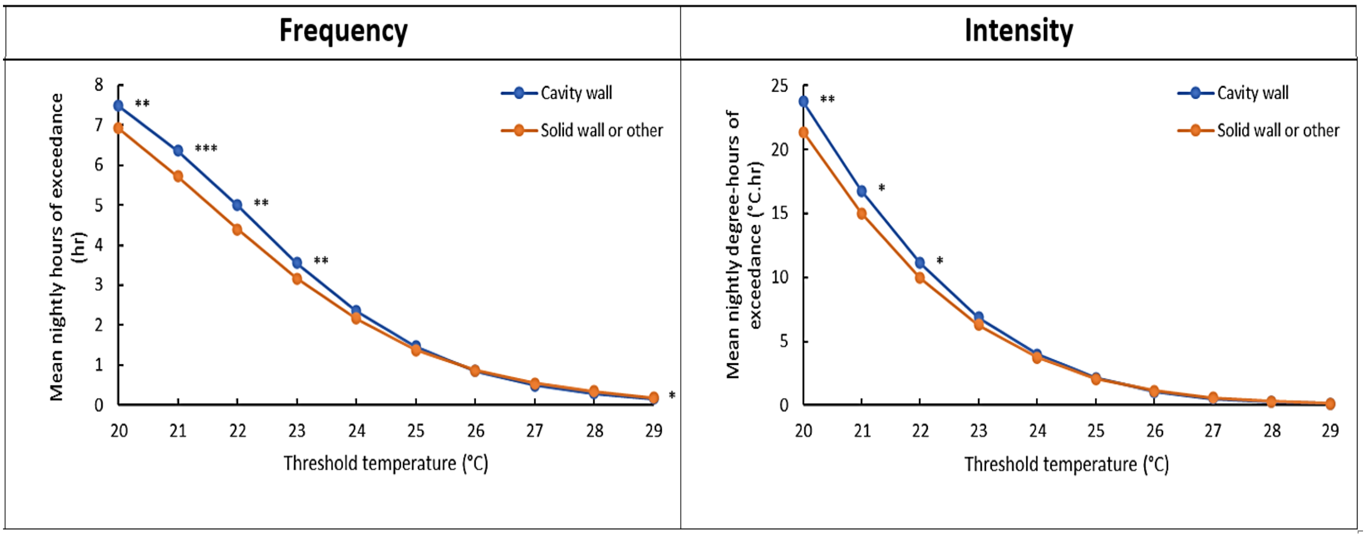
[6] The UK method of calculating Energy Performance Certificate energy rating bands is described in DECC, 2014.

frequency and intensity of exceedance were however non-normal, so comparisons were made after Box Cox power transforms of the data had been applied. Any significant differences in the results shown in the figures thus relate to the transformed values of the mean frequency and intensity of exceedance, whereas comparisons of the prevalence of overheating are based on the actual values.

For each room in both houses and flats the frequency and intensity of threshold exceedance was plotted and the significance of any differences at the 1%, 5% and 10% levels indicated in the conventional manner: $p<0.01$, ∗∗∗; $p<0.05$, ∗∗; or $p<0.1$, ∗. The way results are presented is illustrated in Figure 2 using the frequency and intensity of threshold exceedance in the bedrooms of houses with different wall types as the example[7].

Both the frequency and intensity plots show that the exceedance at thresholds above 24°C are not significantly different between the bedrooms in houses with cavity walls and the bedrooms in houses with solid walls (Figure 2). For houses with either cavity walls or solid walls the mean frequency of exceedance of a mean night-time temperature of 27°C in bedrooms[8] is about 30 minutes per night for the May to September period. The mean intensity of exceedance of this thresholds is 0.5-0.6°C.hour per night over the same period.

Figure 2: Influence of wall type on the frequency and intensity of exceedance of different temperature thresholds in the bedrooms of houses in England (∗∗∗, ∗∗, ∗, significant at p<0.01, p<0.05, p<0.1 levels).



At lower temperature thresholds, which are not associated with overheating, bedrooms are significantly warmer in houses with cavity walls than solid walls (Figure 2). For example, in houses with cavity walls, bedrooms exceed the 20°C mean night-time temperature threshold for 7.5 hrs per night on average, the mean frequency of exceedance in solid wall homes is 7hrs per night. Thus, the wall cavity, which may, or may not be insulated, had the desired effect - keeping the bedrooms warmer but without any associated increase in the frequency or

---

[7] The plotted mean frequency and intensity values are weighted and so represent the whole English stock.

[8] This is the lowest temperature associated with bedroom overheating. At a mean nightly temperature of 27°C sleep quality will degrade for some people.

intensity of overheating. This result is reinforced when the other energy efficiency measures are examined (see below).

Overall, the frequency and intensity plots produce very similar information. For every temperature threshold, the building characteristic relative exceedance is the same, and the difference between them is similar. In fact, for all the energy efficiency measures (and other characteristics) investigated, and for both flats and houses and bedrooms and living rooms, the frequency and intensity plots produced very similar results. Therefore, in the results section below, illustrative plots are only shown for the mean frequency of exceedance.

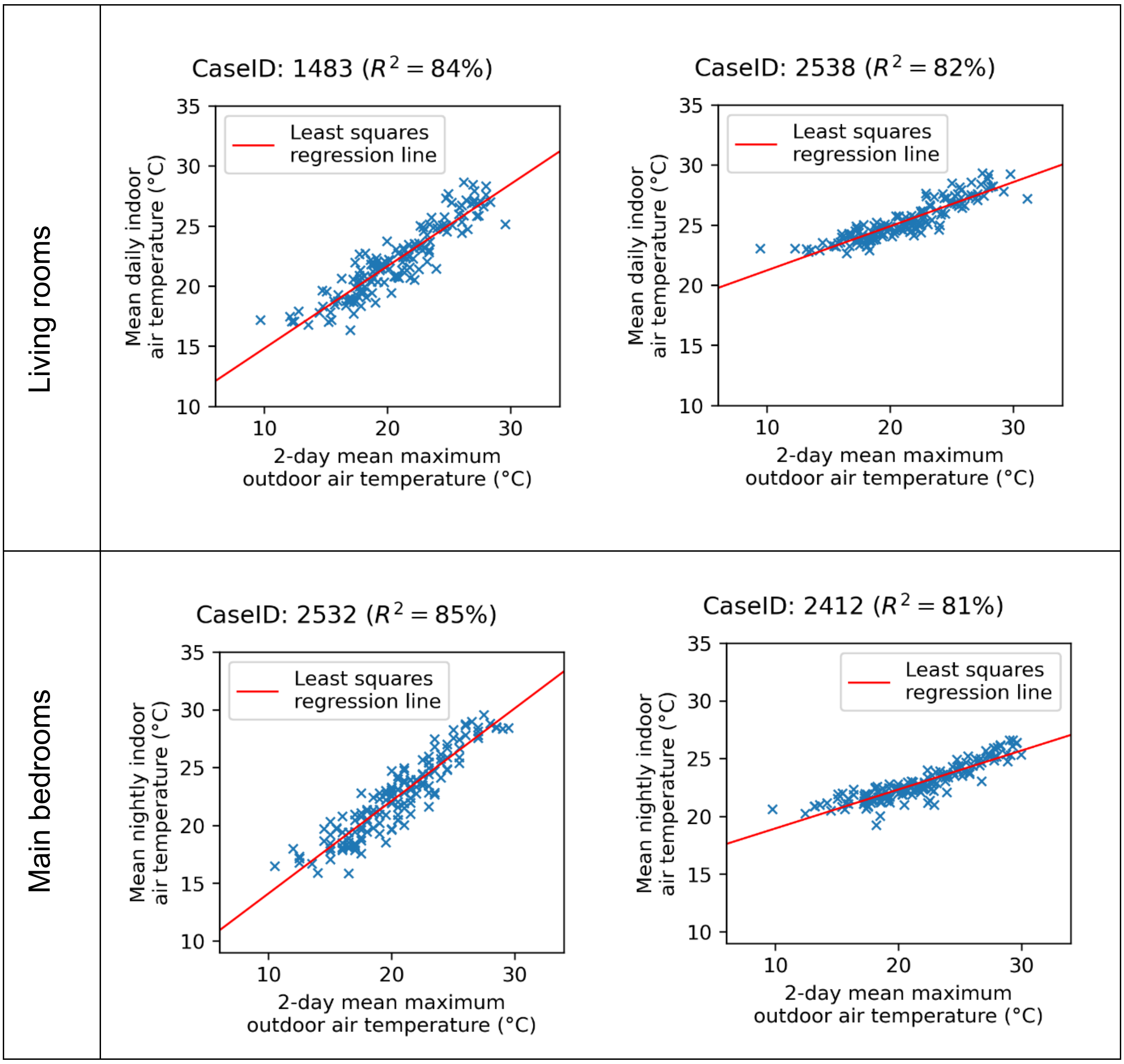
Overheating sensitivity

The response of indoor temperatures to changes in outdoor temperature is influenced by many things, for example, occupant behaviour and, more importantly for this work, the inherent characteristics of the dwellings - the areas of glazing, the insulation levels, external shading, internal heat gains etc. To reveal the response of indoor temperatures to outdoor temperatures (Temperature sensitivity analysis DESNZ - Li, 2024b) the concept of '*temperature signatures'* (Drury, 2023) was exploited. It is an approach that can answer questions such as: '*How fast do indoor temperatures increase as the outdoor temperature rises'* and, '*Do hot weather spells have a disproportionately greater effect on the indoor temperatures of energy efficient buildings compared to less efficient buildings?*'

In the UK, heatwave warnings are issued if the three day mean maximum temperature is expected to exceed 28°C in and around London, 25°C in the north of England/Scotland/Northern Ireland/Western Wales/Devon/Cornwall, and 26°C or 27°C elsewhere (Met Office, 2022). The two day mean outdoor temperature has been shown to correlate with increases in summertime mortality and morbidity (Armstrong et al., 2011). The temperature signature analysis is based on plotting the mean indoor temperature against the two-day mean maximum outdoor temperature, 2DMM.

For the sample of 616 living rooms the *mean daily temperature* (07:00-22:00) was plotted against the 2DMM temperature for the two previous days. Similarly, for the 591 bedrooms, the *mean nightly temperature* (22:00-07:00) was plotted against the 2DMM temperatures calculated using the previous day's maximum and the maximum on the current day (Temperature sensitivity analysis DESNZ - Li, 2024b). For both rooms, in most dwellings, a strong linear relationship was derived; for 75% of bedrooms and living rooms the correlation coefficients (r) exceeded 0.84 and 0.79 respectively (e.g., Figure 3).

Figure 3: Example temperature signatures in two bedrooms and two living rooms



The 2DMM was calculated using the weather data collected at the Met Office station nearest to each house (see BEIS, 2021b). The maximum values of 2DMM temperature between May and September varied from 33°C to 25°C depending on dwelling location.

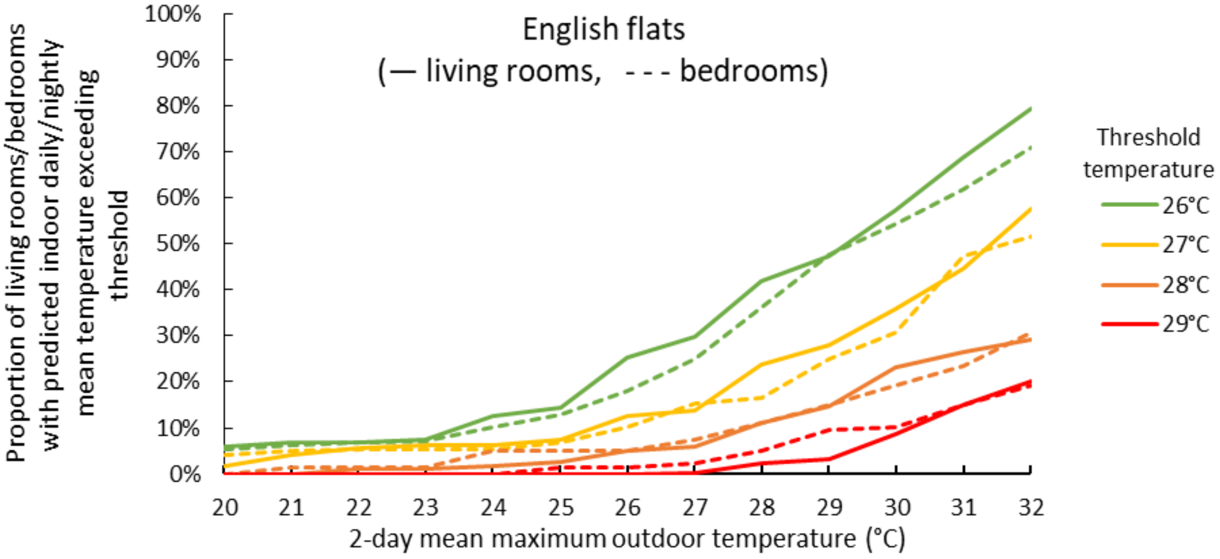
For living rooms, on average, the mean daily temperature increased at a rate of about 0.4°C for each 1°C increase in 2DMM temperature, the increase of the mean nightly temperature in bedrooms was about 0.5°C for each 1°C increase in 2DMM. However, there was considerable variability. For some rooms, in some homes, the mean temperature increased rapidly with the 2DMM outside temperature (e.g., Figure 3, living room ID1483, bedroom ID2532) in other dwellings the mean temperatures were less sensitive to the outside temperature (e.g., Figure 3, living room ID2538, bedroom ID2412).

The temperature signatures (Figure 3) indicate whether, at any particular 2DMM outdoor temperature, the room temperature exceeds a particular threshold value. For bedroom ID2532, a mean night-time temperature threshold of 27°C is exceeded for all 2DMM temperatures above 25.5°C. For bedroom ID2412, the threshold is never exceeded, the maximum mean nightly temperature of 26.6°C occurring when the 2DMM temperature reaches 30°C.

Observation of approximately linear relationships motivated fitting of linear mixed-effects models of daily/nightly mean temperature for living rooms/bedrooms as a function of 2DMM outdoor temperature (Temperature sensitivity analysis DESNZ - Li, 2024b). The proportion of rooms in the EFUS sample that are predicted to exceed a chosen mean temperature threshold at each 2DMM outdoor temperature can thus be determined[9].

The overheating sensitivity plot (Figure 4) shows the proportion of English flats with a model-predicted mean daily living room temperature that exceeded each threshold from 26°C to 29°C alongside the proportion of bedrooms with model-predicted mean nightly temperatures exceeding these thresholds. For both rooms, the proportion that exceeds the threshold temperatures escalates rapidly as the 2DMM temperature increases, but the sensitivity of the nightly bedroom temperatures and the daily living rooms temperatures to the 2DMM is similar (this was not so for houses however, see Figure 6 below). At a 2DMM temperature of 27°C, which approximates the heatwave threshold for middle England, approximately 13% of the bedrooms in English flats (c0.7 million in total) are predicted to have mean nightly temperatures exceeding 27°C.

Figure 4: Influence of the 2DMM temperature on the proportion of living rooms and bedrooms in English flats with a predicted daily/nightly mean temperature during occupancy exceeding different thresholds.



Similar plots to Figure 4 can be produced to compare dwellings with and without a particular energy efficiency measure, or other characteristic; such comparisons are presented below.

Results

The results for which there is clear and consistent evidence are presented thematically, drawing together the findings from the evidence review, the reanalysis of the EFUS

---

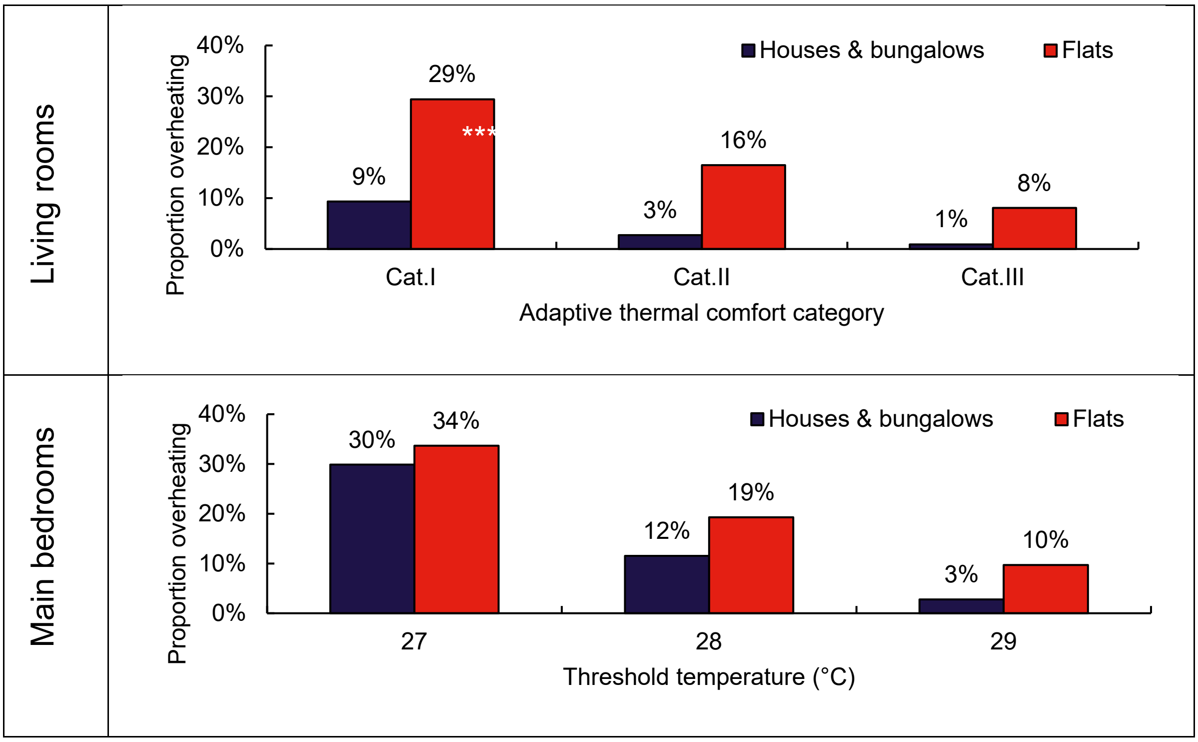
[9] These result can then be weighted to give the proportion for whole English stock.

data and the previous EFUS2017 analysis. The aim is to provide the best possible picture of the effect of energy efficiency measures, and some other dwelling characteristics, on summertime temperatures in English homes.

Prevalence of overheating in English homes

Prior to considering the effects of energy efficiency measures on room temperatures it is useful to report the prevalence of summertime overheating in the living rooms and bedrooms of flats and houses as defined by the established and emerging definitions given above[10] (Figure 5).

For bedrooms, there was no significant difference in the prevalence of overheating in flats and houses except at a threshold temperature of 29°C. At a mean nightly temperature threshold of 27°C, the prevalence of overheating was 30% for houses and 34% for flats (Figure 5). As the threshold temperature increases, the prevalence in flats was greater than in houses e.g., 10% flats cf. 3% houses at a threshold of 29°C. Thus, in England as a whole, during 2018, the main bedroom of around 568,000 flats and 577,000 houses[11] would be so hot that a quality night's sleep would be unlikely for most people on at least 7 nights during the summer. Figure 5: The prevalence of overheating in the living rooms and main bedrooms of English homes during the hot summer of 2018. Differences in prevalence between flats and houses that are significant are indicated (*, **, *, significant at $p<0.01$, $p<0.05$, $p<0.1$ levels).**



---

[10] The absolute figures for living rooms reported here differ slightly from those published previously (BEIS, 2021a, Lomas et al., 2021). Both sets of results used the same adaptive overheating criterion, but in the previous work the CIBSE TM52 method of exceedance calculation was used (CIBSE, 2013) whereas here the more recent TM59 (CIBSE, 2017) method of calculation is used.

[11] The 2021 census reported 24.93 million dwellings in England of which 5.68 (22.8%) were flats, maisonettes or apartments (ONS, 2023).

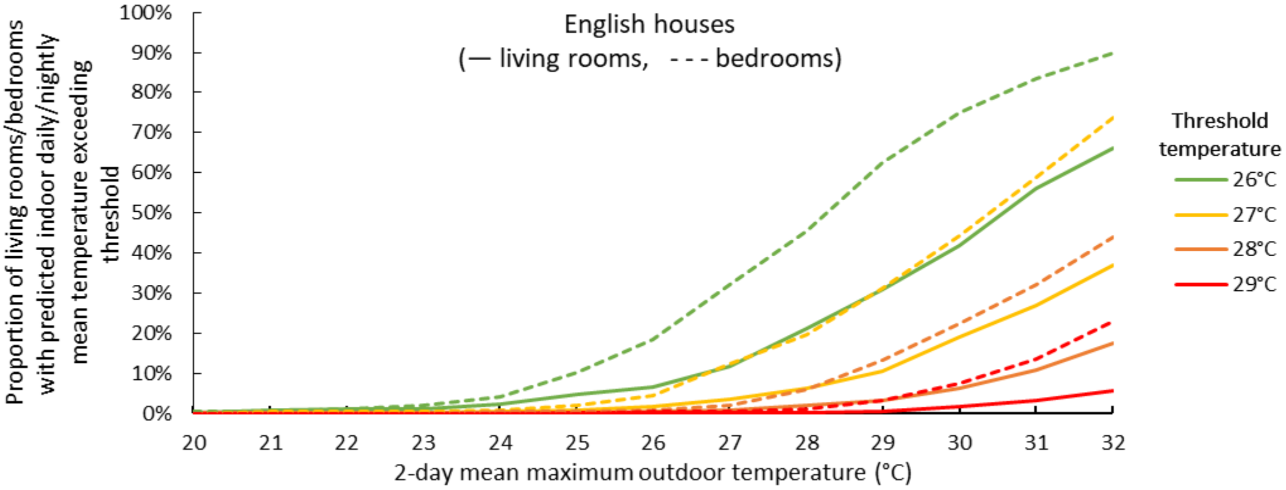
For living rooms, the prevalence of overheating in flats was significantly greater than in houses ($p<0.01$) for the Cat.I threshold[12] (Figure 5); a result which aligns with that from the previous EFUS2017 analysis (BEIS, 2021a; Lomas at al., 2021). For the Cat. II threshold (see Figure 1), which meets modest expectations of thermal comfort, 16% of flats overheated cf. 3% of houses. Thus, in 2018, around 909,000 flats and 577,000 houses in England had living rooms that exceeded the overheating threshold temperature adopted by the building regulations, Part O, concerning the mitigation of overheating risk in new homes (HMG, 2021).

Temperatures in living rooms & bedrooms

Previous analysis of the EFUS2017 data set and the re-analysis undertaken in the recent work, provided consistent evidence about overheating in living rooms and bedrooms.

In houses, bedrooms were warmer at night than living rooms were during the day. The overheating sensitivity plot (Figure 4) showed that, in flats, the proportion of bedrooms expected to exceed any chosen threshold temperature at night, was similar to the proportion of living rooms expected to exceed the same threshold during the day. In houses however, the proportion of bedrooms predicted to exceed any chosen threshold temperature was much greater than the proportion of living rooms predicted to exceed the threshold (Figure 6). For example, at a 2DMM temperature of 27°C, four times more bedrooms were predicted to exceed a threshold of 27°C than were living rooms.

Figure 6: Influence of the 2DMM outdoor temperature on the proportion of living rooms with a mean daily temperature, and bedrooms with a predicted mean nightly temperature exceeding different temperature thresholds.



The influence of flat level on room temperatures

Although the primary focus of this work was energy efficiency measures, it is worth noting the substantial influence that the position of a flat within a building has on indoor temperatures.

---

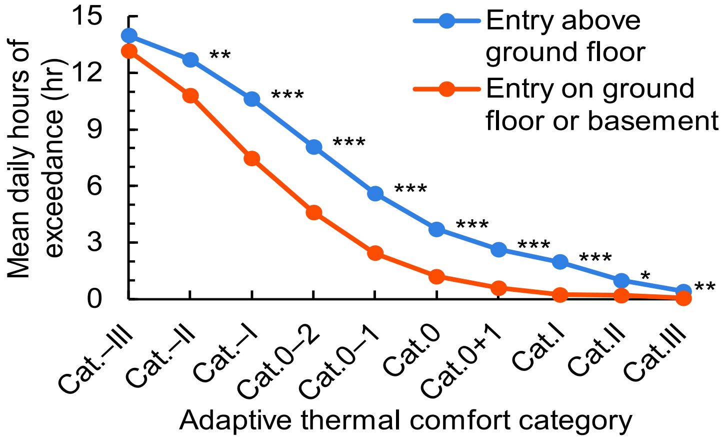
[12] The results for Cat.II and Cat.III thresholds were also significant ($p<0.01$) but the lowest expected count was below 5 which is the cutoff adopted to define a valid chi-squared test.

Importantly, the floor level of a flat has a much larger influence on indoor summertime temperatures than any of the energy efficiency measures examined. The influence of floor level on temperature was broadly similar for both living rooms and bedrooms.

Compared to the flats on other levels, top floor flats were significantly warmer and ground floor flats significantly cooler. Flats on the top floor of buildings experienced a significantly higher prevalence of overheating in both living rooms and bedrooms than flats on the lower floors of buildings. Conversely, flats entered on the ground floor or below experienced a significantly lower prevalence of bedroom and living room overheating (Prevalence, frequency and intensity analysis DESNZ - Li, 2024a). For example, the prevalence of overheating in bedrooms based on a 28°C temperature threshold was 35% in top floor flats and just 2% in flats entered at ground level.

Compared to flats on other floors, the mean frequency of exceedance of all the living room and bedroom temperature thresholds was higher in top floor flats and lower in flats entered at ground level (Prevalence, frequency and intensity analysis DESNZ - Li, 2024a); these differences in exceedance were almost always significant[13]. For example, the mean daily hours of exceedance of the Cat.I threshold in top floor flats was 2h/day (Prevalence, frequency and intensity analysis DESNZ - Li, 2024a) compared to just less than 12mins/day in ground floor flats (Figure 7).

Figure 7: Influence of the flat entry level on the frequency of exceedance of different temperature thresholds in living rooms (∗∗∗, ∗∗, ∗, significant at p<0.01, p<0.05, p<0.1 levels).

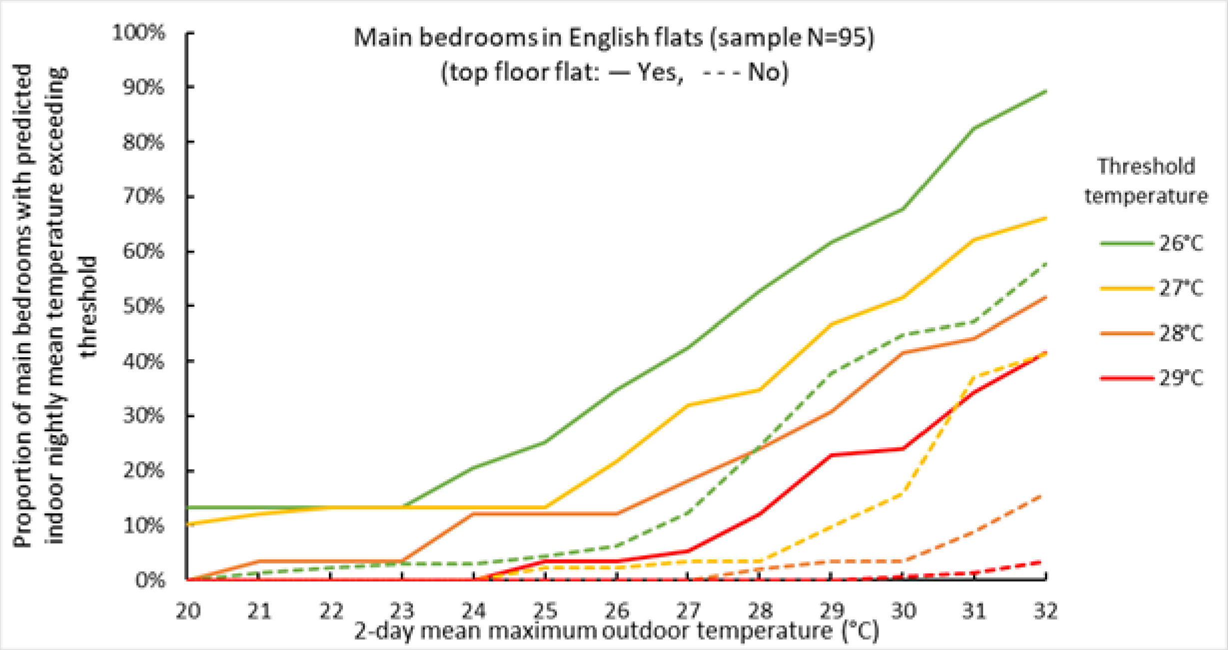


The overheating sensitivity analysis reinforced these results demonstrating that for all 2DMM temperatures, and for both living rooms and bedrooms, the predicted proportion exceeding each overheating threshold was much greater in top floor flats and much lower in flats entered at or below ground level. For example, at a 2DMM temperature of 27°C, the mean nightly bedroom temperature exceeded 27°C in 32% of top floor flats (Figure 8) but in only 2% of flats entered at or below ground level. The predicted proportions for living rooms were similar.

---

[13] The frequency of exceedance in the main bedrooms of top floor flats were not significant at threshold below those associated with overheating.

Figure 8: Comparison of top floor flats and flats on lower levels: influence of the 2DMM outdoor temperature on the proportion of bedrooms with a predicted mean daily temperature exceeding different thresholds



Interestingly, below a 2DMM temperature of about 24°C, the proportion of living rooms and bedrooms exceeding the 26°C and 27°C thresholds (10-12%) did not change (e.g., Figure 8). This suggests that the warm bedroom conditions were a result of internal heat sources rather than the outdoor conditions. High internal heat gains are a known contributor to overheating in flats (e.g., McLeod and Swainson, 2016).

Effect of overall energy efficiency rating on room temperatures

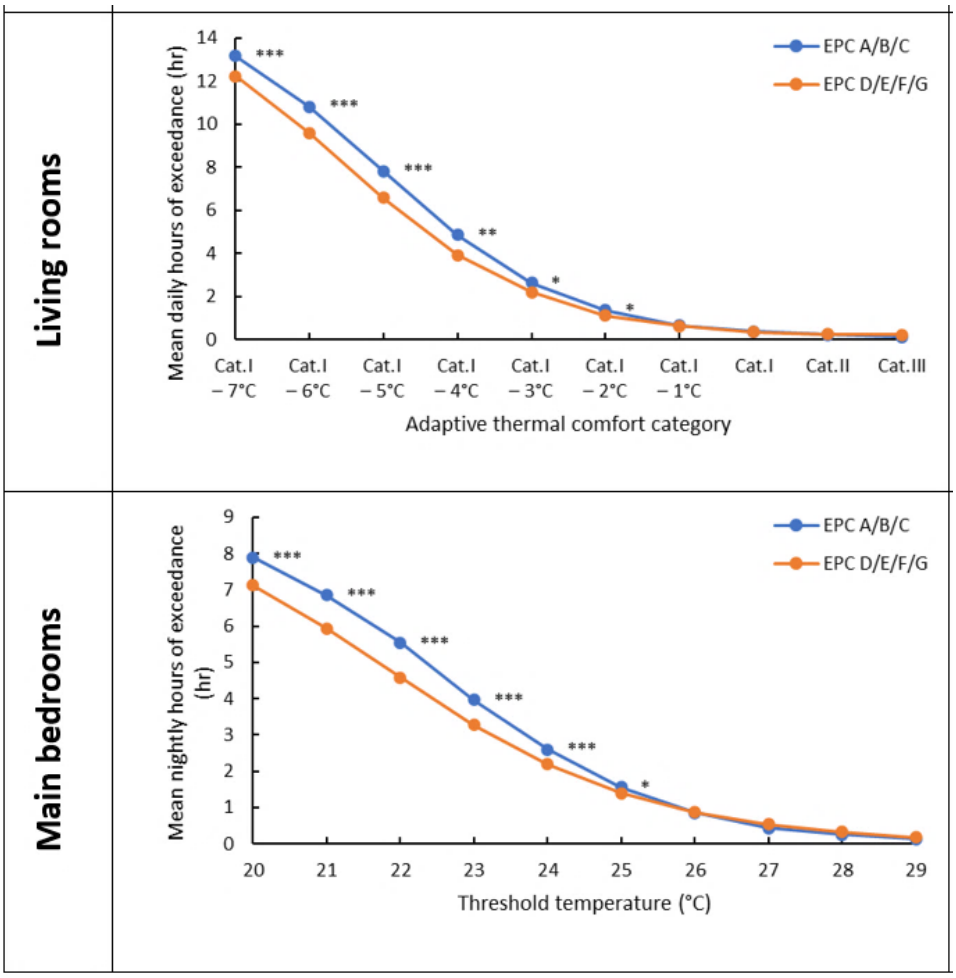
The effects of the overall energy efficiency rating on the temperatures in living rooms and bedrooms is based on the re-analysis of the EFUS2017 data only. The evidence review produced no quality information on this matter.

Houses with a higher energy efficiency rating were warmer but did not have any additional risk of overheating[14]. More energy efficient houses, (EPC energy efficiency rating bands A, B or C), had living rooms that more frequently exceeded thresholds associated with cold thermal discomfort than did less efficient houses (bands D to G). Put another way, there were significantly fewer daily hours of cold discomfort in the living rooms of more energy efficient homes (Figure 9). For example, at the Cat.-II threshold, which corresponds to modest expectations of cold discomfort, energy efficient homes had living rooms below this threshold for about 7 occupied hours a day on average, whereas less efficient homes were cold for about 8 hours each day on average.

---

[14] As stated throughout this and the accompanying reports, this statement applies to the summer of 2018 rather than future climate scenarios

Figure 9: Influence of the energy efficiency of houses on the frequency of exceedance of different temperature thresholds (*, **, *, significant at *p*<0.01, *p*<0.05, *p*<0.1 levels).**



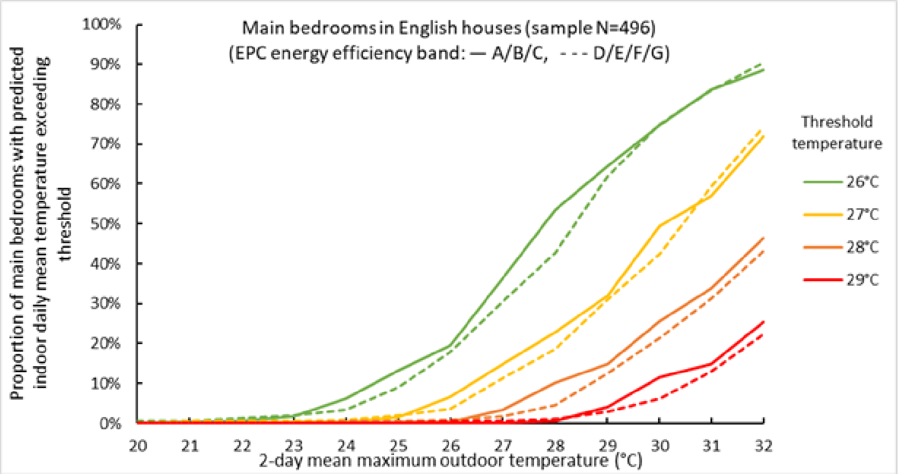
At the temperatures associated with overheating in living rooms, there was no significant difference in either the frequency or intensity of threshold exceedance (Figure 9).

The results for bedrooms were similar. The exceedance of bedroom threshold temperatures signifying overheating was similar in the energy efficient and less energy efficient houses, but at thresholds below those signifying overheating, the bedrooms in more energy efficient houses were warmer than in less efficient houses (Figure 9).

The overheating sensitivity analysis indicated that, as the 2DMM temperature increases, so too did the predicted prevalence of temperatures above each threshold temperature. However, for both living rooms and bedrooms (Figure 10), the increase in predicted prevalence with 2DMM temperature was broadly similar for energy efficient and less energy efficient houses.

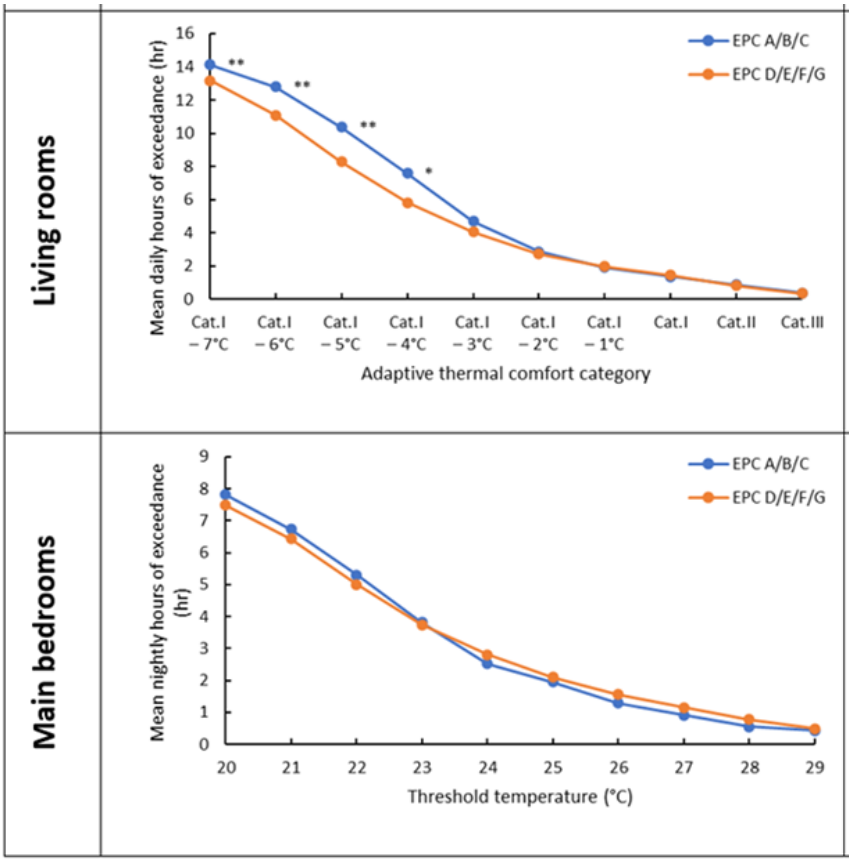
The previous EFUS2017 analysis (BEIS, 2021a; Lomas et al, 2023), suggested that living rooms in homes in the higher energy efficiency rating bands had a greater prevalence of overheating. However, that analysis mixed together flats, which by virtue of their built-form tend to be inherently more energy efficient, and houses. By separating houses from flats this re-analysis brings clarity.

Figure 10: Comparison of energy efficient and less energy efficient houses: influence of the 2DMM outdoor temperature on the proportion of bedrooms with a predicted mean nightly temperature exceeding different thresholds.



The energy efficiency rating of flats had limited impact on room temperatures. The living rooms of energy efficient flats more frequently exceeded thresholds associated with cold discomfort than did those in less energy efficient flats (Figure 11), but there was no significant difference for the intensity of exceedance. In bedrooms, there were no significant differences in either the frequency (Figure 11) or intensity of exceedance of any threshold temperature.

Figure 11: Influence of the energy efficiency of flats on the frequency of exceedance of different temperature thresholds (∗∗, ∗, significant at p<0.05, p<0.1 levels).



The rate of rise of living room and bedroom temperatures as the 2DMM outdoor temperature increased was also similar between energy efficient and less energy efficient flats.

Importantly, therefore, the overall energy efficiency rating of flats had no effect on the exceedance of thresholds associated with overheating in either living rooms or bedrooms.

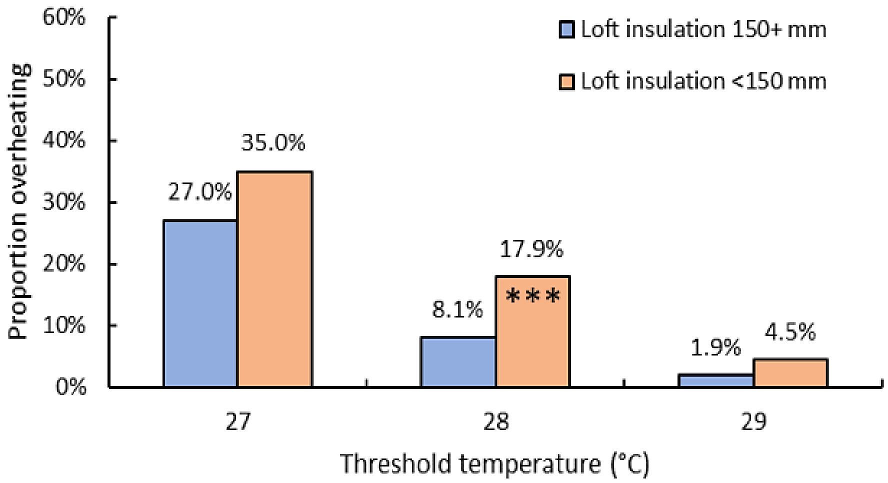
Effect of individual energy efficiency measures on room temperatures

The effects of energy efficiency measures on the internal temperatures are presented where there was robust evidence from either the temperature exceedance or temperature signature analysis. The literature review provided high-quality evidence supporting a number of the findings. Also reported are results for which energy efficiency measures had no observed effect on overheating.

In houses, increased loft insulation may reduce the risk of overheating in bedrooms. Overall, the thickness of loft insulation had little effect on room temperatures. However, in houses with more than 150mm of loft insulation, there was a significantly *lower* prevalence, frequency and intensity of overheating in bedrooms, especially at the higher overheating thresholds, 28°C or 29°C (Figures 12 and 13)[15]. The thickness of loft insulation had no effect on the frequency or intensity of overheating in flats or in the living rooms of houses.

The evidence review found moderate quality evidence supporting these observations based on results from both modelling work and others' field studies.

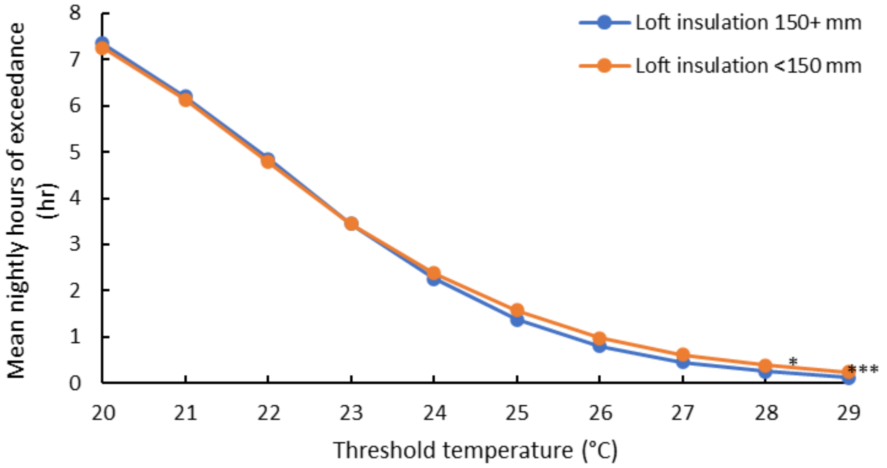
Figure 12: Influence of loft insulation thickness on the prevalence of overheating in the bedrooms of houses (*, significant at *p*<0.01 level).**



---

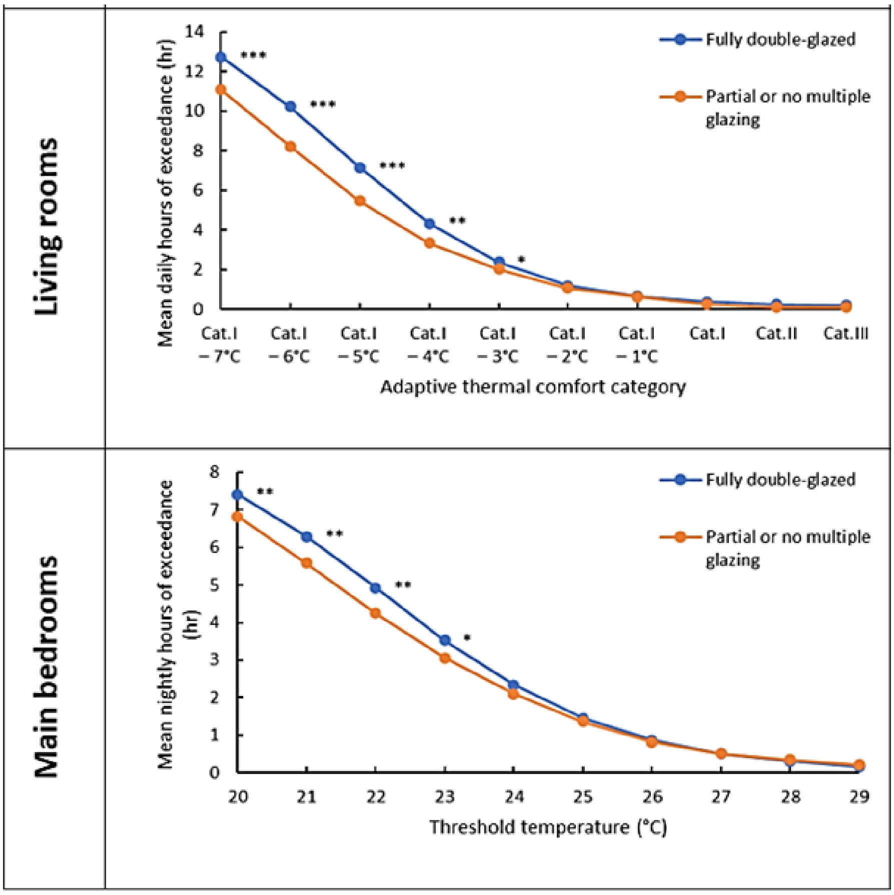
[15] The previous EFUS2017 analysis (Lomas et al, 2021) observed no significant difference in the prevalence of measured overheating in either living rooms or bedrooms. This may be because flats and houses were combined and the insensitivity of flats to loft insulation masked the effect in houses.

Figure 13: Influence of loft insulation thickness in houses on the frequency of exceedance of different temperature thresholds in bedrooms.



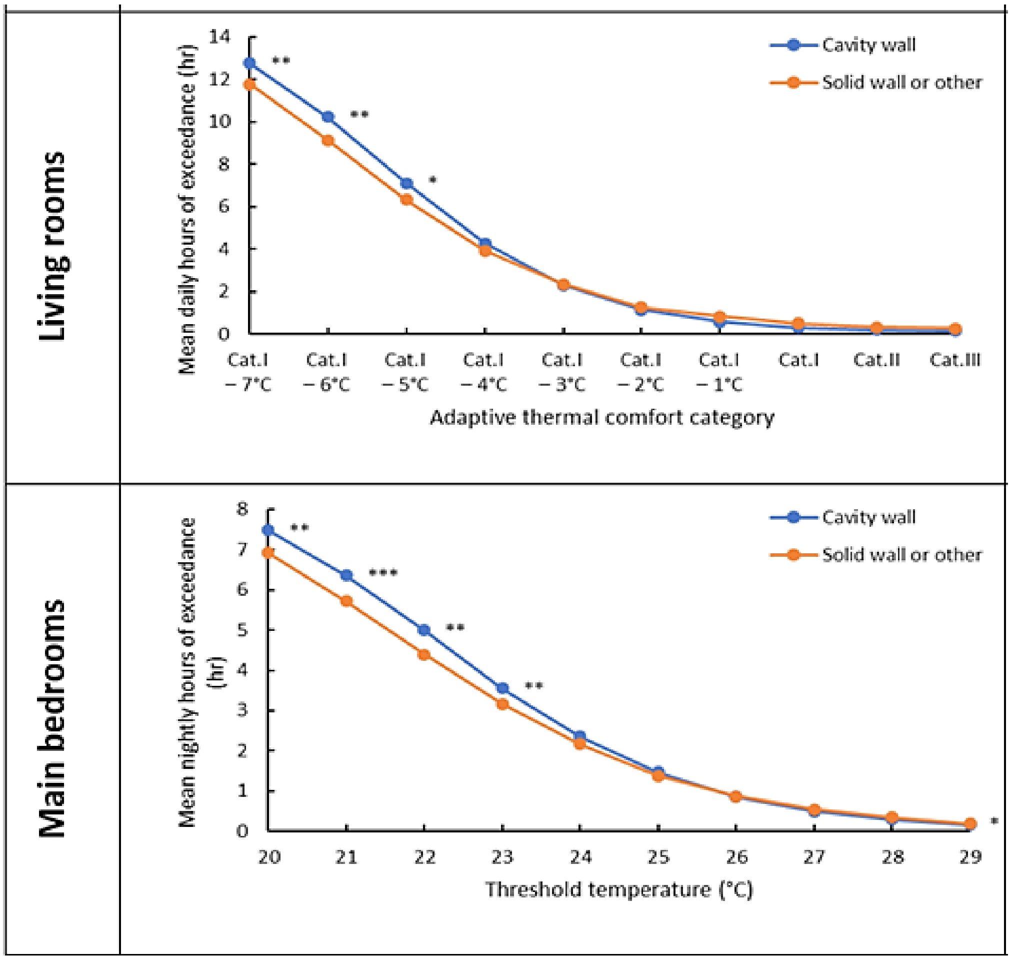
For both houses and flats, double glazing kept rooms warmer but did not affect the risk of overheating. Whether or not houses and flats had double glazing had no significant effect on the frequency and intensity of exceedance of threshold temperatures associated with overheating in either living rooms or bedrooms. However, the living rooms and bedrooms houses and flats with double glazing were significantly warmer at temperature thresholds below those associated with overheating, which is the intended purpose of energy efficiency measures (e.g., Figure 14).

Figure 14: Influence of double glazing in houses on the frequency of exceedance of different temperature thresholds (*, **, *, significant at *p*<0.01, *p*<0.05, *p*<0.1 levels).**



Houses with cavity walls, rather than solid walls, were warmer but did not have a greater risk of overheating. The frequency of exceedance of living room temperature thresholds associated with cold thermal discomfort was significantly greater in houses with cavity rather than walls. There was, however, no significant difference in frequency or intensity of exceedance of thresholds associated with overheating (Figure 15). Likewise, bedrooms in houses with cavity walls were significantly warmer, but only at temperatures below those associated with overheating (Figure 15). Wall construction had no significant effects on temperatures in flats. The EFUS2017 data set does not indicate whether the wall cavities were or were not insulated.

Figure 15: Influence of house wall type on the frequency of exceedance of different temperature thresholds (*, **, *, significant at p<0.01, p<0.05, p<0.1 levels).**

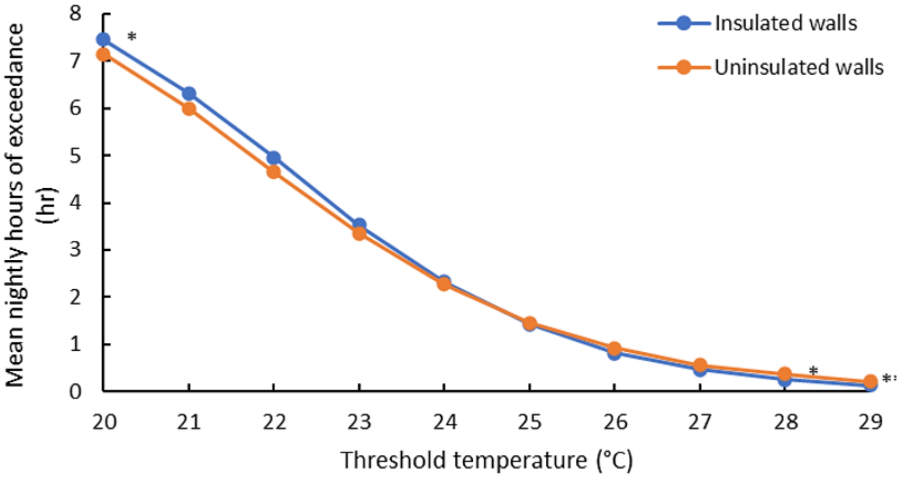


The overheating sensitivity analysis indicated that, as the 2DMM external temperatures increase, the rate of increase in the proportion of rooms exceeding any chosen threshold temperature was largely unaffected by the wall type.

For both houses and flats, the presence of wall insulation had a limited impact on room temperatures, but for some house types, the risk of overheating may be reduced. In the living rooms of both houses and flats, the exceedance of temperature thresholds associated with cold discomfort was significantly greater in dwellings with insulated walls[16]. The exceedance of temperature associated with overheating was not influenced by the presence of wall insulation. For bedroom the presence of wall insulation had little impact on the exceedance of any of the temperature thresholds, however, the bedrooms of houses with insulated walls had a significantly lower exceedance of the highest overheating temperature threshold, 29°C (Figure 16).

The findings of the evidence review were complementary; there is high quality evidence from modelling studies indicating wall insulation can reduce the frequency of exceedance of overheating thresholds in houses with a large external wall area, e.g., detached and semi-detached houses[17].

Figure 16: Influence of wall insulation on the frequency of exceedance of different temperature thresholds in the bedrooms of houses (∗∗, ∗, significant at p<0.05, p<0.1 levels).



Matters for further investigation

The evidence review also provided evidence about three other matters of importance.

Internal solid wall insulation may increase the risk of overheating. There is high-quality evidence from modelling studies and field experiments indicating that retrofitting internal wall insulation causes a small increase in room temperatures at thresholds associated with overheating. However, the effective use of existing ventilation and shading measures may readily overcome any increased risk of overheating. Further investigation is suggested.

Increased levels of insulation may make internal summertime temperatures more sensitive to occupants' use of ventilation devices. There is moderate quality evidence from modelling studies, supported by a field experiment, that indoor temperatures are more sensitive to occupant behaviour in well-insulated buildings. Further work on the interplay of

---

[16] But only at the 5% or 10% level and only for the Cat.-III and Cat.-II thresholds.

[17] Although the evidence review also provided high quality evidence that the *prevalence* of overheating was not influenced by whether walls were insulated or not.

insulation measures and the provision of adequate, effective and usable ventilation and shading is suggested.

Overheating risk is likely to be increased in dwellings built to very high energy efficiency standards. There is moderate quality evidence from a meta-analysis and a field study report that, compared to dwellings typical of the current housing stock, there is an increased risk of overheating in homes built to the Code for Sustainable Homes (DCLG, 2010) and Passivhaus (PHI, 2015) standards. Findings from two modelling studies align with those findings. However, very energy efficient, modern homes often incorporate other features that affect indoor temperatures, such as larger window areas and mechanical ventilation systems. The specific influence of the high energy efficiency standards, when effective summertime shading and ventilation is provided, warrants further investigation.

Conclusions

The overall conclusions are given here in a readily digestible form; details are in the results section above and the three underpinning reports. The conclusions are based on evidence from the literature review and the further analysis of the EFUS2017 dataset of temperatures measured in English dwellings during the hot summer of 2018.

Principal observations

The following few conclusions address the primary aim of this research. Detailed conclusions for each of the energy efficiency measures studied are given below.

- The overall energy efficiency rating of English houses and flats did not significantly increase the risk[18] of summertime overheating in either living rooms or bedrooms, neither did the installation of individual energy efficiency measures.
- English houses with a higher overall energy rating were warmer during cool summer weather. The frequency and intensity of cold discomfort in living rooms was therefore significantly reduced and bedrooms were warmer.
- The proportion of English bedrooms and living rooms predicted to exceed any chosen threshold temperature increased as the daily outdoor temperature increased. However, neither the overall energy efficiency rating nor the individual installed energy efficiency measures affected the rate of indoor temperature increase.
- More work is needed to understand the effect on overheating of very high domestic energy efficiency levels, especially when associated with established, and usable heat mitigation measures.

These overarching observations, which are supported by both the analysis and the literature review, indicate that energy efficiency measures had their intended effect. They increased

---

[18] Risk (of overheating) is used in the conclusions to report, concisely, results supported by all three analysis methods.

living room temperatures at thresholds associated with cold discomfort without increasing the frequency and intensity of exceedance of thresholds associated with overheating. Likewise, energy efficiency measures kept bedrooms warmer without affecting the prevalence of overheating.

There is good reason to expect such results. As the outside temperature approaches levels that are thermally comfortable, the difference between the inside and outside temperatures decrease and so fabric insulation and reduced air leakage (infiltration) have little impact on heat flows. Additionally, and complementary to this, the results suggest that occupants have similar opportunity to control heat (e.g., shading and ventilation), which they use with similar effectiveness, in homes with different energy efficiency measures.

The finding that the rate of increase of indoor temperatures with outdoor temperatures is largely unaffected by the energy efficiency measures installed in current English homes is important. It indicates that the objective of reducing energy demand by making existing English homes more energy efficient can proceed without compromising efforts to mitigate the overheating effects of a warming climate.

English homes and overheating

To provide context it is useful here to present conclusions about overheating due to factors other than energy efficiency measures.

- Approximately 4.6% of the main bedrooms in English homes (1.1 million) were so warm during the summer that they would frequently preclude attainment of a quality nights' sleep.

  The prevalence of bedroom overheating in flats was three times greater than in houses. Thus, in the English housing stock, 3% of the main bedrooms in houses (0.6million) and 10% of the main bedrooms in flats (0.6 million), had night-time temperatures during the summer that exceeded 29°C on seven or more nights between May and September.

- In houses, bedrooms were warmer at night than living rooms were during the day.

  During periods of warm weather typical of heatwaves[19], four times more bedrooms in houses were predicted to exceed the overheating threshold of 27°C at night[20] than were living rooms during the day. In flats there was no difference in the proportions of living rooms and bedrooms exceeding any chosen overheating threshold.

  Considerations of thermal physics would suggest that bedrooms could be warmer because they are less well shaded than ground floor rooms, they are often less thermally massive, heat gains during the day are less likely to be managed than in the occupied, ground floor rooms, and, of course, hot air in ground floor rooms can flow up to bedrooms at higher levels.

---

[19] Taken here as a 2DMM temperature of 27°C.

[20] The mean nightly temperature at which sleep quality begins to degrade for some people (Lomas and Li, 2023)

- Flats entered above ground level were significantly warmer than flats at ground level.

In the living rooms of flats above ground level, rather than at ground level, there was a significantly higher frequency and intensity of exceedance of all threshold temperatures ranging from uncomfortably cold to uncomfortably hot. During weather periods typical of heatwaves, 25% of the main bedrooms in flats above ground level were predicted to be so hot that a quality nights' sleep would be difficult for some people. Only 2% of ground floor flats had bedrooms that were predicted to be this hot.

- Flats on the top floor of buildings were significantly warmer than flats on lower floors.

Around 27% of living rooms in top floor flats failed to meet the current building regulations' overheating threshold; just 2% of flats entered at ground level failed this criterion. Compared to flats at lower levels, top floor flats had living rooms with a significantly higher frequency and intensity of exceedance of all threshold temperatures ranging from uncomfortably cold to uncomfortably hot. During weather periods typical of heatwaves, 32% of bedrooms in flats on the top floor were predicted to be so hot they were likely to preclude a quality nights' sleep for some people. Only 2% of flats entered at ground level had bedrooms that were predicted to be this hot.

Effect of overall energy efficiency rating

- Homes with a higher overall energy efficiency rating had warmer living rooms and bedrooms but no increased risk of overheating.

In the living rooms of houses, the frequency and intensity of temperatures above thresholds associated with cold discomfort was greater in more energy efficient houses than in less efficient houses. There was, however, no significant difference for temperatures associated with overheating in either living rooms or bedrooms. The predicted prevalence of overheating in both rooms increased at a similar rate as the outdoor temperature increased.

- The overall energy efficiency rating of flats had limited effect on the temperatures in bedrooms and living rooms.

Living rooms were warmer in more energy efficient flats but the exceedance of temperatures associated with overheating was unaffected. Overall energy efficiency did not influence the exceedance of any temperature threshold in the bedrooms of flats. The predicted prevalence of overheating in both rooms increased at a similar rate as the outdoor temperature increased.

Effect of individual energy efficiency measures

The presence of energy efficiency measures reduced the occurrence of temperatures associated with cold discomforts but did not increase the risk of overheating. In some houses, loft and wall insulation may reduce overheating risk.

- Double glazing kept houses and flats warmer but did not affect the risk of overheating.

There was no significant difference in the risk of overheating in the living rooms or bedrooms of houses or flats between those with and without double glazing. However, in both houses and flats with double glazing, living rooms and bedrooms were significantly warmer at temperature thresholds below those associated with overheating.

- Increasing the thickness of loft insulation may reduce the risk of serious overheating in the bedrooms of houses.

In the bedrooms of houses with more than 150mm of loft insulation, there was a significantly lower prevalence of overheating, and a significantly lower frequency and intensity of exceedance of temperature thresholds associated with overheating. The literature review provided evidence supportive of these findings. Loft insulation had no significant effect on temperatures in the living rooms of houses or the living rooms and bedrooms of flats. Neither did loft insulation have an obvious effect on the rate of increase of indoor temperatures with outdoor temperature.

- Cavity walls, rather than solid walls kept houses warmer but did not affect the risk of overheating.

In both the living rooms and bedrooms of houses, the exceedance of temperatures below those associated with overheating was greater in houses with cavity walls rather than solid walls. There was no significant difference in the frequency of exceedance of overheating threshold temperatures. The cavities of many houses may have been insulated, but the prevalence of solid wall with insulation is likely to be much lower.

- Whether or not walls were insulated had a small impact on room temperatures but may reduce the frequency of overheating in the bedrooms of houses with large wall areas.

Focusing specifically on whether walls were insulated or not provided results that were complementary to those above. The differences in exceedance between insulated and uninsulated walls were small, and non-significant for most temperature thresholds. However, at the highest overheating temperature threshold, 29°C, bedrooms were significantly cooler in the houses with insulated walls. The evidence review revealed high-quality complementary evidence from modelling studies indicating that wall insulation can reduce the risk of overheating in dwellings with larger wall areas, such as detached and semi-detached dwellings.

Opportunities for further investigations

Analysis using temperature signatures to predict the sensitivity of overheating to changes in outdoor temperature holds promise for much more extensive investigations. For example, into the effects of regional weather variations on internal dwelling temperatures and overheating, and the effects of climate change on the prevalence of overheating.

Higher areas of unshaded glazing are likely to increase the risk of overheating. There may be co-incidence between the risk of overheating in flats compared to houses and their glazed areas. The English Housing Survey includes the areas of glazing for the monitored dwellings; access to these data would enable further investigation.

Overheating in dwellings is an active area of research and development, so new evidence of the effects of energy efficiency measures, and other dwelling design features, is continuing to emerge. The literature search revealed articles from overseas countries with similar weather to the UK, these have been catalogues and archived but not yet examined.

References

Armstrong BG, Chalabi Z, Fenn B, Hajat S, Kovats S, Milojevic A, Wilkinson P. (2011) Association of mortality with high temperatures in a temperate climate: England and Wales. Journal of Epidemiology and Community Health, 65(4), p. 340-345. doi:10.1136/jech.2009.093161 (Available at: https://pubmed.ncbi.nlm.nih.gov/20439353/ Accessed 280723).

BEIS (2021a) Energy Follow Up Survey: thermal comfort, damp and ventilation: Final report. Department of Business Energy and Industrial Strategy, 81pp. (Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1018726/efus-thermal.pdf Accessed 020823)

BEIS (2021b) Methodology Report: 2017 Energy Follow up Survey, Building Research Establishment for the Department of Business Energy and Industrial Strategy, 41pp.

BSI (2019) Energy Performance of Buildings - Ventilation for Buildings, Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics - Module M1-6. EN 16798-1:2019, British Standards Institution, 82pp,ISBN 9780580858680.

CIBSE (2013) Limits of Thermal Comfort: Avoiding Overheating in European Buildings CIBSE Technical Memorandum TM52, Chartered Institution of Building Services Engineers, London, 26pp. ISBN 978-1-906846-34-3.

CIBSE (2017) Design Methodology for the Assessment of Overheating Risk in Homes CIBSE Technical Memorandum TM59, Chartered Institution of Building Services Engineers, London, 17pp.

Collins, A.M., Coughlin, D., Miller, J., Kirk, S. (2015). The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide. Department for Environment, Food and Rural Affairs and Natural Environment Research Council, December, 78pp. (Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/560521/Production_of_quick_scoping_reviews_and_rapid_evidence_assessments.pdf Accessed 270723)

DCLG (2010). Code for Sustainable Homes -Technical Guide. London: Department for Communities and Local Government, November, 192pp. ISBN 978-1-85946-331-4. (Available at:

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/5976/code_for_sustainable_homes_techguide.pdf Accessed 010823)

DECC 2014. The Government's standard assessment procedure for energy rating of dwellings, 2012 edition, SAP 2012, version 9.92, rev. Feb. and June 2014 to include RdSAP2012, UK Building research Establishment on behalf of the UK Department of Energy and Climate Change, 234pp. (Available at: https://files.bregroup.com/SAP/SAP-2012_9-92.pdf Accessed 010823)

Drury P (2024a) The effect of energy efficiency measures on summertime overheating in UK dwellings: an evidence review. Report for the Department for Energy Security and Net Zero, Loughborough University, under contract number PS22100, August, 58pp.

Drury P (2024b) The summertime overheating signature of UK homes, PhD thesis, Loughborough University.

Eames M, Kershaw T, Coley D. On the creation of future probabilistic design weather years from UKCP09. Building Services Engineering Research and Technology. 2011;32(2):127-142. doi:10.1177/0143624410379934

HMG (2021). The building regulations 2010, overheating approved document O, requirement O1: overheating mitigation, regulations: 40B, 2021 edition for use in England, Her Majesty's Government, 44pp, ISBN 978-1-914124-80-8. Available at: https://www.gov.uk/government/publications/overheating-approved-document-o Accessed 280723)

Li M (2024a) The effect of energy efficiency measures on summertime overheating in UK dwellings: prevalence, frequency and intensity analysis. Report for the Department for Energy Security and Net Zero, Loughborough University, under contract number PS22100, August, 15pp

Li M (2024b) The effect of energy efficiency measures on summertime overheating in UK dwellings: temperature sensitivity analysis. Report for the Department for Energy Security and Net Zero, Loughborough University, under contract number PS22100, August, 15pp.

Lomas, K. J., Watson, S., Allinson, D., Fateh, A., Beaumont, A., Allen, J., Foster, H., & Garrett, H. (2021) Dwelling and household characteristics' influence on reported and measured summertime overheating: A glimpse of a mild climate in the 2050's. Building and Environment, 201, 17pp, 24 May. https://doi.org/10.1016/j.buildenv.2021.107986.

Lomas KJ and Li M (2023) An overheating criterion for bedrooms in temperate climates: Derivation and application. Building Services Engineering Research and Technology, Vol 0, Iss. 0, 33pp. https://doi.org/10.1177/014362442311831.

Lomas, K. J., Oliveira, S., Warren, P., Haines, V. J., Chatterton, T., Beizaee, A., Prestwood, E., & Gething, B. (2018). Do domestic heating controls save energy? A review of the evidence.

Renewable and Sustainable Energy Reviews, 93, 52–75. https://doi.org/10.1016/j.rser.2018.05.002.

G. Madge (2019). Study examines drivers of 2018 UK summer heatwave, Meteorological Office, 2019. (Available at: https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2019/drivers-for-2018-uk-summer-heatwave. Accessed 30 April 2021).

McCarthy M, Christidis N, Dunstone N, Fereday D, Kay G, Klein-Tank A, Lowe J, Petch J, Scaife A and Stott P (2019) Drivers of the UK summer heatwave of 2018, Weather, in: RMMets, V.74 Iss. 11, Royal Meteorological Society, 15 November, p. 7. (Available at: https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/wea.3628 Accessed 280723).

McLeod, R. S., & Swainson, M. (2016). Chronic overheating in low carbon urban developments in a temperate climate. Renewable and Sustainable Energy Reviews, 74, 201–220. https://doi.org/10.1016/j. rser.2016.09.106

Met Office (2022) UK Climate Change in action, Press Office, 29 March. (Available at: https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/heatwave-threshold-changes Accessed 290723)

ONS (2023) Number of dwellings by housing characteristics in England and Wales. Dataset. Census 2021. Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/housing/datasets/numberofdwellingsbyhousingcharacteristicsinenglandandwales Accessed 250723]

PHI (2015). Passive House Requirements. Passive House Institute. (Available at: https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm Accessed 010823)

Roberts BM, Allinson D, Diamond S, Abel B, Bhaumik CD, Khatami N and Lomas KJ (2019) Predictions of summertime overheating: Comparison of dynamic thermal models and measurements in synthetically occupied test houses. Building Services Engineering Research and Technology, Vol 40, Iss. 4, pp 512-552. https://doi.org/10.1177/0143624419847.

Wiley (nd). Grading of Recommendations Assessment, Development and Evaluation (GRADE). Essential Evidence Plus, John Wiley and Sons. (Available at: https://www.essentialevidenceplus.com/product/ebm_loe.cfm?show=grade Accessed 270723).

This publication is available from: https://www.gov.uk/government/collections/heat-pump-research