Meta-analysis of summertime indoor temperatures in newly-built, retrofitted and existing UK dwellings

Rajat Gupta*, Matt Gregg, Robert Irving
Low Carbon Building Research Group, School of Architecture, Oxford Brookes University, Oxford, UK
*Corresponding email: rgupta@brookes.ac.uk

This paper presents the results of a meta-analysis of hourly indoor summertime temperature datasets gathered during the summer of 2013 (May to September), from 63 dwellings, located across the UK. The sample consisted of unmodified dwellings (existing); dwellings with varying levels of fabric improvements (retrofitted) and dwellings constructed to higher levels of the Code for Sustainable Homes (new). Indoor and outdoor temperature data from bedrooms and living rooms from these homes were collected at five-minute intervals using temperature sensors. These data were processed and analysed for summertime overheating, using both static criteria (CIBSE Guide A) and the criteria associated with the EN15251 adaptive thermal comfort model (CIBSE TM52). The results show that despite a relatively cool summer, sufficiently high temperatures were found in a high proportion of dwellings, which were overheated according to the static criteria, although the prevalence of overheating was found to be much lower when assessed by the adaptive method. Considerably higher temperatures were found in bedrooms, much higher than living rooms. Interestingly, dwellings with higher levels of insulation experienced overheating twice as frequently as uninsulated dwellings. It is necessary to consider the overheating risk during the design and retrofit of homes, to avoid air-conditioning in future.

1. Introduction

Despite the relatively mild climate of the UK, concern has increased about summertime temperatures in dwellings due to the health effects of high temperatures and the possibility that these may occur more frequently with the forecast rise in global temperatures (Armstrong et al., 2010, Hajat et al., 2014, McGill et al., 2017). Longer term heat-waves with consequent heat stress can especially be fatal to vulnerable people, with the 2003 heat-wave being the most severe example from recent times, during which as many as 70,000 excess deaths occurred between June and September across Europe as a whole (World Health

Organisation, 2008) and 2,100 in London alone (Mayor of London, 2011). Whilst the summer of 2003 was very unusual for the current climate, projections indicate that similar extreme weather events will take place every two or three years by the 2050s (Mayor of London, 2011), and by the 2080s such temperatures would be considered unusually cool (Eames et al., 2011).

Though such overheating may be prevented by the use of air-conditioning, this will add, undesirably, to greenhouse gas emissions through increased energy use and refrigerant emissions. The fabric of the dwelling can provide a cool buffer against hotter weather, however, with the implementation of the higher level of fabric efficiency (i.e. improved U-values and air-tightness) under current UK Building Regulations, overheating in newly-constructed dwellings has become a concern (ZCH, no date, McGill et al., 2017), particularly due to the perception that it is caused by the ‘excessive’ levels of insulation required to reduce heating energy consumption and hence CO_2e emissions to meet the requirements of the UK Climate Change Act. The recent focus on overheating has brought a realisation that both the definition of, and the criteria for assessing overheating in naturally-ventilated residential buildings are inadequate (CIBSE, 2013). Underestimation of overheating may leave occupants with houses that are uninhabitable during the hotter days of the year. However, overestimation of overheating may lead to the installation of many unnecessary air-conditioning units. Moreover, if the causes of overheating were to be wrongly attributed, for example, to high levels of insulation, then many opportunities for energy saving in the heating season might be lost through under-insulation. It is important to note that evidence has continuously shown that occupants of these well-insulated dwellings are often more comfortable during the winter season (Schnieders and Hermelink, 2006, Mlecnik et al., 2012, McGill et al., 2015).

The aim of this study is to undertake a meta-analysis of indoor environmental data (air temperature, CO_2 levels) collected from several studies (conducted by authors) to examine the variations between the different methods of assessing overheating, and the relationships that emerge between indoor summertime temperatures and construction, dwelling type, occupant characteristics and other environmental variables (such as CO_2 levels). The study is significant in that it undertakes statistical analyses of environmental data gathered at the same time from existing houses ranging widely in age and location, both having had retrofit energy efficiency improvements and without, and new houses built to the highest energy efficiency levels under the UK standards current at the time (DCLG, 2006). This allows the examination of the differing effects of built-in and retrofit energy efficiency measures and unimproved housing on indoor temperatures, whereas the previous studies lack the ability to make these distinctions.

2. Evidence to date: review of overheating studies

Previous large-scale studies (more than a few dwellings) examining summer temperatures in UK dwellings have included Lomas and Kane (2013) who found, in a study of 230 dwellings in Leicester, that a sizeable proportion had temperatures outside the ranges anticipated by the BS EN 15251 model. The following table summarizes the methodology, location, typologies and key findings of overheating studies conducted in UK dwellings.

Table 1. Summaries of studies reviewed for this paper

Study & methodology	Location(s): size	Typologies	Key findings relevant to overheating
Wright et al. (2005) *Monitoring study specifically conducted to observe temperatures under heat wave conditions*	Manchester, North West, UK: n=4 dwellings London: n=5 dwellings	Manchester: n=2 detached, n=2 semi-detached houses; London: n=4 flats, n=1 semi-detached	This study took place during 2003 heatwave. Data showed that heat gathered during the day was retained at night; that with a daily average of 25.4°C in Manchester, 25°C was exceeded for up to 71% of the study's duration, and 28°C for up to 20% with 10% typical; that with a daily average of 29.3°C in London, time over 25°C exceeded 90%, and 28°C for up to 80%. For adaptive comfort, substantial proportions of the monitoring period were found to exceed the upper threshold in both locations, with London dwellings at 69%.
Yohanis and Mondol (2010) *Monitoring study focusing on the 'performance gap' in IAQ in lower energy houses throughout Scotland*	Northern Ireland: n=25 households	Detached, semi-detached, terraced & bungalows – different forms of terrace not distinguished	This study did not specifically target overheating. Results show a very small proportion of dwellings with average daily temperatures exceeding 24°C but did not record the overall maximum temperatures reached.
Lomas and Kane (2013) *Monitoring study of existing dwellings focusing on winter heating temperatures*	Leicester, East Midlands, UK: n=268 existing homes	All types	Analysis of 230 free-running homes using both static and BSEN15251 adaptive criteria indicated that flats tended to be significantly warmer than other house types. Solid wall homes and detached houses tended to be significantly cooler. Temperatures in the homes were much lower than anticipated by the BSEN15251 model.

Beizaee et al. (2013) *Re-analysis of data collected in the Carbon Reduction in Buildings (CARB) study over the summer of 2007*	All 8 GO Regions of England: n=207 dwellings	All normal typologies but distinguishing purpose-built and converted flats and house conversions	Complex. Bedrooms in general are more likely to be assessed as overheating, possibly because of lower fixed-temperature criteria. Using adaptive criteria, a large proportion (~70%) of dwellings were assessed as excessively cool, being below the Category II comfort temperature for a significant proportion of the time.
Gupta and Barnfield (2014) *Data collected during study to evaluate success of Low Carbon Communities*	N=63 dwellings in North East, North West, South East, Wales GO Regions; all existing dwellings.	All normal types	In summer, for dwellings with substantially improved fabric, mean living room temperature was found to be higher (22°C), than that in dwellings with fewer fabric improvements was 21°C. Higher peak temperatures (maximum = 35°C) were found in the dwellings with more improvements than those with less (maximum = 29°C). Over 70 per cent of improved dwellings had temperatures in bedrooms higher than 26°C for more than 1 per cent of occupied hours compared to approximately 50 per cent less insulated dwellings. Similar differences were found in living rooms.
Sharpe et al. (2014) *Monitoring study to observe extent of the 'performance gap' in low-energy housing*	N=26 dwellings from north of Scotland (Inverness) to south (Lockerbie)	All normal types except detached houses; includes n=5 houses to Passivhaus standards.	24 bedrooms (94%) were found to have overnight summer average temperatures >21°C and 68% to have temperatures >23°C. There are 10 bedrooms (28%), which were found to exceed 25°C overnight.
Sameni et al. (2015) *Study focusing on overheating in flats to Passivhaus standard*	Coventry, West Midlands: varied between 5 and 11	Flats – level unstated, to Passivhaus standards, living rooms only	72% of the flats had significant risks of overheating according to the Passivhaus criteria. Similar degrees of overheating were found under '*adaptive*' criteria, though this was reduced with longer occupancy hours.
Holmes et al. (2015) Reviews heat indices to help identify indices for a potential indoor heat-safety standard	Worldwide	N/A	Analysis of heat stress indices, suggesting Wet Bulb Globe Temperature and Predictive Heat Strain as optimum measurements for indicating heat stress in occupants.
Gupta and Kapsali (2016) *Evaluating the 'as-built' performance of an eco-housing development in the UK*	N=2 dwellings located in southeast England	Code for Sustainable Homes level 4 End-terrace, mid-terrace	Overheating using the adaptive method was significantly lower than overheating prevalence using the static method. This emphasised the need to cross-relate physical monitoring data with occupant interviews, which did not reveal summertime overheating to be a major concern.
Vellei et al. (2016) *Investigating the overheating risk in refurbished social housing.*	N=46 retrofitted social housing dwellings in Exeter, UK	flats (n = 18), semi-detached (n = 17), terraced (n = 9) and detached homes (n = 2).	Nine dwellings overheated; kitchens and bedrooms most overheated.
McGill et al. (2017)	53 dwellings throughout	flats (n = 18),	High summertime temperatures; 27% of

Meta-analysis of indoor temperatures in new-build housing	the UK: Scotland (n = 20), the East Midlands (n = 11), the South East (n = 6), the South West (n = 5), Wales (n = 4), London (n = 3), Yorkshire and Humber (n = 2), and Northern Ireland (n = 2)	semi-detached (n = 15), terraced (n = 12) and detached homes (n = 8).	living rooms exceeding 28°C during August. 5% annual occupied hours > 25°C, 57% of bedrooms and 75% of living rooms were classified overheated. Overall, 30% of living rooms exceeded the adaptive comfort threshold of > 3% occupied hours $\Delta T \geq 1$ K.
Mavrogianni et al. (2017) *Inhabitant actions and summer overheating risk in London dwellings*	94 dwellings in London with widely distributed ages from pre-1900 to post-2007	flats (n = 38), semi-detached (n = 15), terraced (n = 34) and detached homes (n = 7).	Monitoring data indicated that London homes and, in particular, bedrooms are already at risk of overheating during hot spells under the current climate.

Beizaee et al. (2013) performed a similar study based on 207 dwellings across the UK. This study found that a large proportion of living rooms and bedrooms had more than 5% of their occupied hours above the CIBSE recommended temperature thresholds of 25°C and 24°C respectively. Across the regions of the UK, warmer homes were found in the South East, the East, East and West Midlands, with cooler homes in the North East, North West and Yorkshire. The oldest dwellings (pre-1919) were found to be significantly cooler than more modern homes, solid wall houses cooler than those with cavity wall construction and detached homes cooler than those of other built-form types. This study also found that dwelling temperatures in cooler UK regions were correspondingly cooler than those in warmer regions, inferring from this that a further level of adaptation, dependent on region, is required. In London, Mavrogianni et al. (2017) found that bedrooms were already at risk of overheating during hot spells under the current climate. They also found that in the 94 dwellings monitored for temperature and behaviour, around 70% of respondents tended to open only one or no windows at night, mainly due to concerns for security. The study highlighted the importance of occupant behaviour in mitigating overheating.

In Exeter, UK, Vellei et al. (2016) conducted a monitoring campaign in living rooms, kitchens and bedrooms of 46 newly-retrofitted free-running social houses. The overheating risk was evaluated using the CIBSE TM52 adaptive method. Of the nine dwellings that overheated, it was found that kitchens and bedrooms are the rooms with the greatest overheating risk among the monitored spaces. The study also explored the higher risk of exposure to older and vulnerable occupants. In contrast, both Sameni et al. (2015) & Schnieders and Hermelink (2006) evaluated a large number of newly-built Passivhaus dwellings in the UK & Germany, Austria and Switzerland respectively. The studies both found significant levels of overheating in the dwellings as per the Passivhaus overheating assessment method. In the UK (Sameni et al., 2015) two-thirds of the dwellings exceeded the overheating threshold; however they were less overheated using the adaptive standard (BSI, 2008). In the German-Austrian-Swiss study overheating was less of an issue with a temperature of 27 °C being exceeded in only 'exceptional cases'. McGill et al. (2017), reviewed the indoor temperatures in 53 newly built low-energy BPE programme dwellings to investigate the prevalence of overheating. The study found evidence of high summertime temperatures, a high prevalence of overheating in the newly built housing, and the need to provide adequate summertime ventilation provision in airtight homes. An important feature of this study like those before it (Gupta et al., 2017, Gupta et al., 2016, Gupta and Kapsali, 2016), is that it also considered both the static and adaptive methods for overheating assessment.

It is evident from the review of literature that there are limited studies which have undertaken a collective empirical analysis of the risk of summertime overheating in existing, retrofitted and newly-built homes using static and adaptive methods. This is what this study seeks to address.

3. Methods

This meta-analysis was conducted using primary datasets gathered from one large-scale monitoring study and three smaller studies. For all the studies, monitoring data were collected between 1 May and 30 September 2013 in nine different locations in the UK, ranging from Swansea in the west to Tyneside in the north and west London in the south. The large-scale study, known as EVALOC, covered 57 existing dwellings in six locations across the UK. The dwellings in these locations include a mix of existing (unchanged) and retrofitted dwellings. For EVALOC, temperature data were collected via sensors linked to a wireless network within the house, from which it was transmitted to a webserver for accumulation and download as required for analysis. In some dwellings data were also acquired by individual 'button' loggers for direct download to a PC.

The three smaller studies each consisted of two new-built dwellings and were carried out as Building Performance Evaluation (BPE) studies, being accompanied by a detailed survey of the occupant satisfaction with the dwellings and a comparison dwelling as built with the original design. Because of the higher level of air-tightness enforced by Code for Sustainable Homes, all these houses have mechanical ventilation with heat recovery (MVHR) installed to provide ventilation and prevent condensation from excess humidity. Temperature data for the BPE studies were collected every five minutes from wireless sensors transmitted to a data-hub and uploaded over Global System for Mobile Communications network to a website for acquisition. The environmental data were limited to a period of between three and nine months with some gaps in the data due to the limitations of the data loggers. Sufficient data were collected over the summer period to assess overheating.

In all the studies, external temperature and RH were also collected by the same methods for all dwellings with the exception of C3 and C8 where external temperatures had to be extracted from nearby weather stations due to equipment failures. Table 2 lists the communities of dwellings and their relevant characteristics.

Table 2. Characteristics of the study dwellings

	Location (Code)	No. of dwellings	Dates of construction	Setting
EVALOC	Community 1, South Wales (C1)	11	pre-1919, 1919-44, 1965-80, 1981-90, post-1990	Rural, elevated
	Community 2, Merseyside (C2)	12	1919-44, 1945-64, 1965-80, 1981-90	Suburban, sheltered
	Community 3, North East (C3)	10	1919-44, 1945-64, 1965-80	Suburban, sheltered
	Community 4, Oxfordshire (C4)	10	pre-1919, 1945-64, 1965-80, 1981-90	Rural, elevated
	Community 5, Yorkshire (C5)	5	pre-1919	Urban, elevated
	Community 6, Midlands (C6)	9	pre-1919, 1919-44, 1965-80, 1981-90	Urban, sheltered
BPE	Community 7, Wilts (C7)	2	new-build BPE	Urban, sheltered
	Community 8, London (C8)	2	new-build BPE	Urban, sheltered
	Community 9, Midlands (C9)	2	new-build BPE	Urban, sheltered

Overheating assessment

Research on overheating in dwellings commonly employs two different methods of assessment published by the Chartered Institution of Building Services Engineers (CIBSE). For overheating criteria in non-air-conditioned dwellings, CIBSE's Environmental Design Guide A (CIBSE, 2006) suggests that values for indoor comfort temperatures should be 25°C for living areas and 23°C for bedrooms. CIBSE notes that temperatures are expected to be lower at night with people finding that sleeping in warm conditions is difficult, particularly above 24°C.

Environmental Design Guide A provides these static benchmark summer peak temperatures and overheating criteria:

- 1% of annual occupied hours over 28°C in living rooms
- 1% of annual occupied hours over 26°C in bedrooms

For adaptive thermal comfort, the BS EN 15251 (2008) criteria were developed taking the outdoor conditions and human adaptation into account by identifying comfort limits based on a running mean of external temperature and the quality of the thermal comfort required. Based on this, the CIBSE TM52 (CIBSE, 2013) document suggests a series of criteria by which the risk of overheating can be assessed or identified. For Category II, normal expectation for new buildings and renovations, the first criterion suggests that the number of hours during which the internal temperatures are 1 K higher or equal to the upper comfort limit during the period from May to September should not exceed 3% of occupied hours. For the adaptive assessment, the 'running mean' comfort temperature range was calculated using the external temperatures acquired for each locality.

For both methods of assessing overheating, priority is given to those hours during which each room is occupied. For this study, it is assumed that living rooms are occupied between 7 am and 11 pm and bedrooms are occupied for the remaining hours from 11 pm till 7 am. One limitation of the adaptive method is that it was developed through the study and specifically for the study of non-domestic thermal comfort (Halawa and Van Hoof, 2012, BSI, 2008). The appropriateness of this method for domestic application is yet to be confirmed (McGill et al., 2017, Nicol et al., 2009). Another limitation of both methods is the question as to whether the best approach is to assess whether the current occupants of a dwelling are experiencing overheating during their hours of occupation or whether the purpose is to assess the general likeliness of the dwelling to overheat given potential for occupancy patterns or vulnerability to change. Treating only these occupied periods as significant for overheating could be considered somewhat restrictive since a considerable proportion of the population work shifts and will need to sleep during the day at times of higher outside noise levels, precluding window opening etc. Overall, to understand the outcomes of both overheating methods and to provide data for future studies that may use one or the other, both overheating methods are used to assess the data in this study.

4. Results

Regarding external temperatures, localities in the north (including urban) and those in the rural localities of the south had lower temperatures during the measured period. Those in the urban areas of the south had the highest temperatures. Overall the analysis illustrated a fairly mild climate with only short intervals of high temperatures and comparatively low minima (figure 1), which should enable householders to use night-time cooling if necessary. From cooling degree day (CDD) analysis it would appear that localities C1 and C5 had considerably warmer summers than usual, C3 and C7 somewhat warmer, C2, C8 and C9 were, more or less, as would be expected and C4 and C6 considerably cooler.

Table 3. Cooling degree days based on 15.5 °C: variation against average

	Localities								
CDD	C1	C2	C3	C4	C5	C6	C7	C8	C9
Region	Wales	North West	North East	South East	Yorkshire & Humber	South East	South West	London	South East
Recorded	194	218	216	95	380	138	321	367	367
UK 20 year average*	124	207	179	254	255	243	254	396	396
% Variation	55.8	5.3	20.9	-62.6	49.4	-43.4	26.2	-7.4	-7.4
*http://vesma.com/ddd/index.htm									

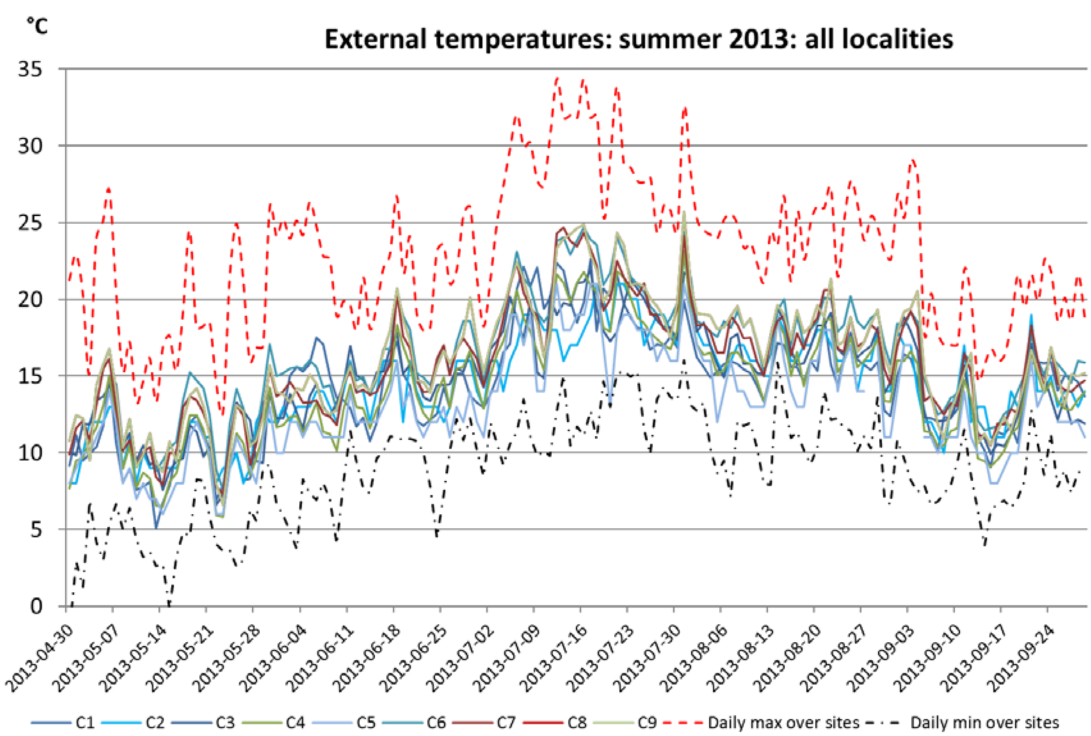

Figure 1. External temperatures: summer 2013: all localities

Overheating in bedrooms and living rooms

Overheating assessment using the static method

Though it was found that overall, 90% of the bedrooms that were measured overheated, the greatest percentage of occupied hours in most bedrooms is within the range of 22-24°C (mostly satisfying the CIBSE standard for comfort temperatures). In contrast, only 8% of living rooms were found to be overheating and the greatest percentage of occupied hours in most living rooms is within the range of 20-22°C (satisfying the CIBSE standard for comfort temperatures) (figure 2).

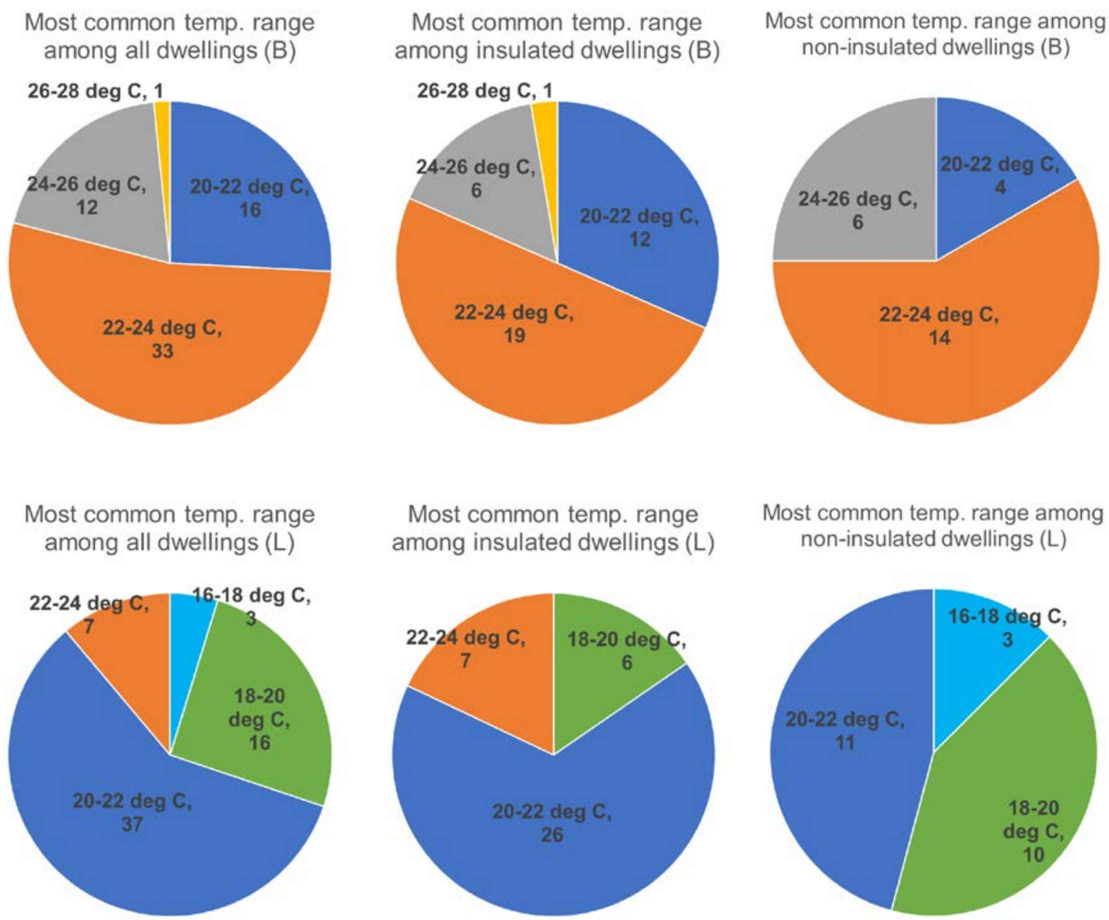

Figure 2. Most common temperature ranges in bedrooms (B) (top row) and living rooms (L) (bottom row)

The most significant result from static overheating analysis for bedrooms is that only one dwelling, C3-H06, out of 63 dwellings in the dataset, did not exceed the 26°C limit. Five dwellings out of 34 with cavity wall insulation and two out of 24 dwellings without wall insulation experienced significant periods of >30°C temperatures. Of the modern houses in the BPE studies, only one, C7-H02, maintains temperatures close to the CIBSE requirement. *Note that the dwellings in C7 were unique in that they are constructed of heavy-weight hempcrete, whereas the other BPE dwellings are light weight timber construction.* Figure 3 shows the six most overheated bedrooms in the set. In these up to 30% of occupied hours are considered overheating at 26°C and up to 10% of occupied hours are at or above 28°C. Three of the six are new build dwellings and all six are insulated. The other half of the figure shows the results in the living rooms for the respective dwellings. Two of the newly-built dwellings (C8-H02 and C9-H02) are overheating in both the bedrooms and the living rooms.

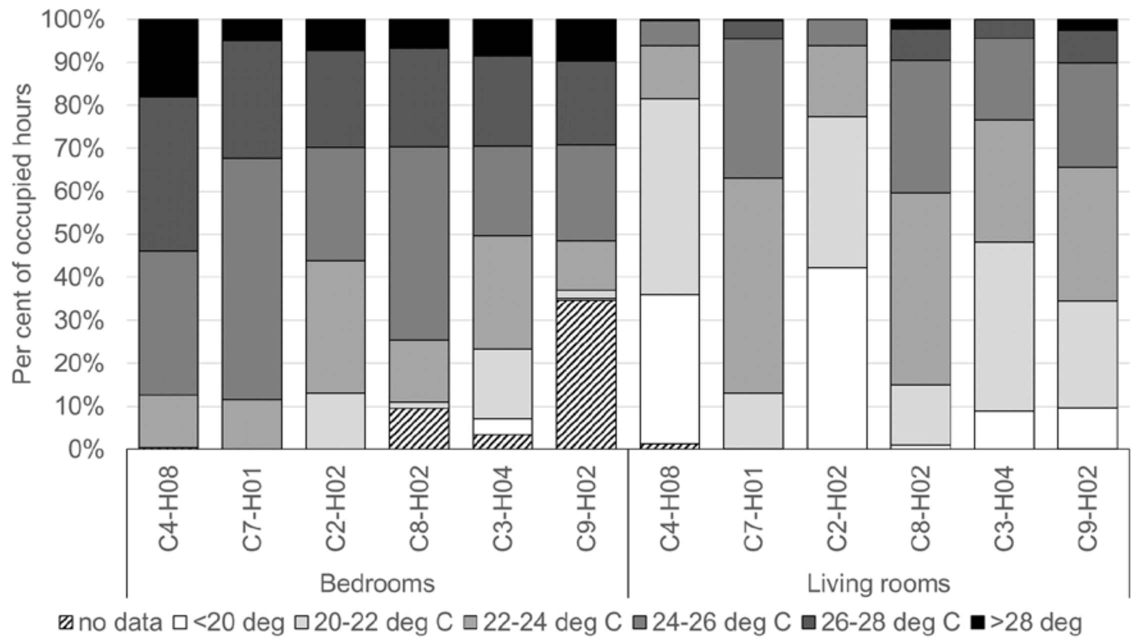

Figure 3. Six most overheated bedrooms & living room counterpart shown for comparison

In contrast to bedrooms there are considerably lower levels of overheating in the living rooms, indicated by the fact that only two houses, C4-H02 and C8-H01 were judged to experience any significant proportion of the summer period >30°C. Figure 4 shows the six most overheated living rooms in the set; incidentally the only living rooms that are overheated. Three of the six are new build dwellings and five of the six are insulated. The other half of the figure shows the results in the bedrooms for the respective dwellings. Overall, the difference in overheating between bedrooms and living rooms is so great that even when applying the overheating threshold for living rooms (1% of occupied hours over 28°C) to the bedrooms, 58% of bedrooms were still found to be overheating. These overheated dwellings are split evenly between insulated and non-insulated

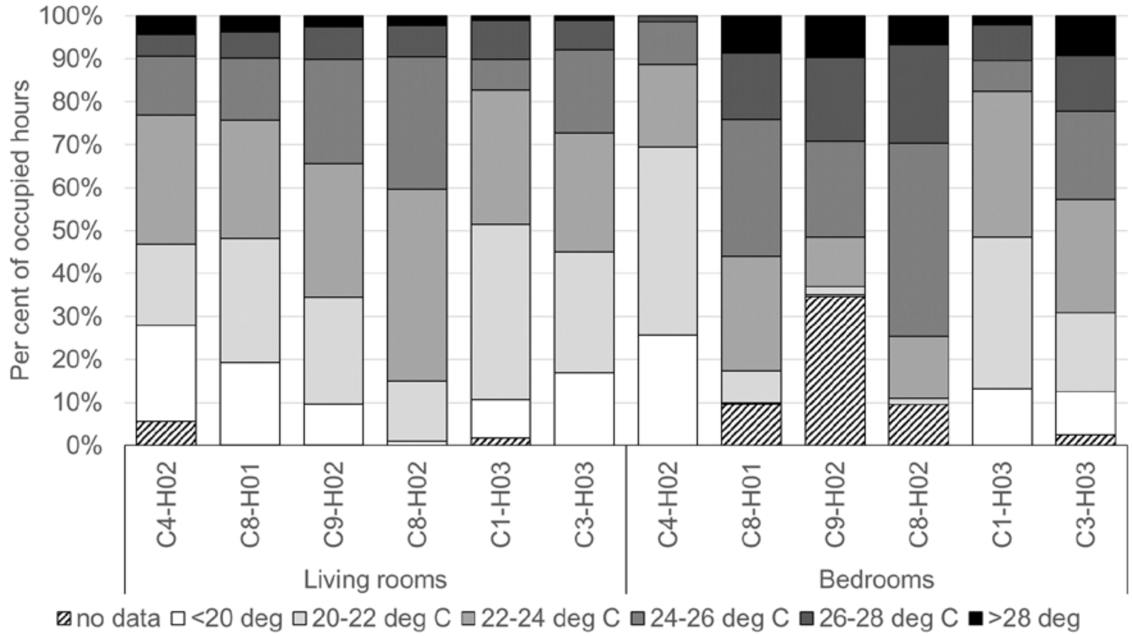

Figure 4. Six most overheated living rooms & bedroom counterpart shown for comparison

Overheating assessment using the adaptive method

Results for overheating assessment using the adaptive method indicates that far fewer houses are judged to overheat under these criteria, six out of the 34 with cavity wall insulation and three out of the 24 with no insulation; total nine. Similarly, fewer instances of overheating were found using the adaptive vs. static method in Gupta and Gregg (2017). There is also a similar lower level of overheating in living rooms according to the adaptive method, with an identical list of dwellings being identified in the cavity wall insulation category plus only one in C4-H04 in the uninsulated category. Table 4 shows all dwellings assessed in the study and their overheating results.

Table 4. All dwellings details

House ID	Wall insulation	Insulation detail	Overheating				CO_2 concentration ppm	
			Adaptive (BS EN15251)		Static (CIBSE)			
			Bedroom	Living room	Bedroom	Living room	Bedroom	Living room
C1-H01	None				>28°C			
C1-H02	None			X	>28°C			
C1-H03	None				>28°C	>28°C	>1750	>1750
C1-H04	Full fill cavity	As-built			>28°C		>2000	>2000
C1-H05	Full fill cavity	Retrofit			>28°C			>1750
C1-H06	None				>26°C			
C1-H07	None				>26°C			
C1-H08	Full fill cavity	Retrofit			>28°C			
C1-H09	Full fill cavity	Retrofit			>26°C			
C1-H10	Full fill cavity	Retrofit			>28°C			
C1-H11	Full fill cavity	Retrofit			>30°C			
C2-H01	None				>28°C			>2000
C2-H02	Full fill cavity	Retrofit			>30°C			
C2-H03	Full fill cavity	Retrofit			>28°C		>1750	
C2-H04	None				>28°C			
C2-H05	Internal (partial)	Retrofit			>28°C			
C2-H06	Full fill cavity	As-built			>30°C			
C2-H07	Full fill cavity	Retrofit			>28°C			
C2-H08	Full fill cavity	Retrofit						
C2-H09	Full fill cavity	Retrofit			>26°C			
C2-H10	Full fill cavity	Retrofit	X		>28°C			
C2-H11	Full fill cavity	Retrofit			>28°C			
C2-H12	Full fill cavity	Retrofit	X	X	>28°C			
C3-H01	Full fill cavity	Retrofit			>26°C			
C3-H02	Full fill cavity	Retrofit			>30°C			
C3-H03	Full fill cavity	Retrofit			>30°C	>28°C	>1750	>1750
C3-H04	Full fill cavity	Retrofit			>30°C		>2000	>2000
C3-H05	Full fill cavity	Retrofit			>26°C			
C3-H06	Full fill cavity	Retrofit						
C3-H07	Full fill cavity	Retrofit			>30°C			
C3-H08	Full fill cavity	Retrofit			>26°C			
C3-H09	Full fill cavity	Retrofit			>26°C			

C3-H10	Full fill cavity	Retrofit			>30°C			
C4-H01	Full fill cavity	Retrofit			>26°C			
C4-H02	Full fill cavity	Retrofit	X	X	>26°C	>30°C		
C4-H03	Full fill cavity	As-built			>26°C		>2000	>1750
C4-H04	None	Retrofit		X	>26°C			
C4-H05	Unknown		X		>26°C			
C4-H06	None				>30°C			
C4-H07	None				>28°C			
C4-H08	Full fill cavity	As-built			>30°C			
C4-H09	None		X		>28°C			
C4-H10	None				>28°C			
C5-H01	None				>28°C			
C5-H02	None				>26°C			>2000
C5-H03	None				>28°C			
C5-H04	None				>30°C			
C5-H05	None				>28°C			
C6-H01	None				>28°C			
C6-H02	None				>28°C		>2000	
C6-H03	None				>28°C			
C6-H04	External (partial)	Retrofit			>26°C			
C6-H05	None				>28°C			
C6-H06	None				>28°C			
C6-H07	Full fill cavity	As-built	X		>30°C			
C6-H08	None				>28°C			
C6-H09	None				>30°C			
C7-H01	Solid wall	As-built			>28°C			
C7-H02	Solid wall	As-built			>28°C			
C8-H01	Full fill cavity	As-built	X	X	>30°C	>30°C		
C8-H02	Full fill cavity	As-built	X	X	>30°C	>30°C		
C9-H01	Full fill cavity	As-built			>30°C			
C9-H02	Full fill cavity	As-built			>30°C	>28°C		

Adaptive overheating analysis by dwelling characteristics

For dwelling types, the variation across built form is comparatively small, apart from a small sample of flats (n=2) where overheating durations are at least twice to four times the others. For the house types, the variations do not entirely reflect what is expected from the differences in exposed outside walls. Mid-terrace houses, with the least exposed area have, as might be expected, the highest degree of overheating in as far as bedrooms are concerned. However, semi-detached houses, which would have been expected to have similar characteristics to end-terraces, are much warmer in bedrooms, but similar in living rooms; and end-terraces have the lowest values of all, at 25% of the semi-detached values. For dwelling age analysis, the most obvious group suffering from comparatively higher levels of overheating are those built between 1981 and 1990, where bedrooms exhibit twice the overheating as the next highest group and where living rooms are also significantly affected. The new-builds have highest level of overheating in living rooms. Table 5 shows the aggregated results per dwelling type, insulation and location.

Table 5. EN BS 15251 overheating assessment

	Total		% duration > EN15251 Cat II comfort limit		% duration > EN15251 Cat II comfort limit	
	n.	**%**	**All day**	**Occupied hrs.**	**All day**	**Occupied hrs.**
by House type			**Bedroom**		**Living room**	
Detached	17	27.0	0.4	0.3	0.3	0.4
End-terrace	7	11.1	0.1	0.1	0.1	0.1
Flat	2	3.2	2.5	1.2	0.6	0.6
Mid-terrace	22	34.9	0.6	0.5	0.3	0.4
Semi-detached	15	23.8	0.4	0.3	0.1	0.2
by Construction date						
Pre-1919	18	28.6	0.4	0.2	0.1	0.2
1919-44	12	19.0	0.1	0.1	0.1	0.1
1945-64	12	19.0	0.4	0.3	0.1	0.2
1965-80	9	14.3	0.8	0.3	0.3	0.3
1981-90	5	7.9	1.4	1.2	0.6	1.1
Post-1990	1	1.6	0.0	0.0	0.0	0.0
Current	6	9.5	0.7	0.8	0.7	1.2
by Insulation type						
Full fill cavity	36	57.1	0.6	0.5	0.3	0.5
None	24	38.1	0.3	0.1	0.1	0.2
by Gov Office Region						
London	2	3.2	1.9	2.3	1.1	2.2
North East	10	15.9	0.1	0.1	0.1	0.1
North West	12	19.0	0.8	0.5	0.2	0.3
South East	21	33.3	0.7	0.5	0.3	0.5
South West	2	3.2	0.0	0.0	0.1	0.1
Wales	11	17.5	0.1	0.0	0.1	0.1
Yorkshire & Humber	5	7.9	0.1	0.0	0.0	0.0
By insulation status						

As built-post 2008	6	9.5	0.7	0.8	0.7	1.2
As built-pre 2008	5	7.9	0.5	0.4	0.2	0.4
None	24	38.1	0.3	0.1	0.1	0.2
Post-2008	10	15.9	0.3	0.3	0.3	0.5
Pre-2008	16	25.4	0.6	0.4	0.2	0.2

The results of the insulation analysis show the insulated dwellings experience overheating approximately twice as frequently as those without; more dwellings with a percentage of occupied hours above comfort temperatures by the adaptive method (Figure 5). The analysis also considered whether the insulation was included in the house as-built or was the subject of a subsequent improvement, either before or after 2008 (pre-2008 insulation standards were lower). Again, dwellings with the highest standard of insulation installed as part of the build, post-2008, were assessed as experiencing the highest level of overheating and those with no insulation as the lowest.

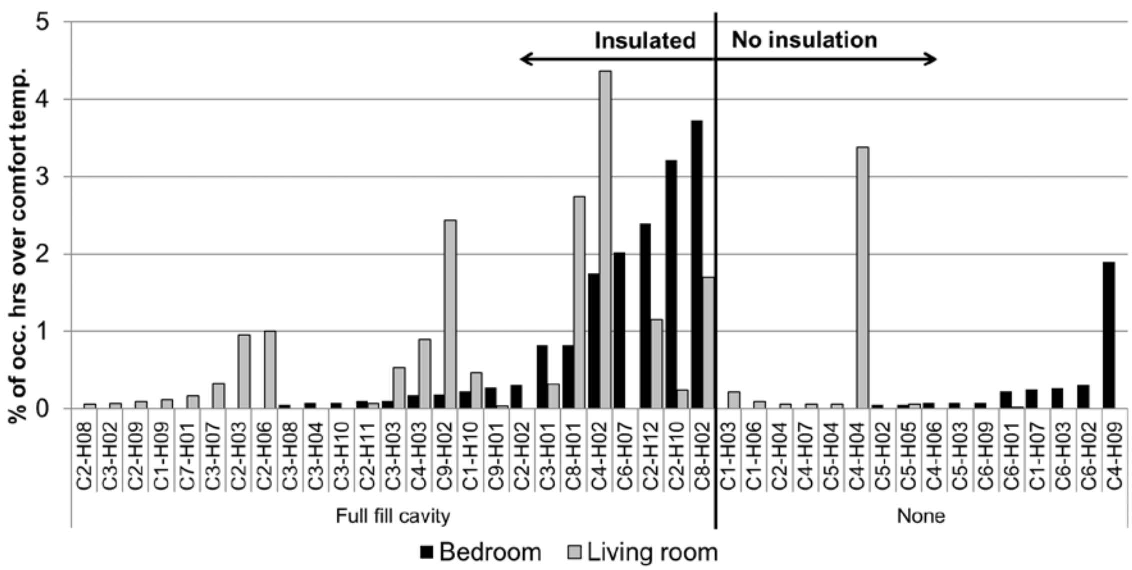

Figure 5. Percentage of hours over comfort temperature (EN BS 15251) by wall insulation. *Note: dwellings are ordered by lowest to highest percentage for bedrooms in each category; dwellings where there was no overheating in either rooms (n=21) are removed from the graph.*

The results of the analysis by UK region show little connection between the relative warmth of the 2013 summer and that of the 20-year average, since the dwellings in Wales, where 55.8% higher CDDs were experienced, were almost entirely devoid of overheating and the highest degree of overheating was experienced in London where the actual CDD showed little difference from the 20-year average.

Indoor CO_2 levels

Carbon dioxide concentrations are employed as proxies for the quality of indoor air and, hence, ventilation standards. While high concentrations in living rooms may make them stuffy and uncomfortable, poor ventilation in bedrooms is a matter of greater concern due to its effect on quality of sleep. Only dwellings in the more intensively monitored group in the main study and four out of the BPE study were monitored for CO_2. The percentage duration of concentration levels is shown in figure 6 for bedroom sensors and figure 7 for living rooms. Monitoring sensor failures are indicated by the gaps in the graphs.

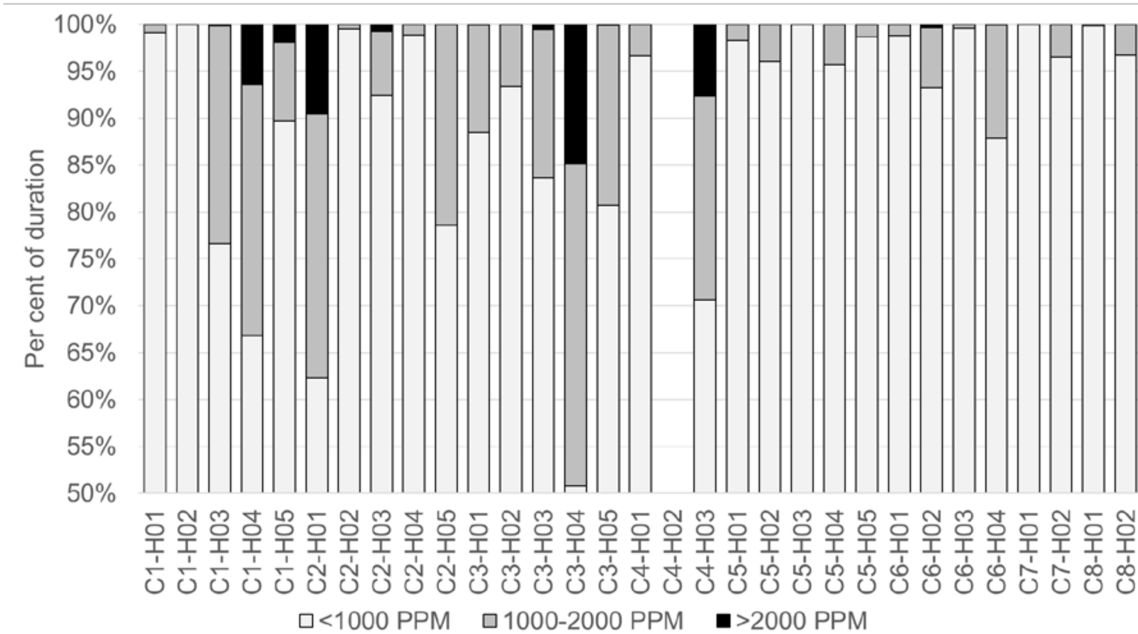

Figure 6. Carbon dioxide concentration: percentage duration: summer 2013: Bedrooms

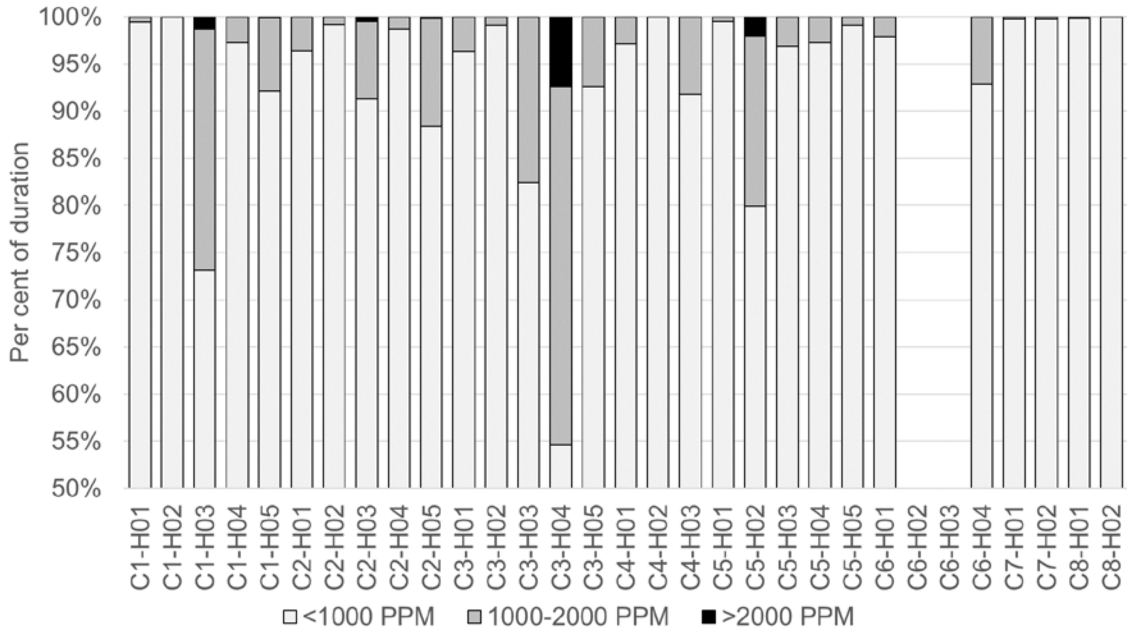

Figure 7. Carbon dioxide concentration: percentage duration: summer 2013: Living rooms

Considering that the concentration of CO_2 below 1000 ppm is an indicator of sufficient air exchanges (CIBSE, 2006), there appear to be ventilation problems in quite a few dwellings but most notable in C3-H04 (in both the bedroom and the living room). As would be expected concentrations above 1000 ppm are more common in bedrooms as they are typically smaller than living rooms. When compared with the overheating results, there seems, however, to be little correlation between the sets of dwellings, with the exception of C3-H04 also appearing in top six overheated bedrooms and C1-H03 as notably overheating in the living room and with over 25% of hours over 1000 ppm. Interestingly, quite a few of the other dwellings listed as registering the highest prevalence of overheating in figures 3 and 4, appear to have excellent ventilation, namely C2-H02, C7-H01, C4-H01, C8-H01. Similarly, there is no overlap between those dwellings judged to be overheating according to EN BS15251 and those with high CO_2 levels. Though they constitute a very small sample size, it is notable that CO_2 levels in the dwellings in the BPE studies (C7-H01, C7-H02, C8-H01, C8-H02) are all comparatively low, possibly indicating the effectiveness of the MVHR systems.

5. Discussion

Of the 63 dwellings, only two were found to have bedrooms not exceeding the recommended temperature of 26°C and 17 (27%) were found to have bedrooms exceeded 30°C. Conversely, only three (4.7%) of the living rooms exceeded 30°C, and 22 (34%) had temperatures less than 26°C. In addition, considerably higher temperatures were found in bedrooms than in living rooms. There are wide variations in temperatures between bedrooms and living rooms even in the same dwelling. Overall, it was found that about 74% (42) of bedrooms had higher maximum temperatures than the living room, with this variation being about 1.5°C, whilst, across the remaining 26% (15), the difference was about 0.5°C. It is considered that the higher bedroom temperatures are attributable to the greater exposure to solar irradiance than living rooms since these are largely located at ground floor level rather than bedrooms which are located on the first floor. Given these findings it is important to consider for new-build and retrofit opportunities that bedrooms are equipped to adaptively cool the space, e.g. daytime shading devices designed for seasonal use.

Dwellings with insulated walls appear more prone to overheating than those without, particularly those built to the most modern specifications. However, it would appear that this tendency is moderated in high thermal mass dwellings such as C7-H01 and C7-H02. The coupling of high thermal mass and progressive insulation standards would benefit from further research as a potential solution to this apparent problem which is projected to be more problematic as the climate changes.

The adaptive method assessed far fewer rooms in the dwellings as overheating compared with the fixed temperature criteria of the static method. It could be argued from these results that the adaptive method adjusts better to changes in external temperature since it will adjust the assessment of overheating to correspond to the occupants' perception. However, it is important to note that the adaptive method was designed within the non-domestic context and would benefit from a domestic counterpart as there is currently no dynamic overheating assessment method designed specifically for UK dwellings.

A *domestic* overheating method will need to be tested in all dwellings types, forms and ages since it is likely that any methods used to assess overheating will, in the future, be incorporated into UK government policy and, hence regulations affecting the design of and provision of cooling systems in, social housing, the efficacy of such methods are economically significant. If the required method over-estimates overheating and causes excessive rates of cooling system installation, this will lead to increase in initial building costs and, once such equipment is installed, it will inevitably be used, resulting in increased energy use (and costs) for cooling. If overheating is simultaneously associated with high levels of insulation, then this may lead to a reduction in insulation levels, resulting in excessive energy use for space heating. Conversely, if the method employed underestimates the extent of overheating, this is likely to result in higher levels of health problems, particularly for the elderly, with consequent cost increases for the health services, as well as the distress for the occupants.

6. Conclusion

This study, based on data collected during the summer of 2013 in nine different locations across the UK assessed the prevalence of summertime overheating in bedrooms and living rooms in existing, retrofitted and newly-built dwellings. The overheating levels in the dwellings, which were all deemed to be 'free-running', i.e. unheated during the period, were assessed using both static and adaptive thermal comfort criteria. Examined from the point of view of the occupants' health, the significance of the accurate assessment of overheating in dwellings is fairly obvious. However, its significance for the policy and practice of designing new, low-energy homes and energy-efficiency retrofit measures is more subtle. Inaccurate assessment of overheating may leave occupants with houses that are uninhabitable during the hotter days of the year, if underestimated, but if overestimated may cause the installation of many unnecessary air-conditioning units. Moreover, if the causes of overheating were to be wrongly attributed, for example, to high levels of insulation, then many opportunities for energy saving in the heating season might be lost through under-insulation. This is particularly relevant for UK social housing where standards are more rigorously applied.

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