Meta-analysis of Indoor Temperatures in New-build UK Housing

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Despite growing concerns about overheating, there is a lack of evidence regarding the scale of the problem, particularly in contemporary UK housing. This paper presents the results of a meta-analysis of indoor temperatures in selected low-energy housing. Temperature data recorded at 5 minute intervals in 60 dwellings across 19 demonstration projects (2012-2014) were collated and analysed to investigate the prevalence of overheating.

Findings evidence high summertime temperatures, with 27% of living rooms exceeding 28°C during August. Based on the CIBSE threshold of 5% annual occupied hours >25°C, 57% of bedrooms and 75% of living rooms were classified as having overheated. Overall, 30% of living rooms exceeded the adaptive comfort threshold of >3% occupied hours $\Delta T \geq 1K$.

The results suggest a fundamental relationship between ventilation and indoor temperatures. The higher minimum and average summertime temperatures observed in MVHR homes ($p<0.05$) and lower temperature range ($p<0.001$) suggest the need for greater attention to adequate summertime ventilation provision in airtight homes. The results demonstrate a high prevalence of overheating in exemplary housing, indicating the need for greater efforts to ensure the effective implementation of strategies to minimise overheating and improve ventilation in low-energy homes.

Keywords: Overheating, Ventilation, Low-energy buildings, Housing

Introduction

Over the last three decades temperatures on the surface of the Earth have risen, with future projections estimating a 4°C average global temperature increase by the turn of the century under a high emissions scenario (IPCC, 2007; Stocker et al., 2013). In the UK, central climate estimates (under a medium emissions scenario) indicate an increase of mean daily summer maximum temperatures of 5.4°C in

England and 2.8°C in northern Britain by 2080, relative to 1961-1990 baseline (Murphy et al., 2010). With this, an increase in the frequency, duration and intensity of heatwaves are expected. Given the experience of the 2003 heatwave in Europe which is estimated to have caused 2,091 excess deaths in the UK alone (Johnson et al., 2005), this is likely to have serious adverse implications on public health particularly the health of vulnerable populations. Increased mortality rates of vulnerable populations such as young children, the elderly and the immobile are of particular concern as these groups are likely to spend a significant majority of their time at home.

To address the causes of Climate Change, a substantial reduction of greenhouse gas emissions is required over the next few decades to, 'reduce climate risks in the 21st century and beyond, increase prospects for effective adaption, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development' (Pachauri et al. 2014, p.17). Efforts to reduce greenhouse gas emissions and maintain global average temperature rises below 2-3°C have resulted in significant changes to the way homes in the UK and across Europe are being designed and built (McLeod et al., 2013). On account of the large proportion of building energy use that may be attributed to space heating (Huovila et al., 2007), mitigation efforts within the construction sector have concentrated on improving the thermal performance and airtightness of building envelopes, to reduce heat loss from infiltration and thermal bridging.

Whilst improvements in thermal performance have addressed problems of heat loss in dwellings, there has been less focus on issues of unwanted heat gains and requisite ventilation in thermally robust dwellings. As explained by the Zero Carbon Hub (2010, p.7),

> *'There is some anxiety that the homes we are building today may be at risk of overheating even in the current climate. Given the prospect of significant warming, well within the expected lifetime of homes, this risk will increase with potentially serious consequences.'*

The Zero Carbon Hub is a non-profit organisation established in 2008, to take day-to-day responsibility for the achievement of the UK government's target of zero carbon homes from 2016. The hub recently undertook a comprehensive study reviewing a considerable body of knowledge relating to overheating in UK dwellings (Zero Carbon Hub, 2015a; 2015b; 2015c; 2015d; 2015e; 2015f; 2015g; 2015h). They stress that one of the most significant challenges of addressing overheating has been the lack of evidence regarding the scale of the problem in a domestic context (2015a, p.10).

Indeed much existing evidence, particularly in relation to the prevalence of overheating in energy efficient new homes, stems from small-scale demonstration projects or survey responses. As posited by AECOM (a multinational Architecture, Engineering, Consulting, Operations and Maintenance firm), in a review of the literature on overheating in homes (2012, p.4), 'The literature describing the current knowledge as to how UK dwellings modify external temperatures is dominated by modelling studies and published measured data is scarce.' Most monitoring studies of the indoor thermal environment in dwellings have focused on winter temperatures, with few exploring the range of conditions experienced during the summer season (Lomas and Kane, 2013). Also, criteria used to define overheating often vary between studies, meaning direct comparison is usually not possible (Zero Carbon Hub (ZCH), 2015a). The ZCH study suggests that, 'Future research which uses the original data from these [small scale monitoring] studies but analyses them in a consistent way would provide further insights' (p.51). The data acquired as part of the Building Performance Evaluation (BPE) programme therefore offers a rare opportunity.

The aim of this paper is to identify the prevalence of overheating in new-build energy efficient dwellings through a meta-analysis of the existing temperature data gathered as part of the Innovate UK (formerly Technology Strategy Board) BPE programme. This will be achieved by; i) Identifying the prevalence of overheating using static (Passivhaus and CIBSE) criteria and the adaptive method, ii) Exploring the relationship between overheating prevalence and building characteristics (including construction, dwelling type and region), iii) Examining seasonal temperature variations, and iv) Comparing indoor temperatures in homes with and without MVHR systems.

Background

Innovate UK Building Performance Evaluation programme

A growing body of evidence is now available to demonstrate that decarbonisation strategies aimed at the housing sector do not always achieve intended results (De Wilde, 2014). To address this performance gap between 'as designed' and 'as built', Innovate UK commissioned the BPE programme, to: i) gain real-world performance data of recently constructed buildings, ii) facilitate learning of the variables and factors that impact performance, iii) embed a culture of Building Performance Evaluation in the UK construction sector and iv), generate a knowledge base of Case Studies (Innovate UK, 2015).

This £8m programme was funded over four years to support a range of BPE studies across the UK in both domestic and non-domestic buildings, including Phase 1 studies looking at post-construction and early occupation and Phase 2 studies looking at in-use monitoring and evaluation over a 2 year period. In the Domestic programme, a total of 53 projects were funded, representing approximately 250 dwellings. Due to the nature of the programme, only projects with high sustainability credentials (Code for Sustainable Home's level 3, 4, 5, 6 or Passivhaus) were funded. All domestic projects evaluated as part of the programme were either new-build or recently constructed since 2008.

To maintain consistency, mandatory testing and evaluation requirements were outlined within the Guide for Project Execution Document[1], which provided recommendations for sensor location, accuracy (±0.5°C), resolution (0.1°C), granularity (5 minute intervals) and monitoring regime. Seasonal temperature data were available for 60 of these dwellings. Consistently-recorded temperature data over a full one year period were available for 53 living rooms and 77 bedrooms in total. To meet the criteria of the funding, all studies were required to follow specific protocols, techniques and tools for data collection to ensure consistency of the information obtained.

It is important to note that the projects included in the Building Performance Evaluation programme were not selected at random, therefore the results may not be representative of all new-build UK dwellings, but they do represent contemporary low energy design and construction strategies. The results may be further limited by the lack of information on orientation and shading,

[1] The Project Execution Document provided guidance on Building Performance Evaluation (BPE) methods and tools to the winning project teams.

and information on building occupants perceptions of overheating within the home. In addition, although a project execution guide was provided under the Building Performance Evaluation programme, measurements were undertaken independently for each project therefore sampling equipment and methodology may have varied.

Defining overheating

One of the biggest challenges of establishing the prevalence of overheating in dwellings is the current inconsistency in the field regarding what particular conditions may constitute overheating. For example, as explained by Dengel and Swainson (2012), there is at present no precise, universally accepted definition of overheating. This is supported by McLeod (2013), who suggests that the particular thresholds at which overheating leads to elevated risk to occupant health has yet to be fully explored. Despite this, numerous methods of quantifying overheating exist, comprising of both ‘fixed’ and ‘adaptive’ approaches.

The adaptive approach recognises that the temperature at which humans feel comfortable indoors varies depending on the running-mean ambient temperature (Humphreys and Nicol, 1998). The BS EN 15251 (BS EN 15251: 2007) standard defines acceptable indoor summer temperature levels using the adaptive method, in free-running buildings where occupants have the ability to regulate indoor thermal conditions through opening and closing windows. It should be noted that these temperature limits were derived by comfort studies in office buildings (BS EN 15251: 2007; Halawa and Van Hoof, 2012) and since comfort conditions have been found to differ significantly between offices and homes (Oseland, 1995), care should be taken when applying this method to a domestic context (Nicol et al., 2009).

The Passivhaus Institute define overheating in homes as temperatures exceeding 25°C for more than 10% of the year (2012). CIBSE (2015, p.5.53) refer to a fixed definition of overheating where, ‘the internal operative temperature should not exceed 25°C for more than 5% of occupied hours and 28°C for more than 1% of occupied hours.’ Operative temperature is a combination of the mean radiant temperature and air temperature, expressed as a single value (CIBSE, 2013). For air-conditioned buildings, CIBSE Guide A (2015) refers to customary summer operative temperatures of between 23°C and 25°C for bedroom and living room spaces. In CIBSE TM 36 (2005), 'warm' and 'hot' temperature thresholds of 25°C and 28°C for living rooms and 21°C and 25°C for bedrooms have been recommended. Lower temperature thresholds in bedrooms were devised since sleep quality and thermal comfort have been found to decrease at temperatures above 24°C (CIBSE, 2006; Humphreys, 1979).

A number of limitations to the use of static criteria for the definition of overheating exist. As suggested by Nicol et al. (2009), whilst the use of a fixed threshold temperature offers a method to establish the occurrence of overheating, it does not provide an indication of the severity. The use of criteria that define overheating based on the percentage of annual occupied hours exceeding a particular temperature threshold may be open to abuse, given the inherent sensitivity of the assessment method and the lack of clarity of what is meant by occupied hours (CIBSE, 2015; Nicol et al., 2009).

However, as expressed by Anderson et al. (2013), the adaptive approach to overheating may also be problematic as it assumes that building occupants can adapt or alter their indoor environment regardless of their environmental or physical circumstances. This is particularly true for sleeping persons and consequently there are no currently accepted adaptive criteria for bedrooms. BS EN 15251 defines the risk of overheating using four categories, ranging from Category I (vulnerable group) to Category IV. To gain an in-depth understanding of overheating prevalence in the monitored dwellings, both static and adaptive approaches were employed.

Overheating in energy efficient dwellings- existing evidence

Performance evaluation of demonstration projects provides the opportunity to learn from experience, avoid pitfalls and ultimately improve the effectiveness of next generation homes (Isaksson and Karlsson, 2006). Despite the importance of building performance evaluation in this regard, there still exists a lack of uptake in practice. Emerging evidence tends to suggest that, 'modern energy efficient, i.e. well insulated, airtight dwellings are suffering from overheating, and that in some cases this is resulting in adverse health effects for the occupants of these properties' (Dengel and Swainson, 2012; p.19). However, without the necessary evidence base to support this, there remains a lack of concerted action to address the risk of overheating in modern airtight homes. As identified in a report commissioned by the Department of Communities and Local Government (AECOM, 2012; p.2), three main questions require addressing: i) Whether overheating is occurring in new dwellings as a result of higher insulation standards and improved airtightness, ii) Whether overheating is occurring in existing dwellings, and iii) Whether retrofitting/refurbishing existing dwellings is likely to increase the risk of overheating or not.

Table 1 presents a summary of existing research that has examined the prevalence of overheating based on physical monitoring in energy efficient European dwellings. Whilst it is clear that some evidence is available, these findings are generally limited to small scale projects using varying methods of defining overheating; indicating that much more work is needed in this area. Sameni et al. (2015) for example, present the results of an investigation of indoor temperatures monitored in 23 social homes in Coventry (UK) constructed to the German Passivhaus standard. They identified significant incidences of overheating, with two thirds of dwellings exceeding the Passivhaus overheating criteria during the summer season. These findings are supported by the results of monitoring studies in Passivhaus certified housing projects in Denmark (Larsen et al., 2012; Larsen and Jensen, 2011) and Wales (Ridley et al., 2014). In Finland however, summer monitoring of 9 low energy dwellings found generally satisfactory temperatures indoors. It should be noted that these homes were equipped with permanent external shading and a cooling system to limit the risk of overheating (Kähkönen et al., 2015).

(Insert Table 1 here)

In Cheshire, monitoring of 4x airtight masonry dwellings by Wingfield et al. (2008) identified mean indoor temperatures of 25°C during the month of July, with peak temperatures exceeding 30°C in some cases. Monitoring of indoor temperature levels in 15 low energy dwellings constructed in the late 1980s in Milton Keynes found that the bedroom and living room temperatures were consistently above external temperatures throughout the year, which may have resulted in overheating during the summer months (Summerfield et al., 2007).

Evidence of overheating of the general UK housing stock has also been observed. In a study by Lomas and Kane (2013), measurements of internal summertime temperatures in 268 typical dwellings in Leicester found approximately 15% of bedrooms exceeded the recommended maximum of 26°C for more than 30% of summer night time hours, during a generally cool summer. Furthermore, an analysis of adaptive thermal comfort methods found that occupants tended not to apply these in practice to achieve comfortable temperatures as anticipated by the BS EN 15251 standard (albeit at low temperatures), which suggests more work may be required to examine the applicability of this standard in a domestic context. In a national survey of overheating risk in 207 English homes, Beizaee et al. (2013) found 21% of bedrooms exceeded the recommended maximum temperature of 26°C for more than 5% of night time hours, with bedrooms of modern homes significantly warmer. They conclude, 'The incidence of warm bedrooms in modern homes, even during a cool summer, is of concern, especially as there is a strong trend towards even better insulation standards in new homes and the energy-efficient retrofitting of existing homes' (Beizaee et al., 2013; p. 1).

Based on the results of a survey of end-users experiences in nearly zero-energy dwellings in the Netherlands where 49% of respondents stated that they found the bedroom too hot in summer, Mlecnik and colleagues (2012) call for improvements to summer comfort conditions in future nearly-zero energy homes. This is supported by the results of similar surveys relating to energy efficient dwellings, with concerns of summertime overheating expressed by both building occupants (Behar and Chiu, 2013; Holopainen et al., 2015; Knudsen et al., 2012; Kotol, 2012; Yakubu, 1996) and building professionals (Davis and Harvey, 2008; Gul et al., 2012). Evidence suggests occupants of low energy dwellings are often more comfortable during the winter season compared to summer (McGill et al., 2015; Mlecnik et al., 2012; Schnieders and Hermelink, 2006).

An evaluation of occupants' experiences of low energy and conventional dwellings in Sweden found that when indoor summer temperatures exceeded comfortable levels, occupants considered or even used supplemental cooling to achieve thermal comfort (Zalejska-Jonsson, 2012). In one low energy housing project evaluated, over 35% of respondents stated that they used supplementary cooling almost every day during summer. These findings are concerning as this would suggest an increased energy demand, which highlights the need for further investigation of summertime temperature levels in low energy homes.

A large number of studies have explored the risk of overheating in UK homes using building simulation tools, to examine future climate scenarios and evaluate the potential impact of mitigation strategies, input data, occupant behaviour, building characteristics and adaption strategies (Jenkins et al., 2013; Mavrogianni et al., 2012; Mavrogianni et al., 2014; Peacock et al., 2010; Porritt et al., 2012; Taylor et al., 2014; Vardoulakis et al., 2015; Williams et al., 2013). Whilst building simulation can be very useful, there is a pressing need to identify the prevalence of overheating from live data, to ensure the protection of occupant health and wellbeing, to provide real world evidence and to support the call for concerted action from policy makers and the UK construction industry as a whole.

Methods

Data collection

Temperature data was acquired from the BPE Phase 2 domestic projects through use of the online central data repository, EMBED (www.getembed.com). Monitoring of Phase 2 projects typically spanned a two year period (2012-2014), during which time monitoring equipment was installed in the dwellings to collect data at 5 minute intervals, in accordance with the BPE programme protocol. Recorded data was uploaded to the open data repository. Cleaning of the data was performed within the EMBED platform, where data greater than two standard deviations from the median was classified as 'in error' and was not used in the calculations. Data checking was then carried out by filtering the data to identify any major discrepancies or sensor failures.

The programme protocol required monitoring of the main living area and main bedroom in each home, accompanied by a series of other sensors and meters to measure energy performance and indoor environmental quality. In practice, consistently-recorded temperature data were not available for all projects, and since monitoring was undertaken at different times for each project, the dataset is quite diverse. Nevertheless, it represents a substantial body of information from which important insights can be gathered.

The dwellings included in this study represent a variety of housing types, including flats (n=18), semi-detached (n=15), terraced (n=12) and detached homes (n=8). Tenure types included social rent (n=21), mixed (n=14), private (n=12), shared ownership (n=3) and leasehold (n=3). The majority of dwellings were of timber frame construction (n=33), followed by masonry (n=10), concrete (n=4), SIPs (n=4) and steel frame (n=2). Airtightness levels were generally low, ranging from 0.26-9.10 $m^3/h/m^2$ @50 Pa, with a mean of 3.4 $m^3/h/m^2$ @50 Pa (SD = 2.1). Occupancy density ranged from 18 to 173 m^3 floor area per person, with a mean of 43 (SD = 26). Dwellings were located in Scotland (n=20), East Midlands (n=11), South East (n=6), South West (n=5), Wales (n=4), London (n=3), Yorkshire and Humber (n=2) and Northern Ireland (n=2).

(insert figure 1)

<u>Data analysis</u>

Exceedance of the Passivhaus and CIBSE thresholds (annual occupied hours) and adaptive comfort criteria were calculated from the raw data downloaded from the EMBED site and analysed using Excel. Following data exclusion (four homes), 53 households were found to have consistent and reliable data. Occupied hours were based on assumptions from previous studies (Beizaee et al., 2013; Sharpe et al., 2014b; Wright et al., 2005) for bedrooms 23:00-07:00 h and 07:00-23:00 h for living room spaces. Statistical analysis was performed using SPSS (version 22). Prior to analysis data distributions were checked for normality and outliers. Mann-Whitney U tests, Kruskal-Wallis, Student's t-tests and Chi-square tests were used to examine differences between groups and across variables.

Analysis of the data to evaluate seasonal conditions was performed using the descriptive statistics generated within the EMBED platform. This was limited to three months during 2013, representative of winter, spring and summer conditions (February, April and August). Only datasets that were complete for each month were included in the analysis.

To identify the prevalence of overheating using the adaptive comfort approach, historic weather data from near-by airports were used for each site to calculate the exponentially weighted outdoor running mean temperature from 1st May to 30th September 2013, using the following equations:

$$T_{rm} = (T_{od-1} + 0.8\,T_{od-2} + 0.6\,T_{od-3} + 0.5\,T_{od-4} + 0.4\,T_{od-5} + 0.3\,T_{od-6} + 0.2\,T_{od-7}) / 3.8 \quad (1)$$

$$T_{rm} = (1-\alpha)\, T_{od-1} + \alpha\, T_{rm-1} \tag{2}$$

Where:

T_{od-1} = Daily mean external temperature for previous day

T_{od-2} = Daily mean external temperature for the day before, and so on

T_{rm-1} = Exponentially weighted running mean from the previous day

α = 0.8

BS EN 15251 defines overheating according to the temperature difference (Δ*T)* between the actual operative temperature and the maximum acceptable temperature, which is rounded to the nearest whole degree (K value). CIBSE TM 52 (2013) suggests the following maximum acceptable temperature ranges depending on four categories, as described below. For the purpose of this study, overheating was defined using Category II for normal expectation for new buildings and renovations.

<u>Category I (High level of expectation for spaces occupied by very sensitive and fragile persons)</u>

upper limit T_{max} (°C) = 0.33 T_{rm} + 18.8 + 2

lower limit T_{max} (°C) = 0.33 T_{rm} + 18.8 - 2

<u>Category II (Normal expectation for new buildings and renovations)</u>

upper limit T_{max} (°C) = 0.33 T_{rm} + 18.8 + 3

lower limit T_{max} (°C) = 0.33 T_{rm} + 18.8 – 3

<u>Category III (A moderate expectation used for existing buildings)</u>

upper limit T_{max} (°C) = 0.33 T_{rm} + 18.8 + 4

lower limit T_{max} (°C) = 0.33 T_{rm} + 18.8 – 4

<u>Category IV (Value outside the criteria- only acceptable for limited periods)</u>

upper limit T_{max} (°C) = 0.33 T_{rm} + 18.8 + 5

lower limit T_{max} (°C) = 0.33 T_{rm} + 18.8 – 5

The adaptive method classes a building or room as overheating if it fails any two of the following three criteria:

i) Criterion 1

The first criteria refers to the number of hours (H_e) during which the temperature difference between operative temperature and maximum acceptable temperature (ΔT) is greater than or equal to one degree (K), and states that this should not be more than 3 per cent of occupied hours between 1st May to 30th September.

ii) Criterion 2

Criterion two addresses the severity of overheating within any one day. To meet this criterion, the daily limit for weighted exceedance (W_e) during occupied hours should be less than or equal to 6. The daily weighted exceedance is calculated using the following equations:

$$W_e = (\sum h_e) \times WF \quad (3)$$

$$W_e = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) + (h_{e4} \times 4) \quad (4)$$

Where:

$WF = \Delta T$ ($If\ \Delta T \leq 0, WF = 0$)

h_{ey} = the period of time (h) when $WF = y$

The guideline value for the weighted exceedance (W_e) of 6, as described in CIBSE TM52, is based on a room with an occupancy of 8 hours. This is in line with the assumed occupancy in bedrooms (23:00-07:00), however may need adjusted for living rooms with higher hours of occupancy (Sameni et al., 2015). For this reason, a weighted exceedance level of 12 was used for living rooms, which is proportional to the increased assumed occupancy of 16 hours (07:00-23:00), in comparison to the standard assumed occupancy of 8 hours.

iii) Criterion 3

The final criterion sets an absolute maximum temperature difference (ΔT) of 4 degrees (K), above which normal adaptive measures are expected to be insufficient to restore occupant comfort.

Results

Prevalence of overheating using Passivhaus and CIBSE criteria

Figure 2 shows the percentage of hours temperatures exceeded the CIBSE and Passivhaus overheating threshold of 25°C. This is revealing in many ways. First, it is evident that a large proportion of monitored bedrooms (57%) and living rooms (75%) exceeded the CIBSE overheating threshold of 5% annual 'occupied' hours >25°C. Correspondingly, the Passivhaus overheating threshold of 10% annual hours >25°C was exceeded in 38% of bedrooms and 58% of living rooms respectively.

(insert figure 2a here)

(insert figure 2b here)

Using the CIBSE threshold of 1% of annual occupied hours exceeding 28°C (see figure 3b), 25% of living rooms were found to be overheating. This prevalence was higher for living rooms of lightweight construction (32%, n=37), compared to heavyweight construction (6%, n=16). 62% of bedrooms were classified as overheating, based on the CIBSE threshold of 1% annual occupied hours exceeding 26°C (figure 3a).

(insert figure 3a here)

(insert figure 3b here)

In some homes (such as H11_a), bedroom or living room temperatures exceeded 25°C for more than 50% of annual occupied hours, indicating significant problems with overheating. Figure 4 illustrates the temperature traces of this home during the month of August.

(insert figure 4 here)

The prevalence of living room and bedroom overheating relative to the building characteristics is presented in Table 2. There were no significant differences in living room overheating prevalence across dwelling type, Passivhaus certification, ventilation type, or region; however there were significant differences across construction type regarding the prevalence of overheating based on the percentage of annual occupied hours exceeding 25°C ($p= 0.026$) and 28°C ($p=0.029$).

Unlike the results of previous studies (Lomas and Kane, 2013; Beizaee et al., 2013), a tendency towards overheating in flats was not observed, based on the Passivhaus and CIBSE thresholds. Of the Passivhaus certified dwellings monitored, 38% of bedrooms and 53% of living rooms exceeded the Passivhaus threshold for overheating (see figure 2).

(insert table 2 here)

Seasonal temperature variation

Analysis of August temperature data revealed widespread problems with summertime overheating. Specifically, average temperatures during August exceeded 25°C in 27% of living rooms and 20% of bedrooms monitored. In 6% of living rooms monitored, August temperatures remained consistently above 25°C. Peak August temperatures exceeded 28°C in 27% of living rooms and 18% of bedrooms. Incidences of overheating however were not limited to the summer season, with temperatures exceeding 28°C in 15% of living rooms during February and 21% of living rooms during April. It is interesting to note that despite the majority of dwellings demonstrating temperature distinctions between seasons, some dwellings appeared to maintain consistently high temperatures year round, with average February and/or April temperatures exceeding August temperatures in some cases (see figure 5).

(insert figure 5 here)

Overall, mean living room temperatures were lowest in February (21.6°C) and highest in August (24.0°C). It is important to note that there did not appear to be a considerable temperature difference between living rooms and bedrooms during February, April or August months, suggesting homogeneous conditions throughout the home (see Table 3).

For the sample as a whole, there were no significant differences in living room temperature across dwelling type. However, within the MVHR group, there were significant differences observed in temperature by dwelling type for February (maximum p=0.048, range p=0.025) and August (minimum p=0.004, mean p=0.013, range p=0.025). The trend was as expected, with the highest August minimum and mean temperatures in flats, followed by terraced, semi-detached and detached homes. For the non-MVHR group, significant differences were observed in temperature across dwelling type for February and August range (p=0.025).

A comparison between lightweight (timber and SIPS) and heavyweight (concrete, steel and masonry) construction found significant differences in living room temperatures during February (max p=0.001, mean p=0.019, range p=<0.000), April (max p=<0.000, mean p=0.028, range p=0.002), and August (minimum p=0.002, range p<0.000). However, all monitored homes in Scotland and Northern Ireland were of timber frame construction, which is likely to have had a significant impact on the results.

For region, there was a decrease in maximum temperature depending on latitude (northern regions with highest maximum temperatures), which was most pronounced during February and April months. Dividing the regions between North (Scotland, Northern Ireland) and South (Yorkshire & Humber, East Midlands, Wales, London, South East and South West), higher mean and range of temperatures during February, April and August were found in Northern homes (p<0.01), however this may be a consequence of construction type (since all homes in the North were of timber frame construction), rather than location.

Indoor temperatures in homes with and without MVHR

Statistical analysis of the temperature data revealed a number of important differences between homes with and without Mechanical Ventilation with Heat Recovery (MVHR) systems. First, average temperatures were significantly higher in dwellings without MVHR systems during February (living room p <0.05) and April (living room p<0.001, bedrooms p<0.05), however higher in homes with MVHR systems during August (bedroom 1 p<0.05) - see Table 3. Peak temperatures were significantly higher in Non-MVHR homes compared to MVHR homes, with this trend most notable in living rooms during February ($p<0.001$) and April ($p<0.001$). It is important to note however that there was a higher proportion of Non-MVHR dwellings located in Scotland, which may have influenced the results (see table 4).

(insert table 3)

(insert table 4)

The range of temperatures observed in each home indicates a tendency for homes with MVHR systems to have greater temperature stability. This was evident during all seasons, however was most significant during April (living room and bedroom 1 $p<0.001$, bedroom 2 $p<0.05$) and August (living room $p<0.001$, bedrooms $p<0.01$), see for example, figure 6. Minimum temperatures were significantly higher in homes with MVHR systems during August (living room $p<0.001$, bedrooms $p<0.05$) and April (living room $p<0.001$), however no significant difference was observed during the month of February.

(insert figure 6)

Average hourly temperature profile

Average hourly temperature profiles for the month of August (2013) for MVHR and Non-MVHR dwellings revealed interesting insights regarding the time of day overheating occurred in bedroom and living room spaces and the relationship between ventilation strategy and indoor temperatures (see Figure 7a and 7b). Importantly, a clear distinction can be made between the average hourly temperature profiles of homes ventilated with MVHR systems compared to those without MVHR, with the latter demonstrating higher hourly temperatures during the month of August. This distinction was most evident between the hours of 08:00 and 13:00, and was more pronounced in the living room in comparison to the bedroom.

(insert figure 7a)

(insert figure 7b)

Overall, August temperatures were generally lowest around 07:00-09:00, with the majority of peak temperatures occurring between 17:00-18:00. The variation in average temperatures throughout the day appeared much greater in living rooms compared to bedrooms.

Adaptive method

Figure 8 illustrates the percentage of occupied hours living room temperatures exceeded the adaptive comfort upper limit from the 1st May to the 30th September 2013. Overall, 30% of living rooms exceeded the adaptive comfort overheating threshold (criterion one) of 3 per cent of occupied hours with a temperature difference (ΔT) greater than one degree K. In addition, 20% of living rooms (n=9) failed criterion three, where temperatures exceeded the adaptive comfort absolute maximum temperature difference of 4 degrees (K) during this period.

(insert figure 8)

The daily weighted exceedance values between the 1st of May and the 30th of September 2013 are presented in figure 9. Overall, 49% of living rooms exceeded the daily weighted exceedance guideline level of 12 at least once during the summer monitoring period.

(insert figure 9)

Discussion

This study set out with the aim of identifying the prevalence of overheating in new-build energy efficient dwellings using temperature data acquired as part of the Innovate UK BPE programme. Whilst it is clear that overheating is a recognised issue in terms of comfort in modern airtight housing (Holopainen et al., 2015; Knudsen et al., 2012; Mlecnik et al., 2012; Rohdin et al., 2014), there is a lack of physical evidence regarding its prevalence. This data therefore provides an evidential basis for this.

Analysis of the prevalence of overheating based on the CIBSE and Passivhaus criteria found that a significant proportion of the homes were overheating in practice; which is in agreement with the findings of previous studies (as outlined in Table 1) and with the findings using the adaptive model. It should be noted however that less homes were categorised as overheating using the adaptive method compared to static methods (see table 5). This however may be attributed in part to differences between the time period under examination; specifically annual occupied hours for the Passivhaus and CIBSE criteria compared to summertime occupied hours (between May and September) for the adaptive model.

(insert table 5)

Whilst the homes in this study were not selected at random and may not be representative of all new-build energy efficient housing in the UK, they do represent emerging standards and methods of construction and therefore provide a useful insight into the potential risk of overheating in exemplary housing. In particular, the high prevalence of overheating in Passivhaus certified dwellings highlights the need for further examination of the causes of overheating in a residential context in the UK.

A key issue however relates to the way in which overheating is defined. Although this study used recognised definitions of overheating, the lack of measured occupancy data was a particular limitation. The potential variability between actual and estimated occupied hours may be more significant in living rooms compared to bedrooms. In bedrooms, it can be reasonably assumed that the room may be occupied between the hours of 23:00-07:00. In living rooms however, occupancy will depend on a multitude of factors that may be difficult to predict in practice and will vary in any case.

While temperatures were generally higher in living rooms, bedrooms may be considered at greater risk given the limited adaption of occupants while asleep, the inherent nature, intensity and duration of exposure and the potential implication on sleep quality (Okamoto-Mizuno and Mizuno, 2012). For this reason, the use of adaptive criteria for bedrooms is not recommended.

The occurrence of overheating during February and April months indicates that the problem is not entirely due to external temperature and solar gains, but is also a problem of internal gains (either active heating or passive incidental gains); or an inability to reduce heat (insufficient ventilation provision, or lack of use of such provision). The lack of temperature distinction between seasons apparent in some homes supports this premise and demonstrates a potential energy component of overheating in modern housing. This may be attributed to a number of factors associated with energy efficient housing, including; greater occupant expectations (Herring and Roy, 2007; Howden-Chapman et al., 2007), improved fabric performance (with no subsequent change in heating behaviour), oversized and/or poor control of heating systems (Liao et al., 2005) and low ventilation rates in practice (Sharpe et al., 2014a; Sullivan et al., 2013).

Similarly, the lack of temperature distinction between living rooms and bedrooms indicates a trend towards homogeneous temperature conditions (or thermal monotony (Chappells and Shove, 2005)) within the home environment. This has implications for building modelling, especially Standard Assessment Methodology (SAP) models for energy rating of new homes in the UK, which assume design temperatures of 21°C for living rooms and 18°C for the rest of the home (DECC, 2012). In the homes with MVHR systems, homogeneous indoor conditions may be attributed to the 'whole house' ventilation concept, however this tendency was also observed in Non-MVHR homes.

The high average and peak temperatures observed during August in both living rooms and bedrooms indicate a significant issue with summertime overheating. It is important to note that analysis of seasonal variation was carried out for the whole month (i.e. not occupied hours only), therefore is likely to include periods of time where the rooms were unoccupied.

A key finding to emerge from the study was the observed relationship between indoor temperature conditions and ventilation methods. The significantly higher average and peak temperatures observed in Non-MVHR homes during February and April months may be explained by lower levels of ventilation, indicated through higher levels of carbon dioxide in these homes (Sharpe et al., 2016).

During August however, mean temperatures were significantly higher in homes with MVHR systems (bedroom 1). An examination of average hourly temperatures during the month of August found consistently higher temperatures in MVHR homes compared to Non-MVHR homes, particularly between the hours of 08:00 and 13:00. Higher August temperatures in MVHR homes may be attributed to a lack of a summer by-pass mode in some MVHR units, or the deactivation of MVHR systems by building occupants during summer; resulting in naturally ventilated houses (through intermittent window opening), without any provision for background ventilation. Likewise, the higher levels of airtightness expected in MVHR homes may also have influenced the results.

There are however a number of caveats to be considered when interpreting these results. Firstly, the majority of Non-MVHR homes were located in Scotland, while a higher proportion of MVHR homes were located in the south (East Midlands). Similarly, the sample sizes between MVHR and Non-MVHR homes were not even and there were a greater proportion of dwellings of timber frame construction within the sample as a whole.

However, while previous work has evidenced problems with ventilation and indoor air quality in modern homes (Crump et al., 2009; Howieson et al., 2013; Sullivan et al., 2013), overheating is often a component of this. In some instances, heat reduction through ventilation is a low-cost activity (for example, summer ventilation of solar gain, or night-time ventilation under 'free-running' mode (Ucci et al., 2011), however during the heating season, venting of incidental gains from energy sources (space and water heating, electrical items) will likely incur an energy penalty.

What was clear was the tendency for homes with MVHR systems to have greater temperature stability, particularly during April and August. This, in combination with significantly higher minimum temperatures observed in homes with MVHR systems (during April and August) may be of significant concern in situations where occupants are exposed to consistently high temperatures indoors. Moreover, although greater stability of internal temperatures may be perceived as beneficial during the heating season, a growing body of research suggests that variable indoor temperatures may in fact, be beneficial for health (van der Lans et al., 2013; van Marken Lichtenbelt, 2015; Wijers et al., 2009). Indeed, the drive towards the achievement of 'neutral' indoor environments may be perceived as an irrational and senseless goal. As suggested by Brager and de Dear (2003, p.178),

> '*the simple goal of creating 'thermal neutrality' in buildings hinders the possibility of creating indoor environments that are richer in their experiential qualities than neutrality, and that have the ability to provide valuable sensory stimulation'*.

Conclusions

The study identifies that, by generally accepted measures, overheating is common within these building types. Overall, 58% of living rooms and 38% of bedrooms recorded temperatures greater than 25°C for more than 10% of the year. Whilst the sample of housing in the study is not statistically representative, the dwellings do represent a large number of case studies of contemporary housing, and the nature of overheating is therefore a cause for concern. Overheating, particularly outwith the summer, may also be an important component of the performance gap for energy use that is emerging in contemporary housing.

The nature and scale of the causes are less clear. In any case, there are likely to be a number of possible causes, but the nature of overheating across different geographical locations and seasons suggests that this is not just a function of external conditions. Whilst there are a range of possible causes, the need for ventilation to act as a mitigating factor is clear and it would appear that there is insufficient provision.

The high prevalence of overheating supports the need for concerted action to address the risk of overheating in modern energy efficient homes. While there is some indication of changes in acceptable comfort or high comfort expectations (evidenced through high mean temperatures during the heating season), this will incur an energy penalty and is likely to contribute to discrepancies between 'as designed' and 'as built' energy performance. Likewise, high incidences of overheating during the summer season are likely to increase energy expenditure through a greater demand for air-conditioning.

The intrinsic relationship observed between indoor temperature conditions and ventilation demonstrates the fundamental importance of internal gains (such as appliances and hot water systems) in homes built to increasingly high levels of insulation and airtightness. This also supports the need for alternative ventilation solutions during the summer season in homes with MVHR systems to ensure adequate provision of background ventilation (where systems may be disabled) and effective purge ventilation for peak lopping. This should be addressed in future revisions of Approved Document Part F of UK Building Regulations.

Moreover, the risks of overheating and mitigating measures need to be better addressed in design. Most design tools are predicated on reductions of energy consumption, and provide no guidance on overheating and ventilation for IAQ. Even more detailed tools such as Passivhaus Planning Package (PHPP) need to take cognisance of UK house standards, and consequences of incidental gains.

Further work is needed to establish a consistent and validated method of determining the prevalence of overheating in a domestic context, based on conclusive evidence of the impact of exposure to high indoor temperatures on health; as opposed to a primary focus on comfort. Similarly, there remains a need to establish the effect on the hygroscopic environment, where high temperatures have the potential to mask high indoor moisture content through low observed relative humidity levels. This may be particularly problematic during rapid cooling. Finally, work is required to establish the impact of high indoor temperatures on the building fabric (such as drying, shrinkage and airtightness) in new-build energy efficient housing.

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Table 1. Prevalence of overheating from monitoring studies of low energy dwellings in Europe

Country	Dwelling description	Monitoring period/location	Summary of findings	Source
Skibet, Denmark	10x Passivhaus	Oct 2008- 2010 in four locations	July 2009- temperatures exceeded 26°C for 40% of time, increasing to 60% during July 2010. Overheating defined by criteria set out in DS/CEN/CR1752	(Larsen and Jensen, 2011)
Wales, UK	2x Passivhaus, detached	May 2012- April 2014- living rooms and bedrooms	Summer bedroom temperatures exceeded 26°C for 8.4% (dwelling 1) and 6.6% (dwelling 2) of time. Bedroom and living room temperatures failed PHPP overheating criteria (25°C >10%) in both homes. Overheating defined by CIBSE (2006), PHPP & BS EN 15251:2007	(Ridley et al., 2014)
Coventry, UK	23x Passivhaus units, (18x flats, 5x terraced)	Aug- Sept 2011, July- Aug 2012, May- Aug 2013, living rooms only	More than two thirds of flats exceeded Passivhaus overheating criteria. Using adaptive thermal comfort model, prevalence of overheating was lower for normal occupants but higher for vulnerable occupants. Overheating defined by adaptive model BS EN 15251 & PHPP.	(Sameni et al., 2015)
Finland	7x low-energy dwellings, 2x low energy flats	June 2012- Sept 2013, living room, bedroom and outside	Summer (June – Aug 2013) mean air temperatures between 21.9- 23.8°C recorded. Peak temperatures ranged from 23.9°C to 26.4°C. The low energy dwellings however were equipped with permanent external solar shading and a cooling system (heat pump/ circulation of cooling liquid in the ground).	(Kähkönen et al. 2015)
Milton Keynes, UK	15 'low energy' dwellings (built late 1980s)	Feb 2005- July 2006, living rooms and bedrooms	Monitored bedroom and living room temperatures were maintained above outside temperatures throughout the year, which may have resulted in overheating during the summer season. Peak temperature data not available.	(Summerfield et al. 2007)
Cheshire, UK	4x airtight masonry dwellings	July-Aug 2006, 5 different locations	Mean internal temperatures of approximately 25°C reported in all four dwellings during the month of July. However peak internal temperatures exceeded 30°C in monitored dwellings.	(Wingfield et al. 2008)
Pays-de-la-Loire, France	2x energy efficient detached dwellings	June 2009- Jan 2012, bedroom and kitchen/ living room	During August 2010, kitchen/living room temperatures exceeded 27°C for 54% of the time in House B and 31% in House E. Similarly, during August 2011 and 2012, House B exceeded 27°C for 21% and 41% of the time.	(Derbez et al. 2014)
South-East England	6x low-carbon housing, terraced/ detached	Jan- Dec 2013, living room and bedrooms	Summer living room temperatures in 4 out of 6 dwellings exceeded the CIBSE overheating criteria of >28°C for more than 1% occupied hours. Bedroom temperatures exceeded 26°C for more than 1% of occupied hours in all six dwellings.	Gupta and Kapsali, 2016
Three sites in Germany, Austria and Switzerland	>100 dwellings built to Passivhaus standard	May-Aug 2001, average house specific temperatures reported	Results from the CEPHEUS project found mean summer indoor temperatures exceeded 25°C in 17.5% of dwellings. Overall, temperatures exceeded 27°C for >5% of time (hourly mean values) in 21% of monitored dwellings. In the development in Austria, temperatures exceeded 28°C for > 5% of time in 16% of homes. Authors suggest comfortable indoor conditions.	(Schnieders and Hermelink, 2006)
Denmark	3x detached Passivhaus dwellings	June-Aug 2009, living room, bedroom, bathroom	Thermal indoor environment assessed using DS/CEN/CR1752. Measurement results demonstrate excessive indoor temperatures in all three dwellings, with one dwelling exceeding comfort requirements (Cat B), with an average summer temperature of 26.6°C.	(Larsen et al. 2011)

Table 2. Comparison of overheating prevalence and building characteristics

	Living room				Bedroom 1			
	n (total)	>5% annual occupied hours >25°C	>10% annual occupied hours >25°C	>1% annual occupied hours >28°C	n (total)	>5% annual occupied hours >25°C	>10% annual occupied hours >25°C	>1% annual occupied hours >26°C
All dwellings	53	40 (75%)	31 (58%)	13 (25%)	55	31 (56%)	20 (36%)	33 (60%)
Dwelling type								
Flat	18	14 (78%)	11 (61%)	4 (22%)	18	8 (44%)	7 (39%)	8 (44%)
Terraced	12	10 (83%)	7 (58%)	3 (25%)	13	9 (69%)	4 (31%)	11 (85%)
Semi-detached	15	10 (67%)	7 (47%)	3 (20%)	15	9 (60%)	5 (33%)	9 (60%)
Detached	8	6 (75%)	6 (75%)	3 (38%)	9	5 (56%)	4 (44%)	5 (56%)
Construction								
Timber	33	26 (79%)	20 (61%)	10 (30%)	36	19 (52%)	13 (36%)	21 (58%)
SIPs	4	3 (75%)	3 (75%)	2 (50%)	4	4 (100%)	1 (25%)	4 (100%)
Total lightweight	*37*	*29 (78%)*	*23 (62%)*	*12 (32%)*	*40*	*23 (58%)*	*14 (35%)*	*25 (63%)*
Concrete	4	4 (100%)	4 (100%)	1 (25%)	2	2 (100%)	2 (100%)	2 (100%)
Masonry	10	5 (50%)	2 (20%)	0 (0%)	11	5 (46%)	4 (36%)	5 (46%)
Steel w. brick & block	2	2 (100%)	2 (100%)	0 (0%)	2	1 (50%)	0 (0%)	1 (50%)
Total heavyweight	*16*	*11 (69%)*	*8 (50%)*	*1 (6%)*	*15*	*8 (53%)*	*6 (40%)*	*8 (53%)*
Standard								
Passivhaus	15	10 (67%)	8 (53%)	3 (20%)	16	8 (50%)	6 (38%)	8 (60%)
Non-Passivhaus	38	30 (79%)	23 (61%)	10 (26%)	39	23 (59%)	14 (36%)	25 (50%)
Ventilation								
MVHR	35	25 (71%)	19 (54%)	8 (23%)	37	21 (57%)	13 (35%)	24 (65%)
Non-MVHR	18	15 (83%)	12 (67%)	5 (28%)	18	10 (56%)	7 (39%)	9 (50%)
Region								
Scotland	20	16 (80%)	14 (70%)	7 (35%)	21	12 (57%)	10 (48%)	11 (53%)
N Ireland	2	2 (100%)	1 (50%)	0 (0%)	2	1 (50%)	1 (50%)	1 (50%)
Total North	*22*	*18 (81%)*	*15 (68%)*	*7 (32%)*	*23*	*13 (57%)*	*11 (48%)*	*12 (52%)*
Yorkshire & Humber	2	2 (100%)	1 (50%)	1 (50%)	2	2 (100%)	1 (50%)	2 (100%)
E Midlands	11	8 (73%)	5 (46%)	3 (27%)	12	7 (58%)	2 (17%)	10 (83%)
Wales	4	2 (50%)	1 (25%)	0 (0%)	4	2 (50%)	0 (0%)	2 (50%)
London	3	3 (100%)	3 (100%)	1 (33%)	3	1 (33%)	1 (33%)	1 (33%)
S East	6	4 (67%)	4 (67%)	1 (17%)	6	4 (67%)	4 (67%)	4 (67%)
S West	5	3 (60%)	2 (40%)	0 (0%)	5	2 (40%)	1 (20%)	2 (40%)
Total South	*31*	*22 (71%)*	*16 (52%)*	*6 (19%)*	*32*	*18 (56%)*	*9 (33%)*	*21 (66%)*

Table 3. Comparison of indoor temperatures in MVHR and Non-MVHR dwellings

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
SD = standard deviation; IQR = interquartile range
T-tests were used for all comparisons except for median temperature range, using Mann-Whitney U

Statistic	Living room			Bedroom (1)			Bedroom (2)		
	All	MVHR	Non MVHR	All	MVHR	Non MVHR	All	MVHR	Non MVHR
February 2013									
n	53	17	36	51	17	34	14	5	9
Minimum	11.4	12.0	11.4	8.1	8.1	11.0	15.1	15.1	17.2
Maximum	33.4	30.0	33.4	31.0	31.0	29.8	29.4	29.4	27.2
Mean (SD)	21.6 (2.4)	**21.0 (2.2)***	**22.8 (2.3)***	20.6 (3.1)	20.1 (3.1)	21.5 (3.2)	21.4 (2.4)	20.9 (2.8)	22.2 (1.5)
Mean Min (SD)	18.5 (2.8)	18.7 (2.4)	18.2 (3.5)	17.9 (3.1)	18.0 (2.8)	17.7 (3.8)	18.2 (1.9)	17.9 (2.1)	18.7 (1.4)
Mean Max (SD)	24.5 (3.5)	**23.2 (3.1)*****	**27.3 (2.5)*****	23.0 (3.9)	**22.1 (3.9)***	**24.6 (3.5)***	24.1 (3.2)	23.3 (3.6)	25.5 (2.1)
Median range (IQR)	4.8 (6.1)	**3.8 (3.9)*****	**8.8 (4.1) *****	4.1 (4.6)	**3.2 (3.0) ****	**7.2 (4.7)****	5.8 (3.3)	4.5 (2.3)	7.0 (4.3)
April 2013									
n	50	15	35	49	15	34	15	6	9
Minimum	10.9	10.9	16.4	10.4	10.4	14.4	13.9	13.9	15.8
Maximum	31.4	29.0	31.4	29.2	28.2	29.2	29.2	25.6	29.2
Mean (SD)	21.8 (1.9)	**21.3 (1.9)*****	**23.0 (1.0)*****	21.3 (1.8)	**20.9 (1.8)***	**22.1 (1.7)***	21.2 (2.1)	**20.2 (1.7)***	**22.7 (1.6)***
Mean Min (SD)	18.4 (2.5)	**18.6 (2.7)*****	**17.9 (1.9)*****	18.2 (2.5)	18.3 (2.6)	18.2 (2.1)	18.1 (2.2)	17.8 (2.3)	18.7 (2.0)
Mean Max (SD)	24.9 (3.0)	**23.4 (2.1)*****	**28.3 (1.8)*****	23.7 (2.4)	**22.9 (2.0)*****	**25.6 (2.2)*****	23.8 (2.6)	**22.4 (1.8)***	**26.0 (2.2)***
Median range (IQR)	5.6 (6.6)	**4.0 (3.5)*****	**10.6 (4.6)*****	4.6 (4.5)	**4.0 (2.8)*****	**7.6 (3.4)*****	6.0 (2.8)	**5.1 (3.9)***	**7.4 (0.8)***
August 2013									
n	52	17	35	52	17	35	17	7	10
Minimum	17.8	19.0	17.8	16.0	18.9	16.0	18.8	21.1	18.8
Maximum	32.2	29.6	32.2	30.5	30.5	30.2	33.4	29.8	33.4
Mean (SD)	24.0 (1.4)	24.3 (1.8)	23.5 (2.1)	23.8 (1.7)	**24.1 (1.6)***	**23.1 (1.6)***	23.8 (1.7)	24.1 (1.3)	23.4 (2.1)
Mean Min (SD)	21.8 (2.0)	**22.5 (1.9)*****	**20.5 (1.5)*****	21.6 (2.1)	**22.3 (1.8)***	**20.2 (2.0)***	21.4 (1.6)	**22.2 (1.2)***	**20.3 (1.5)***
Mean Max (SD)	26.7 (1.9)	**26.2 (1.6)***	**27.7 (2.3)***	26.1 (2.1)	26.1 (2.0)	26.0 (2.3)	26.5 (2.5)	26.2 (1.7)	26.8 (3.5)
Median range (IQR)	4.4 (4.3)	**3.7 (2.3)*****	**7.6 (3.9)*****	4.1 (2.8)	**3.4 (2.7)****	**5.6 (2.8)****	4.2 (2.9)	**3.7 (1.0)****	**5.6 (3.6)****

Table 4. Distribution of MVHR and Non-MVHR dwellings by building characteristics and region

	Dwellings (n = 53)		
	Total (n = 53)	MVHR (n = 36)	Non-MVHR (n = 17)
Dwelling type			
Flats	18 (34%)	11 (61%)	7 (39%)
Terraced	14 (26%)	10 (71%)	4 (29%)
Semi-detached	12 (23%)	6 (50%)	6 (50%)
Detached	9 (17%)	9 (100%)	0 (0%)
Construction			
Timber	36 (68%)	21 (58%)	15 (42%)
SIPs	3 (6%)	3 (100%)	0 (0%)
Total lightweight	39 (74%)	24 (62%)	15 (38%)
Concrete	4 (8%)	4 (100%)	0 (0%)
Masonry	8 (15%)	8 (100%)	0 (0%)
Steel w. brick & block	2 (4%)	0 (0%)	2 (100%)
Total heavyweight	14 (26%)	12 (86%)	2 (14%)
Standard			
Passivhaus	16 (30%)	16 (100%)	0 (0%)
Non-Passivhaus	37 (70%)	20 (54%)	17 (46%)
Region			
Scotland	22 (42%)	7 (32%)	15 (68%)
N Ireland	2 (4%)	2 (100%)	0 (0%)
Total North	24 (45%)	9 (38%)	15 (62%)
Yorkshire & Humber	2 (4%)	2 (100%)	0 (0%)
E Midlands	11 (21%)	11 (100%)	0 (0%)
Wales	2 (4%)	2 (100%)	0 (0%)
London	3 (6%)	1 (33%)	2 (67%)
S East	6 (11%)	6 (100%)	0 (0%)
S West	5 (9%)	5 (100%)	0 (0%)
Total South	29 (55%)	27 (93%)	2 (7%)

Table 5. Living room overheating status based on adaptive and static criteria[1]

	Adaptive method			Passivhaus	CIBSE	CIBSE
No.	Criterion 1 >3% occupied hours ΔT ≥ 1K	Criterion 2 Daily WE during occupied hours >12	Criterion 3 Maximum ΔT ≥ 4K	>10% annual occupied hours > 25°C	>5% annual occupied hours > 25°C	>1% annual occupied hours > 28°C
F1_b	●	■		⬟	✶	
F1_d				⬟	✶	
F1_f	●	■		⬟	✶	▲
F11_a	●	■	◆	⬟	✶	▲
F11_b	●	■	◆	⬟	✶	▲
F11_c	●	■	◆	⬟	✶	▲
F11_d					✶	
F12_a						
F12_b					✶	
F19_a		■			✶	
F7_a						
F7_b				⬟	✶	
F7_c		■		⬟	✶	
H10_a						
H11_a	●	■	◆	⬟	✶	▲
H11_b		■		⬟	✶	
H11_c						
H11_d	●	■		⬟	✶	
H14_a	●	■	◆	⬟	✶	
H14_b					✶	
H15_a						
H15_b				⬟	✶	
H15_c						
H16_a				⬟	✶	
H17_b	●	■		⬟	✶	▲
H17_c				⬟	✶	
H17_d	●	■	◆	⬟	✶	▲
H19_a		■		⬟	✶	
H19_b	●	■	◆	⬟	✶	▲
H20_a	●	■	◆	⬟	✶	▲
H20_b				⬟	✶	
H20_c	●	■		⬟	✶	▲
H20_d						
H3_a						
H3_b		■		⬟	✶	
H3_c					✶	
H3_d		■			✶	▲
H3_e		■				
H3_f					✶	
H3_g				⬟	✶	
H5_a		■		⬟	✶	▲
H8_a	●	■	◆	⬟	✶	
H8_b						
H9_a					✶	
H9_b	●	■		⬟	✶	▲

[1] **Note, only homes with both summertime and annual data were included in the table*