Citation for published version:
Mitchell, R & Natarajan, S 2018, 'Providing Passivhaus: Post occupancy evaluation of certified Passivhaus homes in the UK'.

Publication date:
2018

Overheating Risk in Passivhaus Dwellings

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Abstract

Highly insulated and airtight homes designed to reduce energy consumption, are perceived as having a greater summer overheating risk than less insulated homes. If true, dwellings built to the well-known low-energy Passivhaus standard could be at greatest risk due to the use of superinsulation, especially as the climate warms. Existing studies are inconclusive and even contradictory, mainly due to small sample sizes. Hence, this paper presents the first large-scale overheating risk analysis of UK Passivhaus dwellings using high-resolution internal temperature data from 82 homes across the UK. Both the Passivhaus and the recently published CIBSE TM59 criteria are analysed. Results show that the whole-dwelling Passivhaus standard, which uses a fixed temperature threshold, is met more frequently (83%) than when applied on a room-by-room basis (e.g. only 60% of bedrooms in houses meet the standard). TM59-1A, which uses an adaptive temperature threshold, is easier to meet with 100% of flats and 82% of houses in compliance. However, 55% of bedrooms assessed under TM59-1B fail, with little difference between flats and houses. This is a remarkable finding given that the summers under consideration were either typically mild or cooler than average, and that sleep impairment can significantly affect both physical and mental health. These results suggest that highly-insulated dwellings such as Passivhaus, should consider overheating in individual rooms, rather than at whole-dwelling level. Analysis should be undertaken throughout the year with particular attention to bedrooms, using either the good-practice PH-5% exceedance threshold which maps well to TM59-1B, or TM59-1B itself.

Practical Application

Overheating risk in new dwellings is an industry concern. Having the correct tools to predict this risk at design stage is important to help design comfortable and healthy dwellings for both today's climate and future, hotter climates. Comparing two different tools and their methodologies using in-use data is critical to gain confidence in their application at the design stage and to further understand overheating risk, including which dwelling types and rooms are more vulnerable to overheating.

1. Introduction

Overheating in buildings is said to occur when the heat built up within a dwelling cannot be easily rejected or removed [1]. Elevated solar and internal gains are often implicated as causal mechanisms, especially when combined with lowered ventilation rates [2], although other factors such as humidity or occupant behaviour also play a role [3].

The Zero Carbon Hub (ZCH) defines overheating as "*the phenomenon of excessive and prolonged high temperatures in the home, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants"* [1]. However, the effect of high internal temperatures on occupants is more complex and this can partially explain why overheating is poorly understood especially in homes [2, 3]. Nonetheless, temperature standards now exist that allow a primary assessment of overheating risk. Given the expected rise in temperatures due to climate change and the mitigation-driven imperative for low-energy homes, there is an urgent need to assess whether homes built to higher energy efficiency standards overheat because of high levels of insulation and low levels of air permeability.

1.1. Building design and overheating risk

Overheating risk is not limited to highly insulated airtight new buildings. A national survey of the existing stock found overheating in bedrooms and living rooms, with newer homes (post 1990) at a greater risk. The ZCH found 70% of the housing provider organisations who responded to their survey, experienced an overheating issue within their wider stock and homes with the highest risk were identified as single aspect high rise flats in dense urban locations facing south [1, 4-8].

Building simulation studies have shown that improving insulation does not increase overheating risk, given "good" design; i.e. appropriate solar shading and ventilation, especially at night (e.g. comprehensive work in [9]). Indeed, these studies suggest that increasing insulation can assist in reducing overheating. Other risk factors, such as building type, building services, and occupant behaviour are identified and considered relevant [10-15].

Studies that have monitored indoor conditions, show that some homes do seem to be overheating. However, establishing causality has proven difficult with evidence seemingly pointing in both directions with respect to the effect of increased insulation.

For example, some post occupancy research has suggested that overheating risk *is* exacerbated by increases in insulation levels and air tightness [8, 16-19].

At the same time, counter examples exist: lack of roof insulation is a common cause of overheating in older properties [7] and in the European heatwave of 2003 this omission was specifically identified as a risk factor for overheating [20]. The Building Performance Evaluation project of 76 homes drew inconclusive results as to whether homes with higher insulation levels were more at risk: individual instances of overheating were found but robust conclusions could not be drawn [21]. Where overheating does occur, it can often be mitigated through occupant behaviour: The NHBC's report of 4 Passivhaus dwellings found that initially the overheating experienced, by about half the occupants, was reduced once actions were taken to counter this e.g. using external blinds, night-time ventilation and using the summer bypass on the Mechanical Ventilation with Heat Recovery (MVHR) [22]. Hence, a direct relationship between a higher performing building envelope and overheating risk may not exist. However, what is becoming clear is some new homes are overheating and it is important to identify and address the risk factors.

A summary the causes of overheating identified in the literature, grouped by three factors: design, building services and occupant behaviour is given below [1, 5, 7, 23].

Dwelling Design and Location

- Orientation and solar gain, in particular, large areas of south/west/east facing glazing
- Window opening limited for reasons of noise, security, outdoor air quality or insects
- Limited or no cross ventilation, especially night time ventilation
- Lack of, or poorly placed external shading
- Building micro-environment, the heat island effect and lack of mitigation through planting.
- Increases in insulation and air tightness resulting in more heat being retained in the building. Internal insulation impacts on overheating more than external insulation. However, rooms located under uninsulated roofs are also identified as at risk of overheating in contradiction to above.
- Top floor flats are prone to overheating
- Buildings in the South and South East England are more at risk

Building Services

- Summer bypass not present or not activated in MVHR systems
- Heat losses from internal heating, hot water and solar hot water pipework in both individual and communal systems
- Additional electrical demand and internal gains from building services e.g. pumps

Occupant Behaviour

- Limited window opening and night ventilation
- High plug loads from appliances leading to higher internal gains
- Number of occupants and occupancy patterns

In summary, certain building types and aspects are potentially more at risk of overheating and poorly specified or installed building services can exacerbate risk. Ensuring building users are aware of and can ventilate their homes, especially at night, is critical to remove any heat built up during the day. However, prior to identifying causality, the more basic question of the actual extent of overheating in highly insulated real dwellings needs investigation, a gap we address in this paper.

1.2. Overheating and health

While increasing levels of energy efficiency will positively impact on preventing excess winter deaths, increased external temperatures associated with climate change, coupled with a drive for more highly insulated and airtight homes, could result in additional health risks associated with summer overheating. High internal temperatures have an adverse effect on health, through stress, anxiety, and sleep deprivation, which can increase mortality [24]. In the current UK climate, it is estimated there are 800 summer heat related deaths each year compared to 25,000 excess winter deaths [25, 26]. Therefore, the focus on reducing winter deaths is still the higher priority, however it is important not to solve one problem and create another and, without action, summer heat related deaths could rise. The 2003 heatwave resulted in an estimated 70,000 excess deaths across Europe including 2,000 additional deaths in the UK, mainly amongst older people. In the south of England, excess summer deaths increased by 42% [20, 27-29]. During that period, UK summer temperatures were 2°C above the 1961-1990 average. It is estimated that mean summer temperatures will rise in the South East of England by 2°C by 2040 (based on medium predictions) and potentially up to 5.4°C by 2070 based on a high emissions scenario [30].Therefore these higher summer temperatures will not just become more frequent, they will become the norm and by the mid-century, half the summers are predicted to be as warm as 2003 and 2018 [30, 31], potentially raising summer heat related deaths to 5,000 per year [5].

In dwellings, bedroom temperatures are considered more critical as high internal temperatures affect sleep quality, which in turn impact on both comfort and health of the occupant, through an increase in accidents or atypical behaviour [32]. CIBSE Guide A advises maximum indoor operative temperatures of 25°C for living rooms and 23°C for bedrooms, as sleep can be impaired above 24°C. Bedroom temperatures should not exceed 26°C unless a ceiling fan is available [33].

Therefore, dwellings being constructed today need to be designed to not only manage overheating risk now but also be resilient to predicted increases in external temperatures, with a focus on internal temperatures in bedrooms as this room has the biggest impact on health and wellbeing.

1.3. Passivhaus

Passivhaus is the world's leading and fastest growing standard for low energy buildings with over 65,000 buildings certified worldwide and 1,000 buildings in the UK [34]. The Passivhaus energy standard is designed to deliver highly insulated and airtight comfortable buildings with a space heating demand so low that it can be provided through the ventilation system alone, obviating the need for a conventional heating system. The maximum permitted space heating demand in a European climate is $\leq 15 \mathrm{kWhm^{-2}a^{-1}}$ or a heating load $\leq 10 \mathrm{Wm^{-2}a^{-1}}$. In addition, there are absolute limits for air permeability, primary energy use and overheating risk. Passivhaus is a demanding energy standard which can be applied to both domestic and non-domestic buildings [35], and is designed and delivered using the Passivhaus Planning Package (PHPP).

A Passivhaus is also designed for thermal comfort in winter and summer. Indeed, the genesis of the standard is in the determination of the minimum energy needed to provide the highest quality indoor environment. Summer interior temperatures are influenced by external climate, window size, orientation and shading, internal gains, and ventilation rates. To meet the Passivhaus overheating standard, internal temperatures should not rise above 25°C for more than 10% of annual occupied hours. Domestic dwellings are assumed to be occupied 100% of the year for certification purposes (annual hours 8,760), therefore no more than 876 hours per year can be above 25°C. Table 1 gives a summary of the assessment of frequency of overheating and the recommendations by the Passive House Institute to ensure good summer internal comfort [35]. For Passivhaus certification, summer comfort must be 'acceptable' or better (5-10%), but less than 5% is now considered best practice with some designers aiming for 0% [36].

h>25°C	**Assessment**
>15%	Catastrophic
10 -15%	Poor
5-10%	Acceptable
2-5%	Good
0-2%	Excellent

Table 1: Summary of overheating risk criteria

The overheating risk is calculated within PHPP at design stage using the "Summer" worksheet and is applied across the building as whole. The assessment of individual rooms is only recommended in large buildings (usually non-domestic). Critical rooms can be identified within a design and, for example, shading can be added to windows, or night-time ventilation increased, until the frequency of overheating risk for the whole dwelling within PHPP is acceptable [35].

There are limitations with this whole house approach. There may be overall compliance for the dwelling while individual rooms could still be uncomfortable. This methodology also means that different standards cannot be applied to individual rooms e.g. bedrooms where the health impact of overheating is known to be greater. Emerging good practice guidance in Passivhaus design advises on limiting ventilation assumptions through window opening and night time cooling in PHPP at the design stage and minimising user operated shading when possible to reduce overheating risk in operation [37]. This supports the research findings, which identified limited user awareness of actions needed to reduce internal temperatures as a risk factor for overheating [5, 7, 22, 38].

Post occupancy research in the UK

There have been several small-scale post occupancy evaluations of Passivhaus dwellings and the overheating findings are summarised in Table 2.

Citation	No of dwellings	Internal temperatures		Overheating Findings
		Summer average	Winter average	
[39]	1	21.7 °C	21.7 °C	Some summer internal temperatures reached 28°C which were linked to user behaviour. However only 2% of annual hours were over 25°C. Opening windows and cross ventilation helped to reduce overheating.
[40]	2	23.3°C	21.7°C	Summer overheating in some bedrooms and living rooms as measured by both the PH and CIBSE standards, with a high summer overheating risk in one dwelling.
[41, 42]	1	23.6°C	22.4°C	15% of hours where over 25°C in the living room which fails PH standard. CIBSE TM52 standard was not met in the in bedroom. However, occupant survey showed this not to be a problem.

[43, 44]	14	24°C	19°C	Overheating exacerbated by the lack of summer bypass in MVHR and higher internal gains.
[45]	1	25.5°C		Summer temperatures reported as being uncomfortable, Passivhaus and ASHRAE overheating standards not met. Bedrooms over 25°C 29% of the time. Lack of night time cooling and use of boost on MVHR cited as exacerbating overheating.
[46]	4	Between 20°C and 25°C throughout the year		Summer overheating identified with temperatures over 25°C in bedrooms. Overheating exacerbated by limited summer shading and lack of summer bypass on the MVHR. Uninsulated pipework caused high internal gains in summer.
[16]	25			Short monitoring period over the summer showed temperatures over 25°C between 3% and 99% of hours. Flats overheating more than houses. Analysis suggested overheating linked to user behaviour.

Table 2: Summary of Passivhaus overheating case studies.

The studies show that there are overheating risks identified in some of the monitored dwellings and this risk is more prevalent in bedrooms. The incorrect specification and installation of mechanical services can exacerbate overheating, and occupant understanding of increasing ventilation rates, especially at night is important to reducing internal temperatures, supporting the findings of earlier research. Many of these studies point out that the results of one or two dwellings should not be overstated and suggest the need for a larger scale study.

1.4. Adaptive Comfort, CIBSE TM52 and TM59

Passivhaus assumes a fixed maximum internal temperature (25°C) beyond which overheating is considered a risk. The adaptive model of thermal comfort in free running (i.e. naturally ventilated) buildings connects internal comfort temperatures to the external temperatures. It is based on the premise that higher internal temperatures may be tolerated as external temperatures rise and people adapt to their internal conditions by changing clothing, activity or their surroundings for example opening windows or drawing blinds. Internal comfort temperatures therefore will vary as the outdoor temperature changes, rather than being fixed [47]. This approach may account for why some of the homes in Table 2 had higher internal temperatures but were still considered acceptable to occupants. It has been recommended by CIBSE that new buildings use the adaptive comfort method described in CIBSE TM52 rather than fixed temperatures to assess overheating risk, as long as adaption is available (e.g. opening windows, flexibility of clothing etc).

CIBSE TM59 *Design methodology for the assessment of overheating risk in homes,* is an assessment methodology for predicting overheating risk in naturally ventilated and mechanically ventilated domestic dwellings. This combines guidance from CIBSE TM52 *Limits of thermal comfort avoiding overheating risk in European buildings* (aimed primarily at commercial buildings) and CIBSE Guide A which gives limits to bedroom temperatures [3, 33].

CIBSE TM52 describes an adaptive comfort model which is based on two assumptions. (i) how we respond to temperature depends on recent experience and (ii) we can undertake interventions to manage heat e.g. removing layers of clothing or opening windows. Therefore, adaptive comfort is only applicable when occupants have some control of their internal environment, which in a domestic dwelling, unless there are constraints, is generally the case. The criteria of CIBSE TM52 are evaluated against ΔT, defined as:

$$\Delta T = T_{op} - T_{max}$$

Where
T_{op} is the hourly indoor operative temperature (°C)
T_{max} is the upper limit for Category II buildings in EN15251 (°C), given as:

$$T_{max} = 0.33\, T_{rm} + 21.8$$

Where
T_{rm} is the exponentially weighted running mean of daily mean outdoor temperatures (°C):

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

Where
T_{od-n} is the daily mean external temperature of the nth day before the day in question (°C)

CIBSE TM52 contains three criteria which must be met to demonstrate there is no overheating risk at the design stage and is applied to summer months (May to September) only.

Criterion 1. *Hours of exceedance*: which defines the acceptable percentage of hours above T_{max}

$$H_e = \sum \mathrm{h} \;\forall\; \Delta T \geq 1^{\circ}C$$

The summation is performed over all occupied hours (*h*) as defined for the type of building. H_e should not exceed 3% of occupied hours for the months May to September inclusive.

Criterion 2. *Daily weighted exceedance*: deals with the severity of overheating within any one day, which can be as important as its frequency. The W_e threshold is ≤ 6 per day. Where:

$$W_e = (\textstyle\sum h_e) \times WF$$
$$= (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3)$$

And:

$$WF = 0 \;\forall\; \Delta T \leq 0, else\ WF = \Delta T$$
$$h_{ey} = hours\ when\ WF = y$$

Criterion 3. *Upper limit temperature*: sets an absolute maximum daily temperature (ΔT ≤ 4K) for a room, beyond which the level of overheating is unacceptable.

CIBSE TM59 refines Criterion 1 for domestic application and adds a separate and additional criterion from CIBSE Guide A for bedrooms as shown in Table 3.

Criterion 1A Living Rooms, kitchens and bedrooms	Criterion 1B: Bedrooms only
TM52 Criterion 1 is evaluated with summer occupied hours set to the range [09.00, 22:00] for lounges and kitchens (1989 hours per year) and 24 hours for bedroom (3672 hours per year).	To guarantee comfort during the sleeping hours the operative temperature in the bedroom between [22:00, 07:00] shall not exceed 26°C for more than 1% of annual hours (32 hours per year).

Table 3: Criterion for assessing overheating risk in free running domestic buildings CIBSE TM59.

Ideally the TM59 methodology should be applied to all dwellings, though some typologies are identified as being at a greater risk of overheating, and therefore should be prioritised for assessment. These are:

1. Large developments
2. Developments in urban areas, particularly in southern England
3. Blocks of flats
4. Dwellings with high levels of insulation and air-tightness
5. Single aspect flats

Passivhaus dwellings would be included in the fourth category and therefore a group of dwellings to be evaluated. Whilst Passivhaus dwellings have MVHR systems, summer natural ventilation (window opening, especially at night) is possible, and even encouraged. Therefore, the adaptive method is valid for summertime use unless there are site specific reasons which restrict window opening.

2. Method

Our overall aim is to assess the level of overheating in real Passivhaus dwellings using both the Passivhaus and TM59 indicators. To this end, internal temperature data were collected from 82 certified Passivhaus dwellings in the UK. The Technology Strategy Board (now Innovate UK) undertook an £8 million monitoring project of 76 dwelling types, including 35 Passivhaus as part of the Building Performance Evaluation programme. This data, along with other monitoring programs funded by developers and homeowners' own monitoring has been collated to form this large cohort of temperature data.

Of the 82 dwellings, 62 (76%) were houses and the remaining flats (24%), though all flats were low rise. All dwellings had data from a living room and some collected bedroom data. Additionally, in limited homes data was collected from kitchens, bathrooms and dining rooms (see Table 5). Some dwellings were monitored over one year, others for several, but all dwellings have at least one heating and summer season. In total over 2 million hours of temperature data was collected. Table 4 gives a summary of the sites and rooms. It is noteworthy that the CIBSE TM59 criteria use operative temperature (T_{op}) which depends on both air temperature (T_a) and mean radiant temperature (T_m), whereas our data only contain T_a. However, studies have shown that, in practice, the difference between T_a and T_m tend to be small and hence T_a can be taken as a good approximation of T_{op} [48, 49].

Site	Location in UK	Number of homes with data	Number of dwellings on site	Dwelling type	Location of internal temperature sensor	Source of data	Sampling interval
Site 1	Southwest	3	3	House	Living rooms only	Monitoring by developer	hourly
Site 2	Southwest	19	20	House	Living rooms only	Monitoring by developer	hourly
Site 3	Southwest	1	1	House	Living room only	Monitoring by owner	hourly
Site 4	East	13	14	6 Flats 7 Houses	Living rooms in all dwellings, one bedroom in two houses and a flat	Innovate UK data	5 minutes
Site 5	Southeast	1	1	House	Living room, kitchen, bathroom and bedroom	Innovate UK data	5 minutes
Site 6	Southwest	3	18	Flats	Living rooms kitchens and bedrooms	Innovate UK data	5 minutes
Site 7	Wales	2	2	House	Living rooms, kitchens, bathrooms and 2 bedrooms	Innovate UK data	5 minutes
Site 8	Northwest	1	1	House	Dining room, living room bathroom and bedroom	Innovate UK data	5 minutes
Site 9	Southwest	2	3	Flats	Living rooms kitchen and bedrooms	Innovate UK data	5 minutes
Site 10	Northern Ireland	2	5	House	Living rooms, bathrooms and bedrooms	Innovate UK data	5 minutes
Site 11	Northeast	1	28	House	Living room bathroom and bedroom	Innovate UK data	10 minutes

Site 12	Scotland	4	8	House	Living rooms kitchens and 2 bedrooms	Innovate UK data	5 minutes
Site 13	Midlands	1	1	House	Living room and bedroom	Monitoring by owner	30 minutes
Site 14	Northeast	1	1	House	Living room bathroom and 2 bedrooms	Monitoring by owner	30 minutes
Site 15	Scotland	3	14	House	Living rooms kitchens and 2 bedrooms	Innovate UK data	10 minutes
Site 16	Southeast	25	36	9 Flats 16 Houses	Living rooms only	Monitoring by developer	hourly
Total		82					

Table 4: Summary of sites, dwelling types and rooms monitored.

	Living Room	Bedroom	Kitchen	Bathroom	Total
Number or rooms monitored	82	31	12	9	134

Table 5: Summary of room types with measured internal temperature data.

2.1. External temperature data

The data set covered the years 2011 – 2017, all of which were mild to cool summers (Figure 1~~Figure 1~~). Where available, mean hourly external temperature was used from the site-specific monitoring data. When unavailable or insufficient (gaps in data, dates not matching internal temperature data), hourly mean external temperature data was collected from a local weather station from the Centre for Environmental Data Analysis (CEDA) [50].

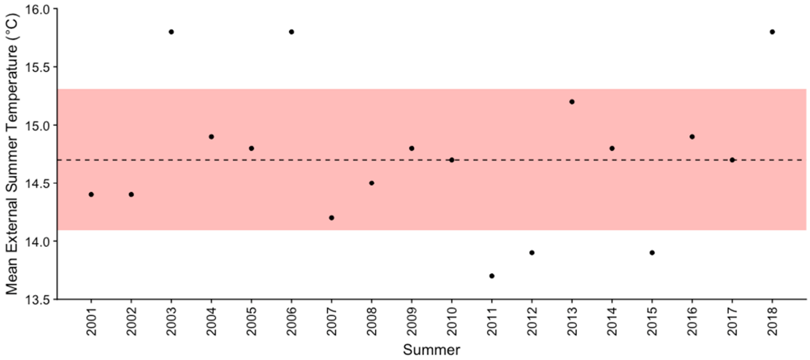

Figure 1: UK summer mean external temperatures between 2001 and 2018. Horizontal line indicates overall mean. The red band indicates 1 standard deviation. Note that the summers of 2011, 2012 and 2015 were cooler than average. Data source: [50]

2.2. Application of overheating criteria

The internal and external temperature data were analysed against the two overheating criteria, Passivhaus and CIBSE TM59, discussed earlier. Study specific details are as follows:

(1) Passivhaus: Requires assessment at whole dwelling level. Hence, we report both a whole dwelling mean as well as individual rooms to assess the appropriateness of using the whole dwelling mean. We use both the 10% occupied hours limit (henceforth PH-10%) and the good practice 5% limit (henceforth PH-5%).
(2) CIBSE TM59 Criterion 1A (henceforth TM59-1A):
    a. applies to bedrooms, living rooms and kitchens, therefore any bathroom data was excluded.
    b. where two or more bedrooms were monitored, these are reported separately.
    c. ΔT is rounded per CIBSE TM52 guidance (e.g. ΔT 0.6°C is rounded to1°C).
(3) CIBSE TM59 Criterion 1B (henceforth TM59-1B) applies to bedrooms only. Hence, if there were two bedrooms measured in one dwelling, these are reported separately.
(4) CIBSE TM52 Criterion 2 (TM52-2) and Criterion 3 (TM52-3) are tested to check if they warrant exclusion from TM59.

3. Results

Figure 2~~Figure 2~~ shows the mean hourly internal temperatures for each dwelling, separated into summer (May to September) and winter (October to April)[1]. Where only one room was measured in the dwelling this was always a living room, when more than one room in a dwelling was measured this was collated into a whole dwelling average. Across all dwellings, mean summer temperature internal temperature is 23.0°C and mean winter internal temperature 20.8°C. (~1K higher than the 20°C assumption made at design stage within PHPP for the heating season). Within these averages there is a considerable range of temperatures. Outliers (Q3+1.5*IQR and Q1-1.5*IQR) comprise 2.2% of the total data.

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[1] Note that the Passivhaus standard effectively includes "overheating" in winter as it is computed annually.

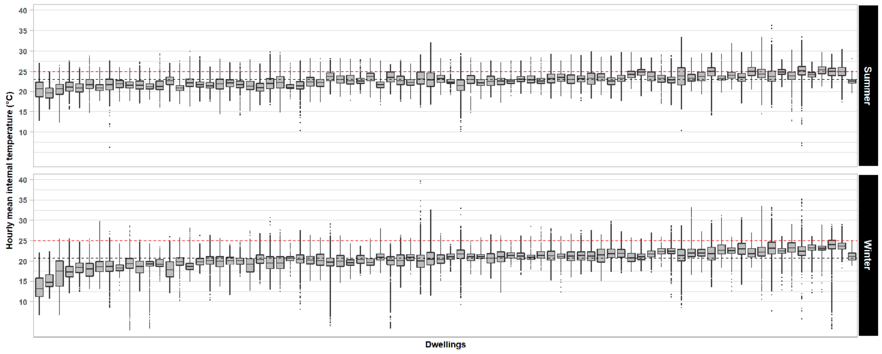

Figure 2: Mean hourly internal measured summer (May to September) and winter temperatures from 82 dwellings. Black dashed line shows mean internal temperatures for summer (23.0°C) and winter (20.8°C). Red dashed line show Passivhaus maximum internal temperature (25ºC).

3.1. Passivhaus overheating risk

To certify as a Passivhaus, the overheating risk (number of hours where internal temperatures are predicted to be over 25°C), calculated in PHPP must be less than 10% of occupied hours. Figure 3~~Figure 3~~ shows the percentage hours of exceedance of internal temperatures for all dwellings, separated into houses and flats. Dwellings where internal temperatures exceed 25°C for more than 10% of annual hours are coloured, with the rest in grey. Good practice in Passivhaus design now suggests reducing the design overheating risk to 5% of occupied hours, so this more stringent standard is also indicated.

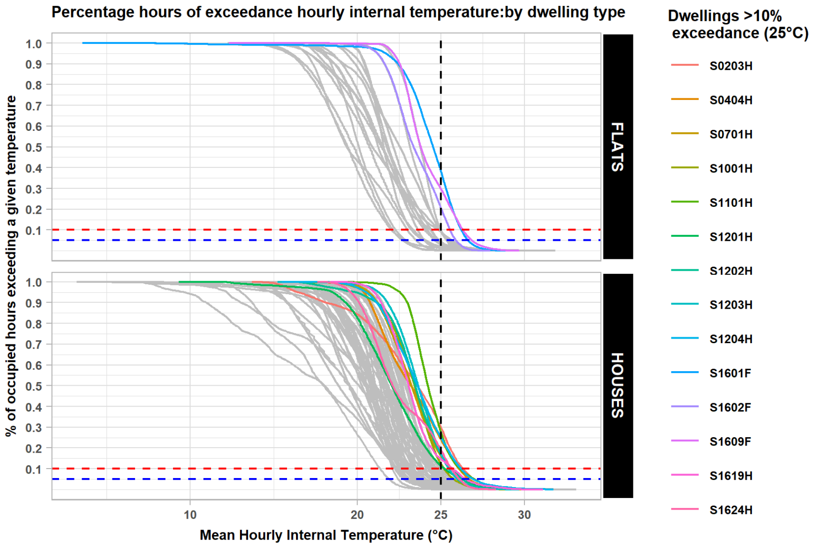

Figure 3: Percentage of occupied hours exceeding a range of internal temperatures by dwelling type. Dashed lines show the intersection of the PH standard 10% exceedance (red), PH good practice 5% exceedance (blue) and 25°C internal temperature (black) thresholds. Each dwelling is referenced by site number (S00), dwelling number and type (H = Houses, F= Flats). Therefore, S0302H is site 03, dwelling 02 and a house. Dwellings with coloured curves exceed the 10% threshold.

14 dwellings (11 houses and 3 flats) have internal temperatures which exceed PH-10%. Hence 82% of houses and 85% of flats meet the standard as shown in Table 6. However, this falls to 65% and 60% respectively, under the PH-5% threshold.

Result Dwelling Type	Number of dwellings	Number of dwellings meeting PH-10%	Number of dwellings meeting PH-5%
Houses only	62	51 (82%)	40 (65%)
Flats only	20	17 (85%)	12 (60%)
Total	82	68 (83%)	52 (63%)

Table 6: Dwellings meeting the Passivhaus standard for overheating risk by type.

While the Passivhaus takes a whole dwelling approach, CIBSE TM59 looks at individual rooms. To allow comparison, PH-10% and PH-5% were applied to individual rooms as shown in Figure 4~~Figure 4~~ with summary data provided in Table 7.

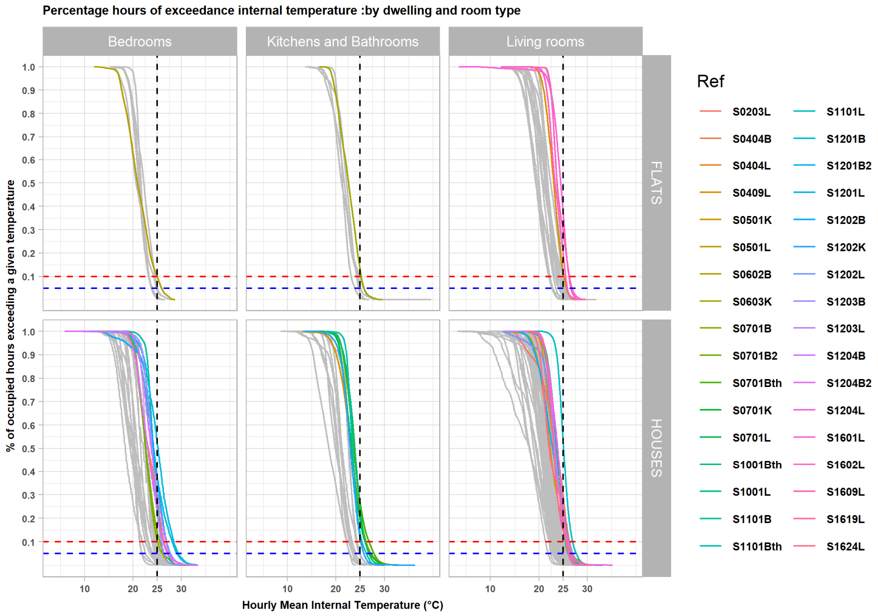

Figure 4: Percentage of occupied hours exceeding a range of internal temperatures by dwelling and room type. Dashed lines show the intersection of the 10% exceedance (red), 5% exceedance (blue) and 25ºC internal temperature thresholds (black). Rooms with coloured curves exceed the 10% threshold.

Our data shows that PH-10% is met in 100 rooms out of 134 (75%) and PH-5% in 80 rooms (60%). Appendix 1 maps these rooms to their dwellings and shows that some homes may meet the whole house standard as specified, with individual rooms exceeding the thresholds.

For example, the living room in S0409, the kitchen and living room in S0501, the living room in S0602 and the kitchen in S0603, fail the standard by room but overall these 4 dwellings met the whole house Passivhaus standard. Some problems apply to most rooms on a site, e.g., site 12 (SO1201- S1204) where 11 out of the 12 rooms monitored failed to meet the standard. This site was known to have an issue with uninsulated service pipework including the solar thermal installation which caused high heat gains in the summer and is likely to have contributed significantly to overheating.

Table 7 shows the percentage of living rooms and bedrooms which met PH-10% standard and the enhanced PH-5% standard. Fewer bedrooms in houses (60%) are meeting PH-10% compared to other rooms (80% and 63%). In the flats a similar percentage of all room types meet the standard (80% and 83%). In total 75% of individual rooms meet PH-10%, reducing to 60% under PH-5%.

Result by Dwelling and Room type	Total number of dwellings / rooms	Percentage dwellings / rooms meeting PH-10%	Percentage dwellings / rooms meeting PH-5%
HOUSES	62	82%	65%
Living rooms	62	80%	63%
Bedrooms	25	60%	56%
Kitchens and bathrooms	16	63%	63%
FLATS	20	85%	60%
Living rooms	20	80%	55%
Bedrooms	6	83%	67%
*Kitchens	5	80%	40%
Total Rooms	134	75%	60%

Table 7: Summary of dwellings and rooms meeting the 10% recommended Passivhaus standard and the 5% good practice thresholds. Note: No bathrooms were monitored in the flats.*

Four instances were found where the whole dwelling met PH-5%, but individual rooms did not (S04:09L, S05:01L, S09:02K, and S15:02L).

3.2. CIBSE TM59

In total 124 rooms (i.e. excluding bathrooms) from 82 dwellings were analysed against TM59-1A, shown in Figure 5~~Figure 5~~ and Table 8.

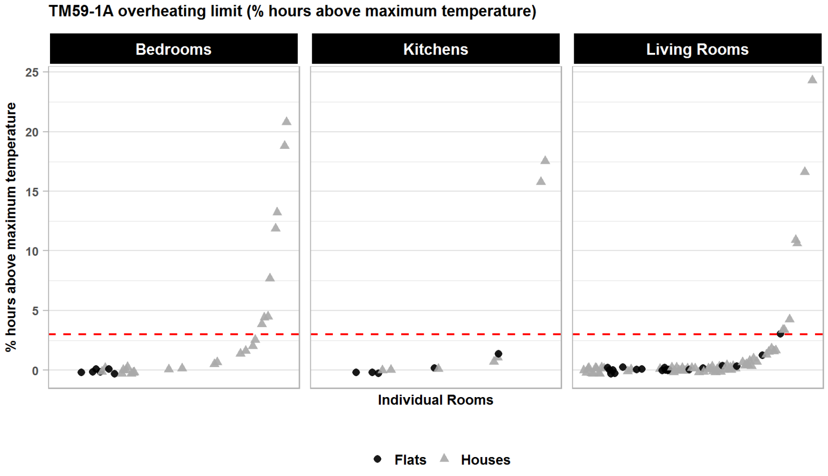

Figure 5: Percent of hours above maximum temperature (T_{max}) as defined by TM59 -1A, split by dwelling and room types. Red dashed line shows the recommended threshold (3%).

Dwelling type	Number of rooms measured	Number of rooms meeting TM59-1A
Flats	31	31 (100%)
Houses	94	76 (81%)
Total	125	111 (89%)

Table 8: TM59 Criterion 1A percentage of hours over maximum temperature all rooms and dwelling types.

All the rooms in flats and 81% of the rooms in houses meet TM59-1A. Further analysis of the houses found that 89 % of living rooms and 71% of kitchens, and 68% bedrooms met TM59-1A as shown in Table 9. The sample for kitchens is small and therefore fewer conclusions can be drawn, but a trend of overheating risk in bedrooms can be seen and this is further analysed below using TM59-1B.

Dwelling type	Room	Number of rooms measured	Number of rooms meeting TM59-1A
Houses	Living rooms	62	55 (89%)
	Bedrooms	25	17 (68%)
	Kitchens	7	5 (71%)
	Total	94	77 (82%)

Table 9: TM59-1A percentage of hours above maximum temperature. Houses only.

Linking T_{max} to the running mean external temperature means potentially higher internal comfort temperatures. Figure 6 shows that mean $T_{max.}$ is between 1-2 °C higher than 25°C for all sites, at 26.5°C for houses and 26.9°C for flats.

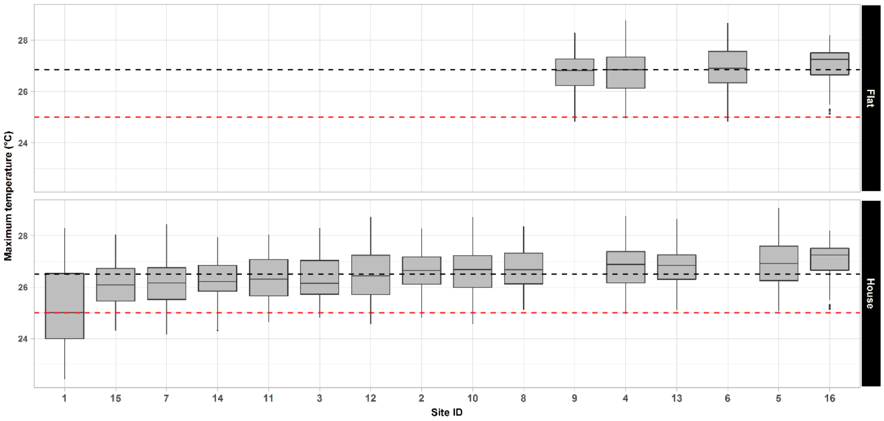

Figure 6: Box and whisker plot of T_{max} computed for TM59 per site, rank ordered by median. The red dashed line shows the Passivhaus 25°C maximum and the black dashed line the means for flats (26.9°C) and houses (26.5°C).

TM59-1B requires all bedrooms to have an internal temperature of less than 26°C for 1% of all night-time hours (between 22.00pm and 07.00am). The results are shown in

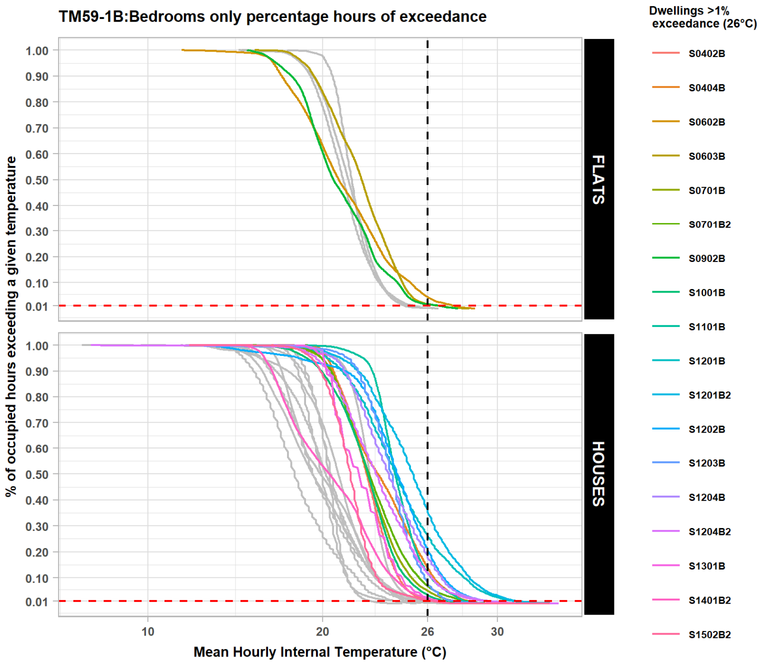

Figure ~~Figure~~ 7 and Table 10. Seven dwellings on 3 sites had more than one bedroom monitored and these are reported as a separate bedroom (B2). The results show that only 45% of the 31 bedrooms meet TM59-1B. As before, all the bedrooms on site 12 (S1201 – S1204) failed to meet the standard. Within the houses and flats, both dwelling types show a similar overheating risk in bedrooms, though the flat sample size is too small to draw wider conclusions.

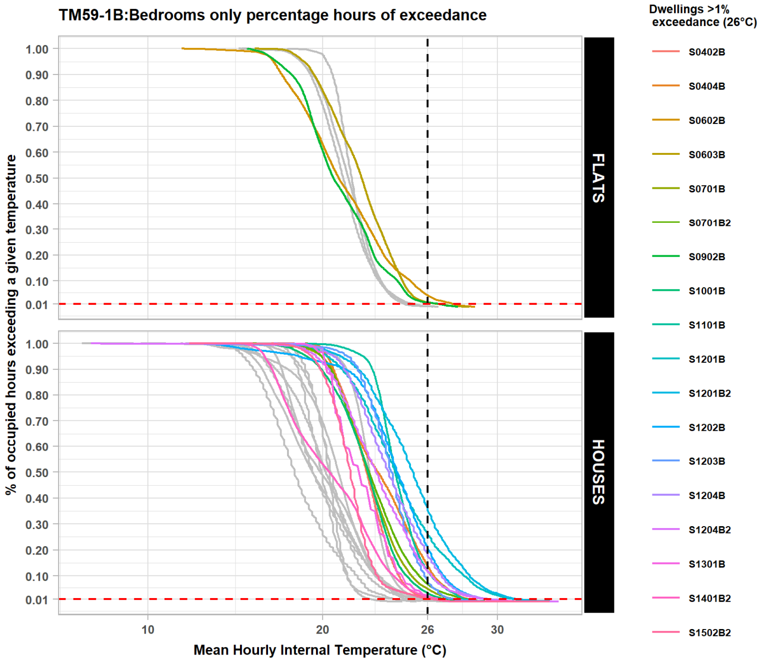

Figure 7: Percentage of occupied night-time hours $\in$ [22:00, 07:00] exceeding a range of internal temperatures in bedrooms. Dashed lines show TM59-1B threshold 1% percent of hours (red) and the 26°C limit (black).

Type of dwelling	Number of bedrooms measured	Number of rooms meeting TM59-1B	Percent rooms meeting TM59-1B
Houses	25	11	44%
Flats	6	3	50%
Total	31	14	45%

Table 10:TM59-1B percentage of night-time hours above 26°C, bedrooms only, 1 bedroom per dwelling.

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3.3. Comparison of CIBSE TM59 and Passivhaus

Table 11 compares the percentage of bedrooms and living rooms which meet all four of the standards[2]. Most rooms meet TM59-1A, and this method did not find an overheating risk in the flats. PH-10% identifies more rooms with an overheating risk especially bedrooms in houses. This is further reduced under PH-5%, particularly for living rooms. Of all the rooms

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[2] Kitchens and bathrooms are not reported, as these are both smaller samples and less time is spent in these rooms.

measured, bedrooms are showing the greatest risk of overheating and this is specifically demonstrated under TM59-1B where less than half of rooms meet this standard

Dwelling type	Room	Number of rooms measured	% of rooms meeting Passivhaus standard (10%)	% of rooms meeting Passivhaus standard (5%)	% of rooms meeting CIBSE TM59-1A	% of bedrooms meeting CIBSE TM59-1B
Houses	Living rooms	62	80%	63%	89%	
	Bedrooms	25	60%	56%	68%	44%
Flats	Living rooms	20	80%	55%	100%	
	Bedrooms	6	83%	67%	100%	50%
Total		113	76%	60%	86%	45%

Table 11: Comparison of CIBSE TM59 and Passivhaus overheating risk criteria by room.

3.4. TM52 Criteria 2 and 3

Although TM52 criteria 2 and 3 are not mandated within TM59, we include them for completeness and to assess whether they identify incidences of overheating that the other standards discussed heretofore miss. Table 12 identifies the number of rooms which fail to meet these two criteria.

Result by Room type	Total number of rooms	Number of rooms meeting TM52-2	Number of rooms meeting TM52-3
HOUSES	87	51 (58%)	81 (93%)
Living rooms	62	39 (63%)	60 (96%)
Bedrooms	25	12 (48%)	21 (84%)
FLATS	26	22 (85%)	26 (100%)
Living rooms	20	16 (80%)	20 (100%)
Bedrooms	6	6 (100%)	6 (100%)

Total Rooms	113	73 (65%)	107 (100%)

Table 12: Number of flats and houses meeting CIBSE TM52 Criterion 2 and 3.

Table 12 shows that 65% of the total rooms meet CIBSE TM52 Criterion 2, and less rooms in houses (58%) meet this criterion compare to flats (85%). Bedrooms in houses perform the worse, with only 48% complying. More rooms meet CIBSE TM52 Criterion 3, with 100% of rooms in flats meeting this standard and 93% of rooms in houses. This shows that whilst there may be times when rooms are overheating, the periods when the severity of internal temperatures is unacceptable is limited. In terms of the utility of these metrics to TM59, every room that failed TM52 Criterion 3 also failed TM59 Criterion 1A (see Appendix). This would suggest TM52 Criterion 3 adds little new overheating information. On the other hand, although not all homes failing TM52 Criterion 2 failed TM59 Criterion 1A, all homes failing TM52 Criterion 2 failed TM59 Criterion 1B, with one exception (Site 14, House 01, Bedroom 02). This would suggest that if a bedroom fails to meet TM59-1B at design stage modelling, there is likely to be an overheating risk for the whole dwelling.

4. Discussion

Both the Passivhaus design standard and CIBSE TM59 provide methodologies for assessing overheating in domestic dwellings. TM59-1A uses adaptive comfort where acceptable internal temperatures rise in relationship with external temperatures, and therefore allows for higher summer comfort temperatures compared to the Passivhaus standard, but with a lower threshold for allowed hours of exceedance. The Passivhaus standard assesses the whole dwelling, over both the summer and heating seasons, while TM59 considers separate rooms and only measures the summer months. TM59-1B applies a separate standard to bedrooms only, to account for a greater impact on health and wellbeing arising from higher bedroom temperatures. While the two assessments approach overheating in different ways, both can be applied to post occupancy data and compared. The following brief observations regarding the relative merits of each method are pertinent here:

- Passivhaus standard:
  - We find that there is little difference between houses and flats with 83% of the dwellings meeting the Passivhaus standard at the whole house level, as prescribed. However, when applied to individual rooms, only 75% of measured rooms meet the standard. Within that group 60% of bedrooms in houses met the standard, with flats faring much better (83%).
  - By taking a whole dwelling approach to overheating, the Passivhaus standard does not differentiate between rooms, and bedrooms are identified here as being particularly at risk. Many of the monitoring programs only measured one room (living room temperatures) which may be masking overheating in other rooms. Reducing overheating risk in the whole dwelling should reduce risk in these rooms, but there is no guarantee, and therefore developing a simple room by room approach to assessing risk could help moderate individual hotspots and ensure that comfort temperatures are consistent throughout the dwelling.
  - Passivhaus good practice guidance suggests aiming for a lower percentage of hours above 25°C, either at 5% or 0% and to stress test using future climate files and reducing reliance on night time ventilation to further reduce overheating risk. When compared to this standard, the number of rooms in compliance reduced to

    60%; with a greater number of living rooms (in both houses and flats), and bedrooms in flats failing to meet this more stringent standard. Hence, decreasing the compliance level to these lower percentages would be a way of ensuring greater confidence in maintaining comfort temperatures throughout the whole house, especially as summer temperatures increase in the UK.
  - It is noteworthy that all the Passivhaus dwellings would have been modelled in earlier versions of PHPP: a significant change to the current version (v9) is the treatment of internal gains, which particularly affects smaller dwellings. This change will reduce a reliance on solar gains to achieve space heating demand, which may impact on overheating risk, and therefore dwellings modelled in this later version, may have reduced overheating.

- CIBSE TM59 standard:
  - TM59 only considers overheating in the summer compared to the annual approach of Passivhaus. This may result in some overheating not being identified if it occurs outside of these months. This may particularly be the case in highly insulated homes when overheating can occur in the shoulder seasons.
  - All rooms in flats met TM59-1A, compared to 82% of rooms in houses. Comparison against the results from using the fixed Passivhaus threshold (see above) suggests that the adaptive threshold of TM59-1A, despite allowing fewer exceedance hours, is easier to pass.
  - The strictest metric (i.e. the one with the highest failure rate) was TM59-1B (55%). Any room failing TM59-1B was also likely to fail all the other standards (including Passivhaus), and there was only one instance of a room failing another standard and not failing TM59-1B (PH-5%, S10:02-BR1, see Appendix). Indeed, TM59 appears to be robust against the exclusion of TM52-2 and TM52-3 since every room failing these criteria also failed TM59-1B (except S14:01-BR2).

5. Conclusions

This paper addresses an issue of growing concern in many parts of the world as the drive to reduce energy and carbon emissions from buildings to mitigate climate change is often implicated in increasing overheating. High incidences of overheating in dwellings could significantly affect physical health and, in extreme cases, lead to death. However, little systematic analysis in highly insulated buildings has been undertaken at scale. Hence, we undertake overheating analyses on a nationally representative sample of 82 highly-insulated Passivhaus dwellings from all over the UK. We use several metrics to assess overheating and our key findings and recommendations can be summarised as follows:

- The current Passivhaus standard of no more than 10% of annual overheating hours to be greater than 25°C is met more frequently at whole-dwelling level (as prescribed) than when the same standard is applied to individual rooms. Hence, a more risk-averse approach to identifying overheating should require compliance at room rather than dwelling level.
- The good practice PH-5% metric produced a failure rate of 44%, with a strong match against TM59-1B, where available (see Discussion). This suggests that where bedroom data is unavailable, the PH-5% metric applied to living room temperatures at design stage, may provide a proxy for identifying overheating risk in bedrooms.

- Where rooms failed, these were predominantly bedrooms. Meeting TM59-1B was more difficult than criterion 1A for both houses and flats. Only 45% of all bedrooms met this standard, and there was less difference between both dwelling types. However, since there was not a one-to-one correspondence between dwellings failing TM59-1A and TM59-1B, the inclusion of both metrics in the standard seems justified.
- In the literature, flats are generally identified as potentially having a greater overheating risk compared to houses, but little evidence for this was found in our data since a similar percentage of flats and houses met the Passivhaus standard. Indeed, application of TM59-1A suggests houses (82%) are less likely to comply than flats (100%). When TM59-1B was applied, both houses and flats were found to have similar risk. The flats were low rise (none above 3 storeys), which may partially account for these results.

Overall, the results for bedrooms are particularly worrying with 55% of all bedrooms failing the TM59-1B standard, given that the summers under consideration were either typical or cool. Impaired ability to sleep can significantly affect both physical and mental health. Hence, we recommend that highly-insulated dwellings such as Passivhaus, consider overheating at individual room level, throughout the year, and with particular attention to bedrooms. We also recommend the use of either TM59-1B or the good-practice PH-5% exceedance threshold, instead of the currently used PH-10% threshold to mitigate this risk.

Acknowledgements

The authors would like to thank EPSRC for their support via the EPSRC Centre for Decarbonisation of the Built Environment (dCarb, EP/L016869/1). EPSRC were not directly involved in the design or implementation of this study.

Data created during this research are openly available for the University of Bath data archive at https://doi.org/dataset created in Pure - upload data - DOI generated.

Appendices

Appendix 1 summary of results

In the table below, we map various metrics used to assess the homes in our database against each other. Coloured cells identify rooms where the given criteria (in columns) does not apply. Blank (white) cells identify rooms that passed the given criteria, whereas those with an "F" indicate failure. Rooms are coded as follows "L" is Living Room, "B" is Bed Room 1, "B2" is Bed Room 2, "BTH" is Bath Room 1, "BTH2" is Bath Room 2, and "K" is Kitchen.

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM52 2	TM52 3
S01	S01:01	House			L						
	S01:02	House			L						
	S01:03	House			L						
S02	S02:01	House		F	L		F			F	

	S02:02	House		F	L		F			F	
	S02:03	House	F		L	F	F	F		F	
	S02:04	House			L					F	
	S02:05	House			L						
	S02:06	House			L					F	
	S02:07	House		F	L		F				
	S02:08	House		F	L		F				
	S02:09	House			L						
	S02:10	House			L						
	S02:11	House		F	L		F			F	
	S02:12	House			L						
	S02:13	House			L						
	S02:14	House			L						
	S02:15	House			L						
	S02:16	House		F	L		F				
	S02:17	House			L						
	S02:18	House			L						
	S02:19	House			L						
S03	S03:01	House			L						
S04	S04:01	House		F	L		F				
	S04:02	House			B				F	F	
					L						
	S04:03	House		F	L		F			F	
	S04:04	House	F	F	L	F	F			F	
					B	F	F	F	F	F	
	S04:05	House			L						
	S04:06	House			L						
	S04:07	House			L						
	S04:09	Flat			L	F	F			F	
					B						
	S04:10	Flat			L						
	S04:11	Flat			L						
	S04:12	Flat			L						
	S04:13	Flat			L						
	S04:13	Flat			L						
S05	S05:01	House		F	BTH						
					B						
					K	F	F	F			
					L	F	F	F		F	
S06	S06:01	Flat			B						
					K						
					L						
	S06:02	Flat		F	B	F	F		F		
					K		F				
					L		F				
	S06:03	Flat		F	B		F		F		
					K	F	F				
					L		F				

S07	S07:01	House	F	F	L	F	F	F		F	F
					B	F	F		F	F	
					K	F	F	F			
					B2	F	F	F	F	F	F
					BTH	F	F				
	S07:02	House			L						
					B						
					BTH						
					BTH2						
S08	S08:01	House			L						
					B						
					BTH						
S09	S09:01	Flat			K						
					B						
					L						
	S09:02	Flat			K		F				
					B				F		
					L						
S10	S10:01	House	F	F	BTH	F	F				
					B		F		F	F	
					L	F	F			F	
	S10:02	House			BTH						
					B		F				
					L						
S11	S11:01	House	F	F	L	F	F	F		F	
					B	F	F	F	F	F	
					BTH	F	F				
S12	S12:01	House	F	F	B	F	F	F	F	F	F
					L	F	F	F		F	
					B2	F	F	F	F	F	F
					K						
	S12:02	House	F	F	B	F	F	F	F	F	
					L	F	F			F	
					K	F	F				
	S12:03	House	F	F	B	F	F		F	F	
					L	F	F				
	S12:04	House	F	F	B	F	F	F	F	F	
					B2	F	F	F	F	F	
					L	F	F	F		F	F
S13	S13:01	House			B				F	F	
					L						
S14	S14:01	House			L						
					BTH						
					B						
					B2					F	
S15	S15:01	House			L						
					B						
					B2						

					K						
	S15:02	House			L		F				
					B						
					B2				F		
					K						
	S15:03	House			L						
					B						
					B2						
					K						
S16	S16:01	Flat	F	F	L	F	F			F	
	S16:02	Flat	F	F	L	F	F				
	S16:03	Flat		F	L		F				
	S16:04	Flat			L						
	S16:05	Flat			L						
	S16:06	Flat		F	L		F				
	S16:07	Flat			L						
	S16:08	Flat		F	L		F			F	
	S16:09	Flat		F	L	F	F	F		F	
	S16:10	House			L						
	S16:11	House			L						
	S16:12	House			L						
	S16:13	House			L						
	S16:14	House			L						
	S16:15	House			L						
	S16:16	House			L					F	
	S16:17	House			L						
	S16:18	House		F	L		F				
	S16:19	House	F	F	L	F	F			F	
	S16:20	House			L						
	S16:21	House			L						
	S16:22	House		F	L		F			F	
	S16:23	House			L						
	S16:24	House	F	F	L	F	F				
	S16:25	House			L						

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