Building Research & Information

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rbri20

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To cite this article: Linda Toledo, Andrew Wright & Paul Cropper (16 Dec 2024): Case study investigation of overheating in low-energy homes: insights from a post-occupancy evaluation in England, Building Research & Information, DOI: 10.1080/09613218.2024.2417274

To link to this article: https://doi.org/10.1080/09613218.2024.2417274

Published online: 16 Dec 2024.

BRI BUILDING RESEARCH & INFORMATION
https://doi.org/10.1080/09613218.2024.2417274

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RESEARCH ARTICLE

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Case study investigation of overheating in low-energy homes: insights from a post-occupancy evaluation in England

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ABSTRACT

This paper presents evidence of overheating in present-day low-energy homes and explores the causes of this phenomenon. The study involved in-depth research on four low-energy homes in England. Three of these were newly built, while the other was retrofitted. Over a period of 11 months, the homes underwent environmental monitoring, and user perspectives were gathered. Additionally, a retrospective analysis was conducted based on the Building Regulations 2010 Overheating: Approved Document O. Overheating was primarily attributed to design factors related to ventilation (linked to both mechanical ventilation and natural ventilation), solar control (inadequate G-values), and the unique architectural elements (roof pod and sunspace). While most occupants employed adaptive behaviours whenever possible to cope with the high indoor temperatures, these strategies proved insufficient in preventing overheating in three out of four cases. The study also compared different methods for assessing overheating in low-energy homes. CIBSE-TM59 was found to be effective in identifying overheating issues and aligning with occupant perceptions. England Building Regulations Part O simplified method failed to account for potential overheating from deep energy retrofits, as well as possible exacerbations from roof pods and from transition spaces. Moreover, all assessments failed to encompass the elevated risk for (permanent or transitory) vulnerable occupants.

ARTICLE HISTORY
Received 12 February 2024
Accepted 29 August 2024

KEYWORDS
Overheating; Building Regulations Part O; assessments; post-occupancy evaluation; energy efficient residential; off-site manufacturing

Introduction

The low-carbon agenda and the inherent risk

The pressing need to reduce greenhouse gas emissions (HM Government, 2021a), and with it, the need to reduce carbon emission from buildings has led to changes in the building regulations in recent years. Such changes are improving the building fabric performance to the effect that homes are now built with strategies to reduce energy losses, such as increased provision of insulation, high levels of air tightness and controlled ventilation systems (HM Government, 2021b, 2021d). Between 1990 and 2019, net greenhouse gas emissions from heat and buildings decreased by 17% in United Kingdom (UK) (HM Government, 2021a). The momentum of the mitigation agenda is foreseen to continue. In fact, the Net Zero Strategy in UK expects that, from 2025 onwards, new buildings will be built ready for net zero by embedding high standards of energy efficiency and low carbon technologies for heating (i.e. fitted with a heat pump or connected to a low-carbon heat network) installed as standard (HM Government, 2021a).

However, real world evidence of overheating in low-energy (energy efficient) homes in temperate climates have been published in recent years. Occupant behaviour, window-to-wall ratio, ventilation systems and environmental controls were found to be central issues in relation to overheating in low-energy homes. In a study monitoring 25 Passivhaus flats in the West Midlands (UK), researchers found that occupant behaviour (window opening, presence of curtains, appliances gains) had a significant impact on overheating (Tabatabaei Sameni et al., 2015). In a study over 60 low-energy homes across UK, instances of overheating occurred in homes equipped with mechanical ventilation with heat recovery (MVHR) (McGill et al., 2017). A report based on 76 energy efficient homes monitored across UK, it was found that window opening practices might be the most influencing factor on overheating than insulation and air tightness (Palmer et al., 2016). In Belgium, a

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study on 23 single-family Near Zero Energy Building (NZEB) homes in Wallonia showed summer thermal discomfort to be frequent in NZEB homes. The same study also linked overheating to larger unshaded glazing surfaces and an improper use of environmental controls (Dartevelle et al., 2021). In addition, a study in 50 low-energy homes in Ireland found that heat pump technology, which needs to operate during the summer to provide domestic hot water (DHW), contributed to indoor heat gain and resulted in overheating in these homes (Colclough & Salaris, 2024). Finally, another piece of research indicated a significant increase in overheating risk, particularly in bedrooms of highly insulated homes in the UK, compared to traditional British housing stock (Jang et al., 2022). Despite similar climate conditions, these studies highlight the multi-faceted nature of overheating in low-energy homes that includes design, fabric specifications, building systems and occupant behaviour. On such basis, one may even contend that energy efficiency measures, if improperly designed, built, operated or understood by its users, can work against thermal comfort and indoor air quality. In fact, studies undertaken in Scotland (Howieson et al., 2014; Sharpe et al., 2015) have confirmed that a significant reduction in air infiltration can have a detrimental effect on indoor air quality (IAQ), with indoor carbon dioxide (CO_2) levels in new dwellings monitored at concentrations 5 times higher than those recommended by the Federation of European Heating, Ventilation and Air Conditioning (REHVA, 2021)

Climate change and temperature rise further increases the risk of thermal stress. Prolonged exposure to heat, alongside with a person's own ability to cope with heat, can overwhelm the body's natural cooling mechanisms. This can trigger a series of heat-related illnesses, ranging from mild cramps to heat exhaustion and even to heatstroke. The latter can be life-threatening particularly in vulnerable elderly and children (Ndlovu & Chungag, 2024). Moreover, sleep deprivation caused by overheating can worsen cognitive performance, disrupt emotional brain function, and increase susceptibility to chronic health conditions and infectious diseases (Buguet et al., 2023).

Overheating guidance and requirements

Overheating risk is typically evaluated by establishing a benchmark temperature, which ideally should not be exceeded. In the UK, CIBSE Guide A offers the 'threshold approach' for overheating assessment (CIBSE, 2006, 2015). This method uses design targets to determine the need for cooling systems. However, this (now superseded) approach has limitations, since, on the one hand, it does not account for the physiological ability of occupants to adapt to their thermal environment, such as adjusting clothing choices, and on the other, it lacks consideration for the extent and duration of overheating episodes. Despite these limitations, the CIBSE Guide A (2006) remains relevant for this study for two reasons: (a) it serves as a common metric used in similar overheating risk assessments within existing research and (b) it reflects the prevailing design criteria at the time when the case study homes in this paper were constructed.

The CIBSE-TM52 'The Limits of Thermal Comfort: Avoiding Overheating' emphasizes the 'adaptive approach' to thermal comfort. This approach recognizes that occupants' thermal perception is influenced by their recent experience of external temperatures (CIBSE, 2013). This methodology, based on the European Standard EN 15251:2007 (now superseded by EN 16798-1:2019) improves on the more restrictive threshold-based approach used in the earlier CIBSE Guide A 2006. Notably, whilst the guidance primarily targets non-domestic buildings, much of it is also relevant to the consideration of overheating in dwellings (CIBSE, 2013). The CIBSE-TM59 'Design methodology for the assessment of overheating risk in homes' (CIBSE, 2017) is the latest developed methodology to assess the risk of overheating in UK residential buildings. The CIBSE-TM59 development process is based on dynamic thermal simulations conducted on high-risk building prototypes, including new flats and extra care homes, strengthening the validity of this methodology.

As reported by Lomas and Kane, the threshold approach is helpful for rapidly comparing temperatures in different homes (Lomas & Kane, 2013). However, in real life, individuals adapt to their environment by modifying clothes or activities, and controlling the indoor temperatures via window opening, use of shutters, etc. In fact, there exists a discrepancy between the 'threshold approach' and the 'adaptive approach', for studies have reported different results (Beizaee et al., 2013; Lomas & Kane, 2013; Mavrogianni et al., 2017). A national scale study of summertime temperatures, English dwellings overheated when temperatures were assessed with the threshold approach criteria despite cold summer conditions, the same homes were found not to overheat when using an adaptive approach (Beizaee et al., 2013). More recently, other authors (Mourkos et al., 2020) highlighted discrepancies between computer simulations using CIBSE-TM59 and real-world data from energy-efficient newly built flats equipped with mechanical ventilation (MVHR) systems. One possible reason for these discrepancies was the model's oversimplification of the MVHR system, directly linking the flat's supply air temperature to the outdoor temperature. However, monitored data revealed that MVHR systems often supply air at significantly higher temperatures (Mourkos et al., 2020).

A study applying CIBSE-TM59 in subtropical region in Australia found it to be too stringent (especially in bedrooms) when compared to occupant responses (Kim et al., 2023). The definition and progressive update on overheating assessments over the years is evidence that our knowledge of the phenomenon of overheating is still partial and has not yet reached the point of allowing to effectively mitigate the risk of overheating in dwellings (Attia et al., 2023).

A recent significant step towards mitigating overheating in new residential buildings in England is the introduction of the Building Regulations 2010 Overheating: Approved Document O (2021 edition) – herein referred to as 'Part O' in this paper – which applies to new residential buildings in England from 16 June 2022 (HM Government, 2021c). Part O is one of the few legal requirements that explicitly tackles overheating. It aims to both limit unwanted solar gains and provide means to remove excess internal heat through ventilation (HM Government, 2021c). Notably, Part O considers not only thermal factors, but also multi-domain factors (i.e. acoustic comfort and indoor air quality) and other factors, such as safety concerns, that might restrict occupant behaviour aimed at overheating mitigation (e.g. window opening). It requires compliance through two methods: a simplified method and dynamic thermal modelling. The simplified method focuses on preventing overheating by avoiding external heat gains ('keeping heat out') and removing excess heat via ventilation. This is achieved through a series of conditions referencing the window-to-floor ratio according to building orientation, solar control measures like external blinds or solar transmittance through glazing (G-value), and overhangs. These measures are applied to the building-scale, so they do not include external shading elements, such as trees or neighbouring buildings. The dynamic thermal modelling method uses the CIBSE TM59 assessment of overheating. For this method, Part O provides opening schedules as well as considerations for situations where opening windows is not safe (like ground-floor dwellings).

Since Part O is concerned with newly constructed buildings and allows for a 12-month transition period before becoming compelling, it does not apply to buildings already registered with building control. Therefore, the number of residential units built to the standards set out in Part O is limited to a small fraction of the total housing stock in England. The authors are not aware of any published studies testing the suitability of Part O. This presents an opportunity for the first study on the application of Part O's overheating mitigation measures. While this research predates the introduction of Part O, findings of the present study can be used (retrospectively) to critically assess whether or not the measures introduced by Part O can be considered effective and a move in the right direction.

This study utilizes data from four low-energy monitored homes collected in 2015 to achieve the following objectives:

(a) Identify evidence of overheating in low-energy dwellings within a temperate climate. This will be achieved by presenting a detailed exploration of design and behavioural factors influencing overheating in such dwellings.
(b) Identify limitations in current assessment methods based on the analysis of the monitored data.
(c) Retrospectively assess the appropriateness of the Part O requirement to prevent overheating. This assessment will be based on the findings from these homes.

As a result, on the one hand, this work provides valuable insights for (i) researchers studying energy efficient design, overheating, and building performance, (ii) architects, informing design strategies to mitigate overheating risk in low-energy buildings, (iii) roof pod designers, providing crucial knowledge about the potential impact of roof pods on overheating and the need for careful integration with overall building design and ventilation systems, (iv) ventilation suppliers, highlighting the importance of offering ventilation systems with summer bypass function and (v) building control officers providing a practical application of the Building Regulations Approved Document Part O and promoting best practices in their role of enforcing regulations.

Methods of data collection

In this study, data collection was designed to provide a better understanding of the overheating risk in low-energy homes, by means of engaging with diagnostic post-occupancy evaluation (POE) to four case study low-energy homes located in the East Midlands and Yorkshire (UK). Diagnostic POE is based on data collected longitudinally and aimed at providing a wide range of performance indicators (Preiser, 1995). Such techniques have been used to map areas of concern in the residences surveyed and their relation to the problem of overheating in the low-energy homes. In this study, POE is performed by means of (a) physical environmental monitoring and (b) a seasonal occupant questionnaire. A limited sample size of four in-depth case studies was chosen due to the exploratory nature of this investigation. The selection of homes aimed for architectural diversity to capture a wider range of potential overheating scenarios: new-build vs. retrofit, lightweight vs. heavyweight construction, East–West vs. North–South orientation, and various dwelling types including terraces, bungalows, and detached dwellings. While acknowledging the inherent complexity arising from such a diverse sample, a unifying characteristic was that all cases exhibited high fabric energy efficiency (high levels of insulation, high levels of airtightness, and controlled mechanical ventilation). This shared feature allowed for a focused investigation of occupant perspective and their role on overheating within the selected low-energy homes. In accordance with the Declaration of Helsinki, this study has undergone ethical approval from the ethics committee of the Faculty of Technology at De Montfort University. The ethical issues identified and addressed are informed consent, privacy and confidentiality, anonymity, and data security.

Physical environmental monitoring

The physical environmental monitoring consisted of continuous measurements in all rooms in each of the four case study homes via calibrated sensors (see Table 1 for specifications). The sensors recorded indoor air temperature at 10-min intervals, continuously, from summer 2015 until spring 2016. The high-resolution measurements allowed to capture temperatures fluctuations. Due to the limited internal memory, data from the loggers were regularly downloaded. This practice resulted not only in a close control of both location and reliability of the sensors but also in the opportunity to submit a questionnaire to the occupants on a seasonal basis.

With the permission of the occupants, the sensors were installed by the first author of this paper. They were located to avoid exposure to heat sources or direct sunlight. Attention was paid to ensure that the sensors would not interfere with the occupants' everyday activities. Pictures with placement of loggers are provided both in Figures 1, 4, 6, 7 (red circle) and details are provided in Appendix A. Recorded air temperature is used in the various analysis in this paper even though some analyses required operative temperature. Nonetheless, as other authors reported, in low-energy buildings and away from direct radiation the difference between the air temperature and the mean radiant temperature is small (Nicol et al., 2012).

Table 1. Specifications of the measuring instruments.

Instrument:	HOBO UA-001-64
Parameter measured:	Temperature
Range:	−20°–70°C
Resolution:	0.14°C at 25°C
Accuracy:	±0.53°C from 0° to 50°C
Response Time:	10 min (airflow of 2 m/s)
Battery life:	1-year typical use
Battery Type:	CR-2032
Memory:	64 K bytes

Seasonal POE questionnaires

The overall aim of the questionnaire design was to capture how reported overheating and occupant behaviour relate to the environmental measurements in their houses. It was used to gather occupants' interaction with windows, ventilation systems, and heating systems as well as questions regarding the perception and the control of temperatures in all rooms. The seasonal questionnaire was submitted five times: early summer 2015, end of Summer 2015, in Autumn 2015, Winter 2016, and Spring 2016. It was instrumental to verify changes in thermal perception throughout the different seasons. As such, the same questionnaire was submitted to look at the responses longitudinally as it was submitted at any house visit. The questionnaire included several open questions to gather qualitative information that occupants felt relevant, and that was not foreseen by the main author while designing the questionnaire.

Case studies

House UK51

This 2-bedroom Victorian terrace house dates from the late nineteenth century back-of-pavement terrace and is located in Leicester (Figure 1). This type of housing is traditionally organized over two floors and each floor have a front room and a rear room. Built on solid brick walls, with a narrow front and a deep layout, these homes traditionally have no insulation, and potentially high levels of air leakage (Hubbard, 2011). In 2010, house UK51 was retrofitted as part of the Technology Strategy Board's Retrofit for the Future competition, aiming to achieve Passivhaus energy standards across various property types and construction methods ('Retrofit for the Future', 2010).

This house was retrofitted according to Passivhaus design principles (Figure 2). However, the Passivhaus standard was not achieved due to pressurization test results exceeding the prescribed limit. The building underwent multiple airtightness tests and additional sealing measures, with a final air leakage rate of 2.8 $m^3/(h{\cdot}m^2)$ at 50 Pascals ('Retrofit for the Future', 2010).

Figure 1. Left: East façade view of the Victorian terrace retrofitted to Passivhaus-like standards. Right: Plans. The red circle indicates the location of the loggers.

Specific Demands with Reference to the Treated Floor Area

	Applied:	Monthly Method	PH Certificate:		Fulfilled?
Treated Floor Area:	91.2	m^2			
Specific Space Heat Demand:	13.4	$kWh/(m^2a)$	15	$kWh/(m^2a)$	Yes
Pressurization Test Result:	4.6	h^{-1}	0.6	h^{-1}	No
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	62.2	$kWh/(m^2a)$	120	$kWh/(m^2a)$	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	38	$kWh/(m^2a)$			
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		$kWh/(m^2a)$		CO_2 kg/m2	14.9
Heating Load:	7	W/m^2			
Frequency of Overheating:	13	%	over 25	°C	
Specific Useful Cooling Energy Demand:		$kWh/(m^2a)$	15	$kWh/(m^2a)$	
Cooling Load:	9	W/m^2			

Figure 2. Passivhaus Planning Package verification results retrieved from the sustainability consultant of case UK51.

To attain Passivhaus standards, extensive internal insulation was applied to floors and walls. The external wall build-up consists of 215 mm exterior solid brick, 150 mm of polyisocyanurate (PIR), 50 mm of mineral wool (RWA45 50), and 13 mm of gypsum board (total thickness 428 mm). This resulted in a 10–15% reduction in usable internal floor area due to the bulky insulation materials (Crilly et al., 2012). To compensate for this loss of space, a new roof room was constructed using off-site methods. Having a room in the loft is not standard practice in these terrace houses, and the choice was made to recover the loss of floor space due to internal insulation ('Project Cottesmore', 2009). Referred to as the 'roof pod' or 'converted loft' in this paper, the roof pod, a warm roof solution, serves as bedroom 2 (see Figure 3). The roof pod build-up consists of a water vapour barrier (Solitex Fronta WA), sarking boards, 75 mm Celotex PIR rigid insulation board, light-gauge steel frame structure, and 60 mm insulated plasterboard (Gyproc Thermaline Super Insulated Plasterboard).

In terms of building systems, principles, hygiene ventilation was provided via MVHR. The MVHR was running at all times throughout the study and with no provision for summer bypass. Ventilation extractions are located on the ground floor kitchen, and the first-floor bathroom. There was a boost switch (for increased ventilation) located in the kitchen. Despite the fact that the house was retrofitted following to high fabric efficiency standards (similar to Passivhaus design principles), the house was also equipped with a standard condensing gas boiler system

Figure 3. Roof pod installation on-site ('Retrofit for the Future', 2010).

for heating with radiators. Occupants were a female adult, her brother with his wife, and their new-born child. The arrival of the newborn occurred during the monitoring period. From this time onwards, the house was occupied at all times in at least one bedroom. The male occupant answered the questionnaires.

House UK52

This is a two-bedroom bungalow built in 2013 in Sandiacre (Derbyshire), see Figure 4. This home is part of a development design to Passivhaus standard. However, this single-story layout typical of a bungalow, results in a higher surface area to volume ratio than, leading to a higher annual heat demand than is required for the standard (see Figure 5). Therefore, while designed following Passivhaus design principles, this bungalow is *not* officially a certified Passivhaus. This house is built using lightweight materials, with external bricks chosen to recall to the traditional British housing. The external wall build-up consists of 102 mm external brick work, 60 mm air cavity, breather membrane, 9 mm of oriented strand board (OSB), 235 mm of Val-U-Therm wall system panel, vapour barrier, 25 mm of rigid insulation (Kingspan's Thermawall), 45 × 35 mm battens, and 12 mm of gypsum board (total thickness 490 mm).

MVHR provided was running at all times throughout the study and with no summer bypass. Ventilation extractions are located in the bathroom and kitchen. There is a ventilation boost switch located in the

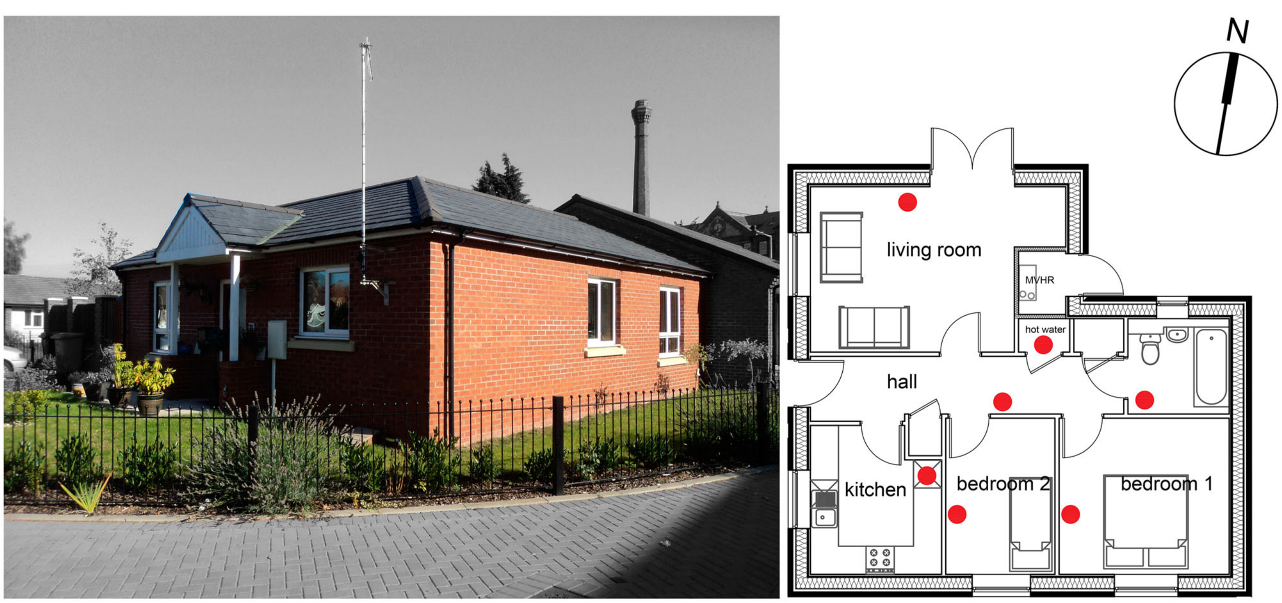

Figure 4. Left: View of the uncertified Passivhaus bungalow UK52 (shaded the entrance facing west). Right: Plans. The red circle indicates the location of the loggers.

Specific building demands with reference to the treated floor area				use: Monthly method	
	Treated floor area	58.7	m²	Requirements	Fulfilled?*
Space heating	Annual heating demand	33	kWh/(m²a)	15 kWh/(m²a)	no
	Heating load	13	W/m²	10 W/m²	no
Space cooling	Overall specific space cooling demand		kWh/(m²a)	-	-
	Cooling load		W/m²	-	-
	Frequency of overheating (> 25 °C)	0.2	%	-	-
Primary Energy	Space heating and dehumidification, cooling, DHW, Auxiliary Electricity and household electricity.	143	kWh/(m²a)	120 kWh/(m²a)	no
	DHW, space heating and auxiliary electricity	104	kWh/(m²a)	-	-
	Specific primary energy reduction through solar electricity		kWh/(m²a)	-	-
Airtightness	Pressurization test result n_{50}	0.6	1/h	0.6 1/h	yes
				* empty field: data missing; '-': no requirement	
Passive House?					no

Figure 5. Passivhaus Planning Package verification results retrieved from the sustainability consultant of UK52.

kitchen. In addition, there is a heat-boost in the form of air supply valve located in the living room to provide an extra level of comfort. Occupants were a couple of retired residents. The second bedroom was occasionally used. The female occupant answered to questionnaires.

House UK54

House UK54 is a 3-bedroom end of terrace house, built in 2013 in a suburban area in York (see Figure 6). This house has higher than building regulations levels of fabric efficiency (see Tables 2 and 3). The external wall build-up consists of 102.5 mm exterior brick, 50 mm of air cavity, 100 mm insulation board, 100 mm concrete block, and 12 mm of gypsum board (total thickness 365 mm). Fresh air is provided by natural ventilation and a centralized mechanical ventilation extract (MEV) in wet rooms. The mechanical ventilation was turned off permanently by the occupants, who preferred to manage ventilation via natural ventilation. In addition, windows are equipped with trickle vents. Heating is provided via traditional radiators connected to a district heating. This home was occupied at all times by a couple of retired residents. Bedrooms 2 and 3 were occasionally used. The male occupant answered the questionnaires.

House UK55

House UK55 is a 3-bedroom detached house, built in 2013 in the same developments (see Figure 7). This house has higher than building regulations levels of fabric efficiency (see Tables 2 and 3) and has the same fabric characteristics as house UK54. The external wall build-up consists of 102.5 mm exterior brick, 50 mm of air cavity, 100 mm insulation board, 100 mm concrete block, and 12 mm of gypsum board (total thickness 365 mm). House UK55 integrates an east-facing sunspace meant to both collect heat during winter and

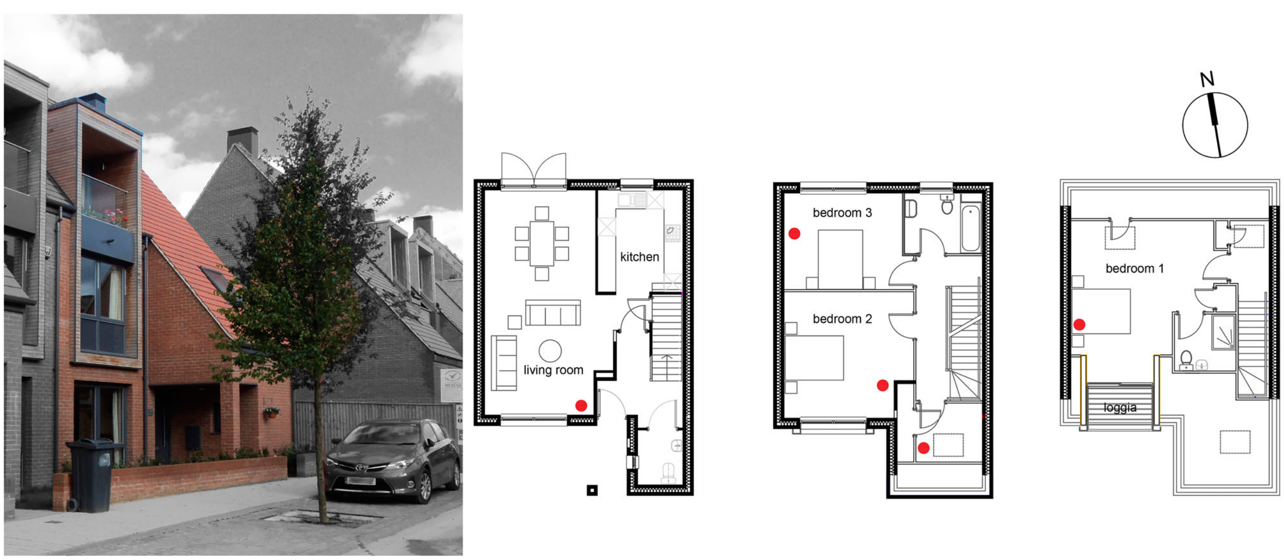

Figure 6. Left: South street façade view of UK54. Right: Plans. The red circle indicates the location of the loggers.

Figure 7. Left: East façade view of UK55. Right: Plans. The red circle indicates the location of the loggers.

to trigger buoyancy ventilation during summer, although the occupants did not used it as intended and kept it closed. The house is equipped with MVHR which was running at all times throughout the study and no provision of summer bypass was in place. Ventilation extractions are located in the ground-floor kitchen and the first-floor bathroom. As for house UK54, this house has a piped heating system connected to the district heating in the development. This house was occupied at all times by a couple of retired residents. The second and third bedrooms were only occasionally used. Responses to questionnaires as well as house details were provided by the male occupant. This house had vulnerable occupants, as one of its occupants suffered from a long-term illness that can alter their perception of heat.

A summary table with all case studies is provided in Tables 2 and 3 below.

Results

Seasonal questionnaires

With the intention to find evidence of overheating by 'asking people first', the results of this study focus on reported overheating and on window opening patterns, from one person per household. These respondents were occupants who managed the energy aspects in their households: an adult male in UK51, an adult female in UK52, an adult male in UK54, and an adult male in UK55.

Reported overheated rooms

One question was specifically designed to gain feedback from occupants and to spot areas of potential overheating within the house. The question was: 'During this time of the year, do you find it difficult to keep comfortably cool in any room?' Participants had to mark the time slots when a room was difficult to keep cool. The time slots were divided into morning (08:00–10:00 and 10:00–12:00), afternoon (12:00–14:00, 14:00–16:00 and 16:00–18:00), evening (18:00–20:00, 20:00–22:00 and 22:00–24:00) and night (00:00–08:00). This allowed for a first-hand approach to the comfort provided to their occupants. This is the reason why there is no mention of the word 'overheating' within the question. The questionnaire ended with an open question to allow participants to provide any information they felt relevant. While the relevant question indicated the time slots of perceived overheating, the frequency of overheating was not gathered. This limitation is integrated with data from the physical environmental monitoring, shown in the next section of this paper.

Looking at Table 4, it becomes evident that occupants reported finding it difficult to keep many rooms cool, especially bedrooms (excluding those in case study UK54). This was true especially in the case studies without thermal mass exposed and with MVHR in use (UK51 and UK52) and particular UK51-bedroom 2 (roof pod bedroom) in different seasons. It is also noticeable that in the questionnaire submitted in Spring 2016 residents reported most cases of rooms as *difficult*

Table 2. Overview of the four case studies with main construction characteristics.

House ID	Dwelling type/year of construction	Energy efficiency standard/location	Internal floor area/ floor to ceiling high $(m^2)/(m)$	U-value ext. walls (W/m^2K)	U-value roof (W/m^2K)	U-value glazing (W/m^2K) average	G-value glazing	Construction type	Thermal mass exposed	Ventilation type	Air Tightness level $m^3/(h.m^2)$ @50 Pa
UK51	mid-terrace/1890, retrofitted in 2010	PassivHaus/Leicester	91/2.5	0.12	0.17	1.31	0.72	solid wall, intern. insulated	no	MVHR (no summer bypass)	2.8 (tested)
	off-site manifatured roof pod					1.31	0.72	lightweight walls	no		
UK52	bungalow/newly built in 2013	PassivHaus/Sandiacre	59/2.5	0.10	0.09	1.08	0.61	lightweight walls	no	MVHR (no summer bypass)	0.44 (tested)
UK54	end-terrace/newly built in 2013	Build. Regs. /York	141/2.5	0.17	0.14	1.12	0.63	insulated cavity wall	YES	MEV	3.9 (tested)
UK55	detached/newly built in 2013	Build. Regs. /York	167/2.5	0.17	0.14	1.12	0.63	insulated cavity wall	YES	MVHR (no summer bypass)	2.98 (tested)

Source: For UK51 and UK52, PHPP and SAP calculations were obtained from sustainability consultants. For UK54 and UK55, SAP calculations were provided by homeowners.

Table 3. Overview of the four case studies with systems description of examined rooms.

House ID	Room	Background ventilation method	Cross-ventilation availability	Solar gains (orientation of glazed areas)	Glazed area (m^2)	Internal shading	External shading
UK51	Living room	Supply air valve	no	East (vertical)	2.5	Light curtains	no
UK51	Bedroom 1	Supply air valve	no	East (vertical)	2.3	Light curtains	no
UK51	Bedroom 2	Supply air valve	yes	East (horizontal) West (horizontal)	0.8	Velux int. screen	no
UK52	Living room	Supply air valve	yes	West (vertical)	0.7	curtains	no
UK52	Bedroom 1	Supply air valve	no	South (vertical)	0.7	curtains	no
UK54	Living room	Trickle ventilation	yes	South (vertical)	2.9	curtains	no
UK54	Bedroom 1	Trickle ventilation	yes	South (vertical)	2.9	curtains	overhang (ext. loggia)
UK55	Living room	Supply air valve	yes	East (adjacent to sunspace), and South, vertical	2.9	curtains	overhang (ext. loggia)
UK55	Bedroom 1	Supply air valve	no	West (vertical)	2.5	curtains	no

Table 4. This table shows the time slots when participants reported difficulty to keep comfortably cool in different rooms throughout the study.

Q1, question 13: *"During this time of the year, do you find it difficult to keep comfortably cool any room? Please specify time slot."*	UK51					UK52					UK54					UK55				
	Jun-15	Aug-15	Oct-15	Jan-16	Apr-16	Jun-15	Aug-15	Oct-15	Jan-16	Apr-16	Jun-15	Aug-15	Oct-15	Jan-16	Apr-16	Jun-15	Aug-15	Oct-15	Jan-16	Apr-16
living room	no	no	no	no	18-22	no	9-16	no	no	14-16	no	no	no	no	no	no	no	no	no	no
kitchen	no	no	no	no	16-22	no	no	no	no	14-16						no	no	18-20	no	no
hall						0-24	0-24	0-24	0-24	20-22	no	no	no	no	no	no	no	no	0-24	no
bathroom (ground floor)						no	no	no	no	14-16	no	no	no	no	no	no	no	no	no	no
bathroom (first floor)	no	no	no	no	18-22						no	no	no	no	no	no	no	no	no	no
bedroom 1 (main)	no	no	no	no	18-22	no	20-8	no	24-8	20-22	no	no	no	no	no	no	14-18	no	no	22-8
bedroom 2	18-24	12-20	24-6	no	14-18	no	20-8	no	24-8	20-22	no	no	no	no	no	no	no	no	no	22-8
bed 3 or lounge	no	no	no	no	no						no	no	no	no	no	no	no	no	no	no
office											11-17	11-17	no	no	no	no	8-12	no	no	no

Notes: The data was collected at various times (and seasons) across the year. Numbers in cells indicate hours of the day.

to keep comfortably cool in houses UK51, UK52 and UK55.

Other noticeable findings of the study are:

- The occupants of house UK51 reported overheating exclusively in bedroom 2 (located in the converted loft and used by one occupant) during most of the monitored seasons. In this bedroom, also known as the roof pod bedroom, occupants attempted to mitigate high temperatures by keeping the internal Velux blinds closed. However, this measure proved insufficient, necessitating the additional strategy of opening windows both day and night, when outdoor conditions allowed for it.
- In house UK52, the occupants reported bedroom 1 (used by two occupants), and the hall to be uncomfortably warm throughout the year. Bedrooms are south oriented with no provision for shading and no window recess. One possible explanation for the difficulty to keep comfortably cool in the hall of case study UK52 is the presence of a nearby cupboard containing a hot water cylinder, which contributed to warming the hall. Occupants also reported difficulty in keeping comfortably cool the west facing living room.
- The occupants of home UK54 reported no issues besides the office (with a Velux window closed at all times due to building works nearby). This issue disappeared once the possibility of window opening was restored after the completion of adjacent building works.
- In house UK55 the occupant did not report overheating issues. However, this house has recorded occurrences of severe overheating. The occupant had a neurological condition limiting their perception of warmth. This confirms that overheating can affect individuals with vulnerabilities, especially if they are unable to perceive overheating (as introduced in the first part of this paper).

Window opening patterns

The questionnaire had a specific question designed to collect information about window opening as a practice to purge heat. The question submitted was: 'How often do you open the windows in order to cool your house?' (never = 0, rarely = 1, once a week = 2, daily = 3, night = 4, day&night = 5). Results are reported in Figure 8.

It is interesting to notice that most occupants of the surveyed homes performed window opening day and night (even outside the summer season). It was also found that rooms where natural ventilation was not used, was due to some restriction rather than the need itself not existing. The open questions, which allowed participants to elaborate on their answers to the other questions, revealed that restrictions to open the windows had origins in (i) physical inability to open the windows (e.g. the window kitchen in UK52), (ii) concerns about security and fear of burglary (especially ground floor windows in UK51 and UK52), (iii) odour disturbance (people smoking in the street in UK51), and (iv) noise disturbance (UK51). In more detail:

- In case study UK51, windows were open in many rooms across all seasons. Whereas bedroom 1 (used by 2 occupants) was kept closed due to noise from the street, bedroom 2 (a converted loft used by one occupant) was kept open day and night, because it was found to be difficult to keep comfortably cool.
- In case study UK52, windows were regularly kept always open during daytime, also in winter. The exception was the window kitchen, which was found to be difficult to reach and open as the

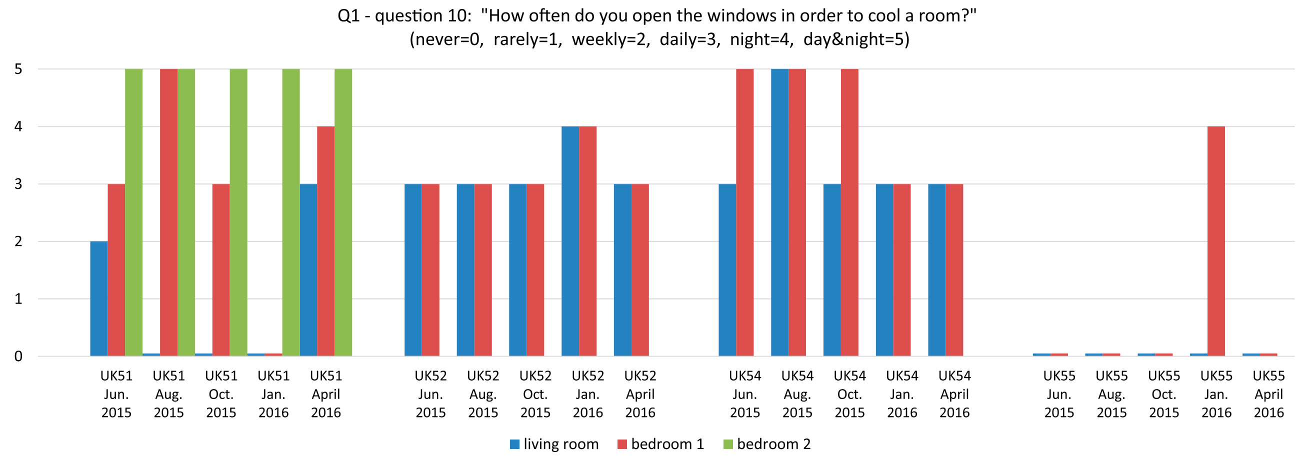

Figure 8. Results of seasonal questionnaire: window opening patterns for living rooms and bedrooms in use throughout the various seasons.

window's handle was out of reach due to the depth of the worktop plus the depth of the wall.

- In case study UK54, all windows were opened at least daily, with instances of day&night ventilation in summer. Construction works prevented occupants from opening the windows in the office room and bedroom 2 (street facing). Occupants of this house managed the house via natural ventilation and found no use for the mechanical extract ventilation provided, which was then turned off. Occupants revealed that they have learnt this adaptive behaviour during their numerous summer holidays in Mediterranean countries.
- In case study UK55, windows were kept shut in bedroom 1 (2 occupants) despite high temperatures. The reason for this was that the occupant explicitly delegated all ventilation purposes (i.e. providing background ventilation and cooling ventilation) to the MVHR system. In fact, in this home MVHR was managed in the misconceived belief that provided air changes would cope with the purging of high temperatures and by so (wrongly) delegating the provision of summer comfort to the MVHR. In addition, it was later connected to the fact that the occupants did not notice how warm temperatures were getting due to a neurological condition that prevented them from feeling the heat.

Focusing solely on bedrooms (Figure 8), it becomes apparent that during the warmer season, occupants of case study UK55-bed 1 (used by two occupants) windows were kept closed. Conversely, occupants of case study UK51-bed 2 (used by one occupant) maintained open windows day and night throughout the entire 11-month monitoring period. It is noteworthy that both rooms occupants reported overheating. However, the persistent overheating in UK51-bed 2 (converted loft) despite continuous ventilation highlights the limitations of this approach. While case study UK55-bed 1 may still benefit from adaptive cooling strategies to reduce temperatures, such as night-time ventilation, the data suggests that case study UK51-bed 2 requires alternative cooling solutions.

Physical environmental monitoring

Summer performance

The summer analysis here presented considers the sensors' recordings from 30 June 2015 until 13 August 2015, at all times. The recorded temperatures of living rooms and bedrooms that were used daily have been analysed to spot the most concerning areas or rooms in the house (rooms used sporadically, such as guest bedrooms, are excluded). This analysis includes a short heatwave that occurred in England (from 30 June 2015 until 2 July 2015). Box and whisker plots and histograms of living rooms and used bedrooms are presented in Figures 9 and 10 respectively. In these figures, rooms where participants declared to be difficult to keep cool are shown with a red cycle.

Descriptive statistics living rooms and bedrooms. When looking at the descriptive statistics in Table 5, it can be observed that most of the high temperatures were in the bedrooms on the upper floors (this tendency did not change in other seasons). The living rooms were characterized by lower temperatures.

Further points to be noted are:

- During the summer, *mean temperatures* of all rooms in all homes are in the range 21.34–23.66°C. The mean temperatures in the living rooms were lower than those of the respective houses' bedrooms.

- *Minimum temperatures* ranged from 17 to 19°C. UK54's temperatures were maintained with no high peaks in temperature, as opposed to the other homes.
- *Maximum temperatures*: across all homes, maximum indoor temperatures ranged from 27 to 34°C. The hottest room (which was the converted loft in house UK51) was consistently identified by occupants to be too hot, particularly during the heatwave. House UK54 exhibited the lowest maximum temperatures, likely attributable to two factors: (i) its unique north–south orientation, reducing solar gain on the south façade partially shaded by an external loggia, and (ii) occupants' regular ventilation practices. Notably, UK54 is the only home without an MVHR system, eliminating potential heat recovery during summer months. In contrast, the overheating homes lacked a summer bypass feature in their MVHR systems, exacerbating overheating conditions.

An important observation is that whilst house UK52 and house UK54 have similar average temperatures (between 22 and 23°C), there is a remarkable difference in thermal experience: whereas the occupants of house UK54 reported that they felt 'sheltered' against heat, the occupants of house UK52 said that at times they wake up and stayed in the living room at night to find some thermal relief.

Heat wave performance

Recorded temperatures of the hottest week during the same summer are plotted for all living rooms and bedrooms in Figures 11–14 and for each room in Figure 15. In addition, Figures 11–14 show also the calculated *Maximum Acceptable Temperature* (T_{max}) and an

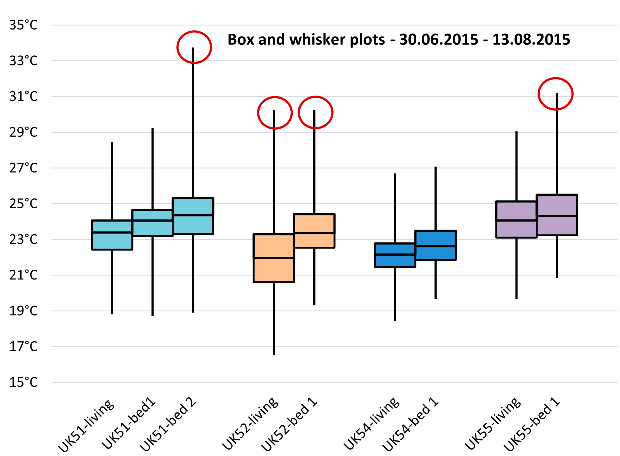

Figure 9. Box and whisker plots of summer temperatures (at all times) of living rooms and bedrooms. Circled in red are the rooms that occupants claimed to be difficulty to keep comfortably cool.

Upper temperature Limit (T_{upp}) according to CIBSE-TM52. This period includes a short heatwave occurring in England from 28 June 2015 to 3 July 2015. Due to unreliable on-site temperature data collected at Sandiacre UK52, data from Leicester UK51 was used. While this approach may not fully capture potential microclimate variations, it is important to note that Leicester and Sandiacre are only about 33 km apart and have similar elevations, with Leicester being about 24 metres higher. Therefore, Leicester's temperature data is considered the best available proxy for Sandiacre UK52.

In this context it should be noted that:

- Graphs in Figures 11–14 show that while external temperatures begun falling from 2 July 2015, the high internal temperatures fell in a similar trend in all houses.
- In home UK52 (Figure 12), in bedroom 1 temperatures remained above 25°C for over three days after the end of the heatwave. This was unexpected since there is no exposed thermal mass. Building materials combined with occupants' tendency to window opening could have lowered temperatures faster than houses with exposed thermal mass (as per homes UK54 and UK55). It is not possible to establish with complete certainty the reason for these temperatures, but it is worth mentioning other concurring sources of internal heat gains such as (a) the continuously operating MVHR (with heat recovery) and (b) the presence of a hot water cylinder in the hall making it difficult to cool (see Table 4 in previous section and Figure 15 below).
- In home UK54, in bedroom 1 temperatures were below the peak day external temperature, but were greater than for the subsequent days. A similar temperatures behaviour was found in home UK55 which has the same building specifications (only difference is the presence of MVHR with no summer bypass). However, the pattern was repeated with a 3–4°C difference higher (see Figures 13 and 14).

Overheating assessment

Homes underwent overheating assessments, using a set of guidance published by CIBSE and using the summer data. Overheating assessments will consider the 'threshold approach' (CIBSE Guide A, 2006), the 'adaptive approach' (CIBSE-TM52, 2013) and the combined approach (CIBSE-TM59, 2017). It should be noted that this set of guidance is intended for simulated data. By contrast, in the context of this research it has been applied to the summer monitored data. This use is justified by the exploratory nature of this research.

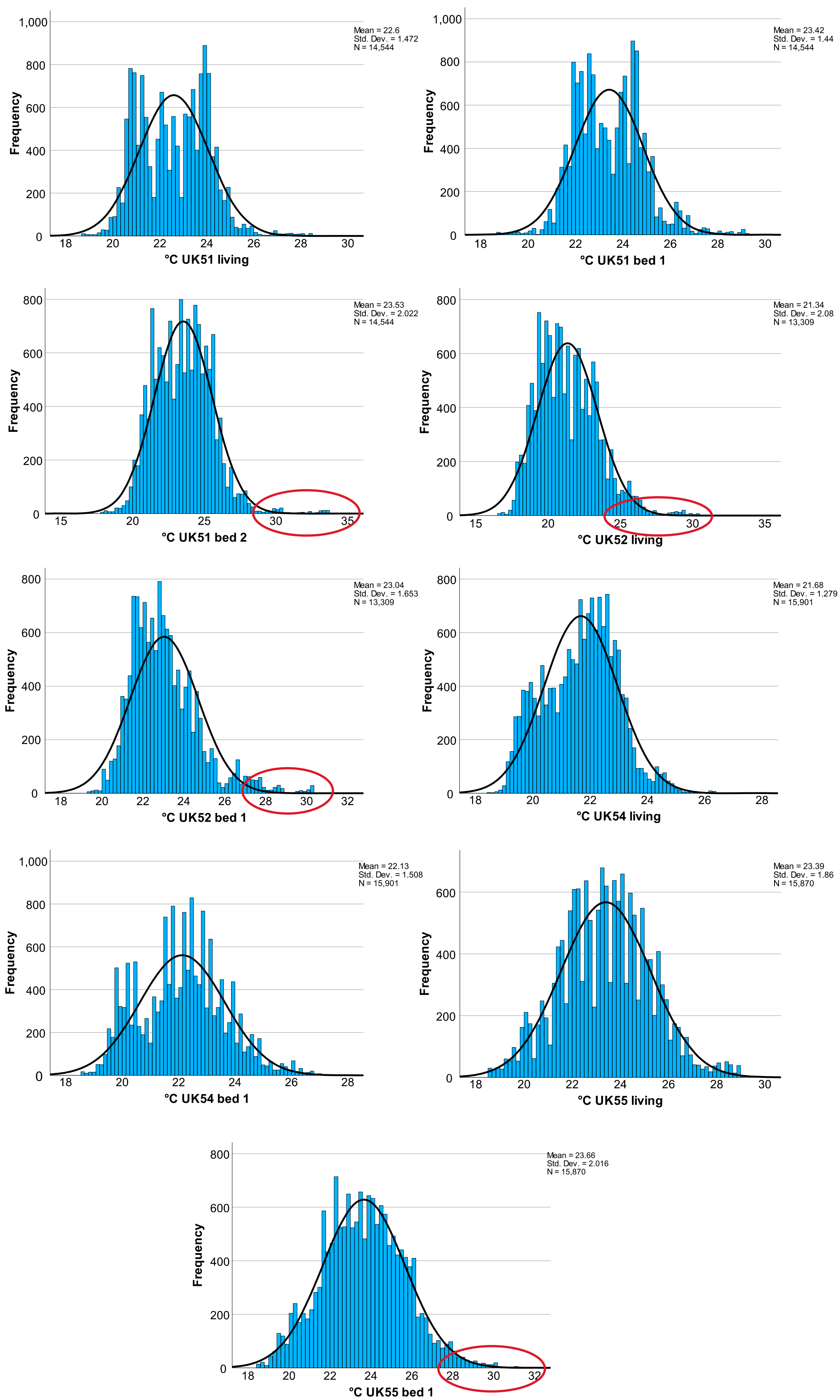

Figure 10. Histograms and normal distribution charts of living rooms and bedrooms during summer (at all times). The right tail (circled in red) in UK51-bed 2, UK52-bed 1 and UK55-bed 1 show the correspondence with the rooms reported to be "*difficult to keep comfortably cool*" and as they were recorded from 30 June 2015 until 13 August 2015.

Table 5. Descriptive statistics (°C) for living rooms and bedrooms, at all times occupied, from 30 June 2015 to 13 August 2015.

	N	Range	Minimum	Maximum	Mean	Std. Deviation
°C UK51 bed 1	14544	11	19	29	23.42	1.440
°C UK51 bed 2	14544	16	18	34	23.53	2.022
°C UK51 living	14544	10	19	28	22.60	1.472
°C UK52 bed 1	13309	11	19	30	23.04	1.653
°C UK52 living	13309	14	17	30	21.34	2.080
°C UK54 bed 1	15901	8	19	27	22.13	1.508
°C UK54 living	15901	8	18	27	21.68	1.279
°C UK55 bed 1	15870	13	19	31	23.66	2.016
°C UK55 living	15870	11	19	29	23.39	1.860
Valid N (listwise)	13308					

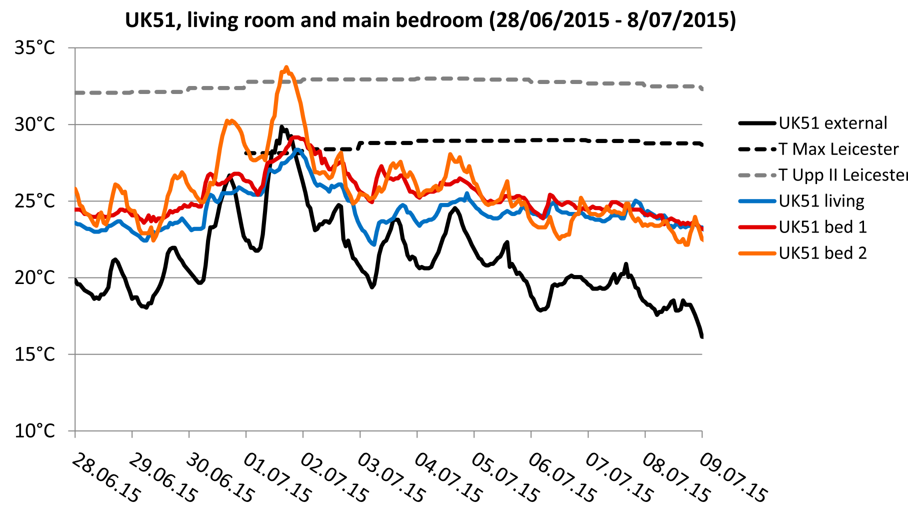

Figure 11. Temperature plots for house UK51 during the hottest week in 2015.

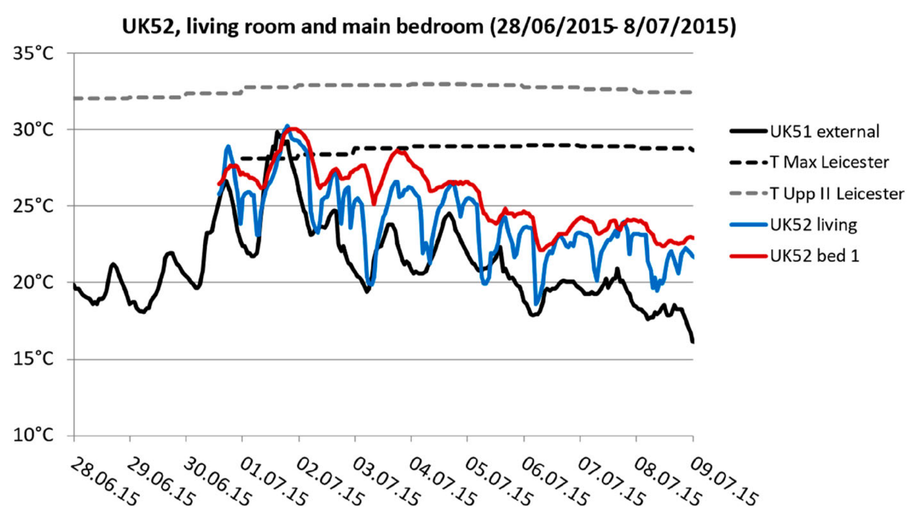

Figure 12. Temperature plots for house UK52 during the hottest week in 2015. Leicester temperature data is used for both as external UK52 data were not available.

The first assessment was performed according to the CIBSE Guide A (2006), which states that overheating occurs by exceeding a single limiting temperature for 1% annual occupied hours (a) in living areas, operative temperatures should not exceed 28°C; and (b) in bedrooms, operative temperatures should not exceed 26°

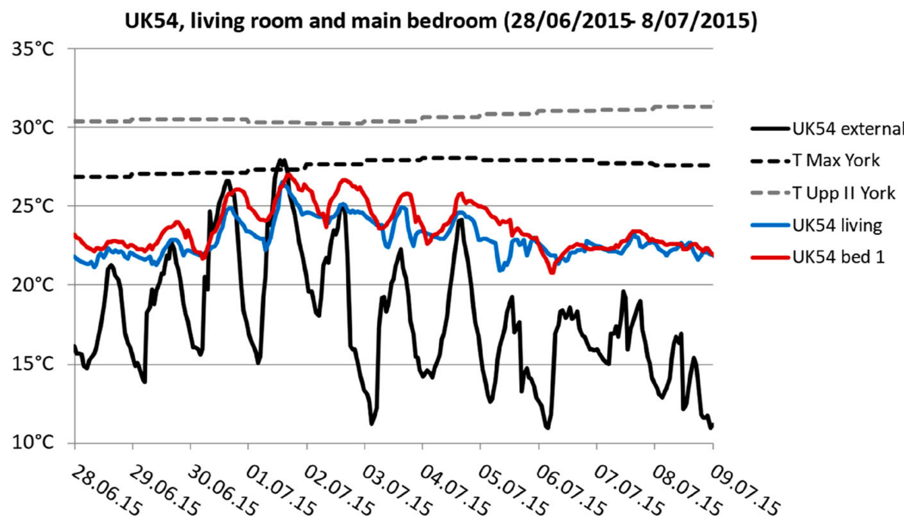

Figure 13. Temperature plots for house UK54 during the hottest week in 2015.

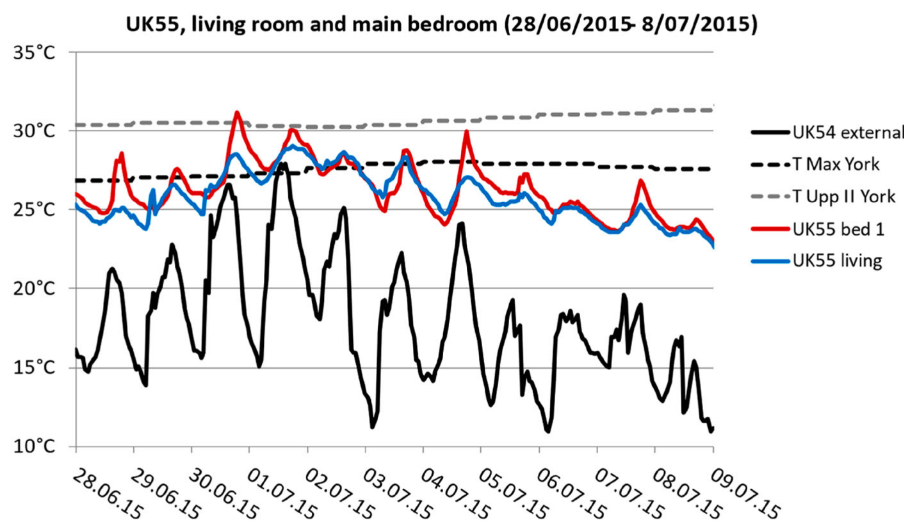

Figure 14. Temperature plots for house UK55 during the hottest week in 2015.

C. If either of these fails, the room is considered to have overheated.

The second assessment was performed according to the adaptive CIBSE-TM52 guidance. Accordingly, any naturally ventilated building would be affected by overheating if that building or one of its rooms fails any two of the following three criteria (period 1st May to 30th September):

- CIBSE-TM52-criterion-1 considers the hours of exceedance in which the temperature difference is greater than, or equal to, one degree (K), which should not be more than 3% of occupied hours;
- CIBSE-TM52-criterion-2 consists of a daily weighted exceedance setting a daily limit of acceptability to allow for the severity of overheating. The weighted exceedance must be less than or equal to 6 h on any one day;
- CIBSE-TM52-criterion-3 introduces a maximum daily temperature – an adaptive threshold – in consideration of the category of building and its comfort expectancy (i.e. category I for vulnerable groups of people, category II for normal expectation of recently built and refurbished buildings).

The CIBSE-TM52 methodology for adaptive assessment required first to calculate the exponentially weighted *Running Mean Outdoor Air Temperature* (T_{rm}). This was obtained by employing the equations provided in box 2 of CIBSE-TM52 and the temperatures recorded with loggers onsite as well as in the premises of the studied homes. The second step consisted of using this weighted temperature and derive a *Comfort Temperature* (T_{Comf}). This was obtained by equation 6 in CIBSE-TM52 (2013). The third step consisted of

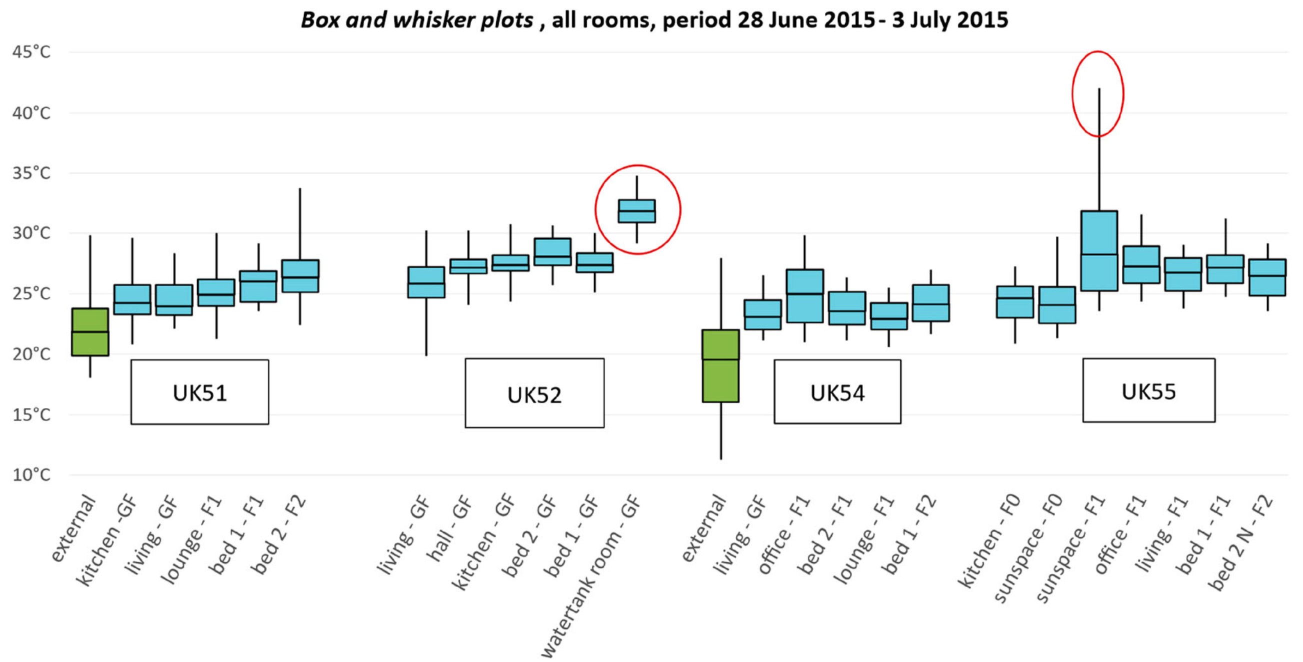

Figure 15. Box and whiskers plots all rooms in case studies at all times during the hottest week. Circled in red: closed with domestic hot water cylinder (left) and first floor of the sunspace (right).

calculating the related *Maximum Acceptable Temperature* (T_{max}) and an *Upper temperature Limit* (T_{upp}) (BSI, 2007). Importantly, these temperatures depend on the categorization of the buildings to allow for consideration of the level of comfort expectation.

CIBSE-TM52 requests to realistically consider the comfort expectations of occupants (2013). This analysis used data gathered from the questionnaire to embed the reality of the case studies. In terms of vulnerability, houses UK51 and UK55 had vulnerable occupants. Importantly, the analysis considered buildings in both categories, i.e. category I (for vulnerable groups of people, henceforth with higher expectation of comfort) and category II (recently built and refurbished buildings, henceforth a normal expectation of comfort). This double assessment – in Cat. I and in Cat. II – was chosen to (a) accurately reflect the level of comfort expected (as it would have been chosen during the design stage) and (b) consider the actual occupancy and vulnerability condition. The analysis also incorporated the occupied hours retrieved from the questionnaire. The third assessment CIBSE-TM59 assessment is formulated for homes that are predominantly naturally ventilated, including those with MVHR. It requires homes to pass two criteria:

- CIBSE-TM59-criterion-1: For all occupied spaces, rooms have to comply with TM52-criterion-1 (hours of exceedance).
- CIBSE-TM59-criterion-2: for bedrooms only and exclusively in the timeframe from 10 pm to 7 am, operative temperatures should not exceed 26°C for more than 1% of annual hours.

In living rooms, it is required that the first and the second steps of CIBSE-TM52 are followed.

In considering the thresholds assessments (CIBSE Guide A 2006 and CIBSE-TM59-criterion-2) whenever 'hours above a threshold' were required, interval resolutions of 10 min were recorded.

Results of the overheating assessment using all three methods indicated that overheating occurred predominantly in bedrooms. The CIBSE Guide A (2006) assessment and the CIBSE-TM59 assessment produced comparable results. By contrast, the CIBSE-TM52 assessment indicated fewer occurrences of overheating. These findings are reported in Table 6.

In the assessment, overheating in house UK51 was found in both bedrooms using both CIBSE Guide A (2006) and CIBSE-TM59 assessments. By contrast, the CIBSE-TM52 assessment method indicated that overheating did not occur. Moreover, CIBSE-TM52 was found not to be consistent with the occupants' responses, who considered bedroom 2 to be too hot for the largest part of the summer. To reflect the reality of occupancy, and consequentially the actual thermal comfort expectation of this building, during the CIBSE-TM52 analysis, house UK51 was also treated as a category I building (BSI, 2007) with a view of reflecting its (temporary) vulnerable occupants. Only under these circumstances bedroom 2 (roof pod) was found to overheat.

Table 6. Results of the overheating assessments.

ID	room	CIBSE Guide A 2006	CIBSE TM52 (Cat.II)	CIBSE TM52 (Cat.I) *	CIBSE TM59
UK51 *	bedroom 1	OVERHEATING	✓	✓	✓
	bedroom 2	OVERHEATING	✓	OVERHEATING	OVERHEATING
	living room	✓	✓	✓	✓
UK52	bedroom 1	OVERHEATING	✓	✓	OVERHEATING
	living room	✓	✓	✓	✓
UK54	bedroom 1	✓	✓	✓	✓
	living room	✓	✓	✓	✓
UK55 *	bedroom 1	OVERHEATING	OVERHEATING	OVERHEATING	OVERHEATING
	living room	OVERHEATING	✓	✓	✓

* prescence of vulnerable occupants

In a similar vein, in house UK52, overheating was found in bedroom 1 with the CIBSE Guide A (2006) and the CIBSE-TM59 assessments. By contrast with CIBSE-TM52, there was no overheating in bedroom 1. Additionally, in this case the CIBSE-TM52 assessment does not reflect the responses given by the occupants, who opted for vacating the bedroom at nighttime during the heatwave in order to find some heat relief. House UK54 did not overheat. Notably, the results of the assessment in case study UK54 were consistent with the occupant responses throughout the seasonal questionnaires. In house UK55, the main bedroom was found to overheat under all assessments. In that house, the entire house's ventilation was managed through the MVHR, and the residents did not open the windows. It is worth underlining that this home had an occupant suffering from a neurological condition affecting their thermal perception, and accordingly should be considered a vulnerable occupant. For this reason, the building can be considered category I (for vulnerable groups of people), as opposed to category II (for normal expectation of comfort).

Discussion

Reported practices of ventilation and perceived overheating

In some instances, responses from the questionnaires corresponds with the loggers' temperatures. For instance, the occupier in house UK51 complained about bedroom 2 (roof pod) in the first survey. This coincided with the overheating assessment. Conversely, responses from house UK55 changed during the monitoring period, and different rooms were mentioned on different occasions. This indicates that the assessment carried out by occupants with health conditions may not be reliable. In addition, responses to Question 13 have provided evidence that consulting only occupants is not sufficient to identify overheating. The main found reasons for this were that people did not want to complain and, as for house UK55, that occupants had a limited thermal perception. Therefore, questionnaires to occupants are to be considered only one part of a more comprehensive overheating assessment.

Another important factor to be considered in relation to overheating is the role of building's adaptive capacities. While (healthy) people may well adapt to find comfort, this possibility is reduced insofar as buildings do not provide different means for adaptation. For instance, the bungalow UK52 was designed for (only) night cooling, and was no equipped with external shading. Incidentally a good portion of new and low-energy homes may present the same features. By contrast, in another case study (house UK51, where bedroom 2 (roof pod) was not comfortably cool despite the window being open during the day and many times during the night) occupants could rely on the temporary shelter provided by the cooler ground floor living room during the heatwave. Importantly, in flats with a more homogeneous temperature, vacating might not be an option.

A temporary unavailability of window opening was also observed in the bedrooms of UK51 and the office of UK54. This demonstrated the risk of relying solely on window opening as a cooling strategy, for ventilation might not be feasible due to several contextual factors such as the inability to open windows, outdoor noise, traffic, or fear of burglary. Furthermore, the unavailability of window opening is to be carefully evaluated in the context of low-energy homes. This evaluation should also account for scenarios where window opening might not be the most effective cooling method, such as during heatwaves when outdoor pollution increases (WHO, 2024).

Differences between the assessments

The occupant survey performed in all four low-energy homes showed that case studies UK54 and UK55 in York provided results that agree in all three methods for overheating assessment (CIBSE 2006, CIBSE-TM52 2013 and CIBSE-TM59 2017). More specifically, house UK54 showed no overheating with all three methods and house UK55 showed overheating with all three methods. While identical in construction details (building fabric specifications and G-value), these two homes differ in orientation (north–south in UK54 vs. east–west in UK54) and ventilation management (frequent window opening in UK54 vs. no window opening in UK55). This difference highlights the importance of both purge ventilation and window orientation, especially considering the lack of external shading in most English homes.

Case studies UK51 and UK52 were shown not to be affected by overheating when assessed using CIBSE-TM52 and, instead, to be affected by overheating when assessed using CIBSE-TM59. In more detail, in both case studies, the TM52 upper limit (CIBSE-TM52-criterion-3) passed; by contrast, it did not pass the fixed threshold of 26°C in the bedrooms. In other words, the adaptive CIBSE-TM52 assessment depicted UK51 and UK52 as an acceptable environment in terms of overheating, whereas the CIBSE-TM59 assessment indicated them as buildings prove to overheating.

This difference was further investigated by taking a deeper look at the temperatures of the hottest day of the recorded period (1.07.2015), and in particular at T_{upp} (see Table 7). Using bedroom 1 in house UK51 as reference, the recorded external temperatures were used to calculate a derived indoor comfort temperature of 25.1°C (step II in the CIBSE-TM52 calculation procedure). From this value, a derived maximum acceptable temperature (T_{max}) of 28.1°C and a derived upper limit temperature for the category of building considered (T_{upp}) of 32.1°C were established (step III in the CIBSE-TM52 calculation procedure). It can be argued that the resulting T_{upp}, would be rarely reached in England (in fact, only UK55 failed CIBSE-TM52-criterion-3) and that CIBSE-TM52-criterion-3 is less likely to fail. Therefore, the condition of overheating appears to rely almost entirely on the other two criteria (CIBSE-TM52-criterion-1 and CIBSE-TM52-criterion-2). The authors of this paper limit this statement when using historic climate data.

CIBSE 2006 and CIBSE-TM59 2017 assessments effectively identified excessively warm temperatures. This corroborates with the occupant perceptions. This makes them valuable assessment tools for quickly identifying potential overheating issues in houses during the post-construction phase, thus ensuring suitability for occupants to implement adaptive cooling strategies (e.g. solar control, ventilation). This contradicts the views of other researchers regarding CIBSE-TM59's reliability (Kim et al., 2023; Mourkos et al., 2020). Finally, the limitations of using monitored data and for a shorter proportion of time for the overheating analysis should be explicitly acknowledged. The overheating analysis here presented is not comparable with predictive assessments based on standard weather years and an annual basis.

Temporary vulnerability

The occupancy was based on occupants' responses to questionnaire; however, during the monitoring period the occupancy changed in some of the case studies. For example, house UK51 had a new-born baby whilst

Table 7. Detail of the CIBSE-TM52 overheating assessment evidencing the calculated comfort (Tcomf) and upper limit (Tupp) temperatures of house UK51-bed1.

	°C external temperature (MEASURED)	°C mean outdoor temperature (CALCULATED)	°C running mean temperature (CALCULATED)	°C "T comf" (CALCULATED)	°C "T max" (CALCULATED	°C "T upp" Cat. II (CALCULATED)	occupied (1=yes)	°C UK51 bed1 temperature (MEASURED)
01/07/2015 02:00	22.0	23.1	19.2	25.1	28.1	32.1	1	26.2
01/07/2015 03:00	22.0	23.1	19.2	25.1	28.1	32.1	1	25.9
01/07/2015 04:00	21.8	23.1	19.2	25.1	28.1	32.1	1	25.7
01/07/2015 05:00	21.8	23.1	19.2	25.1	28.1	32.1	1	25.4
01/07/2015 06:00	22.0	23.1	19.2	25.1	28.1	32.1	1	25.8
01/07/2015 07:00	22.8	23.1	19.2	25.1	28.1	32.1	1	26.0
01/07/2015 08:00	24.4	23.1	19.2	25.1	28.1	32.1	1	26.9
01/07/2015 09:00	26.1	23.1	19.2	25.1	28.1	32.1	0	27.5
01/07/2015 10:00	27.3	23.1	19.2	25.1	28.1	32.1	0	27.6
01/07/2015 11:00	28.3	23.1	19.2	25.1	28.1	32.1	0	27.6
01/07/2015 12:00	28.2	23.1	19.2	25.1	28.1	32.1	0	27.7
01/07/2015 13:00	29.0	23.1	19.2	25.1	28.1	32.1	0	27.8
01/07/2015 14:00	28.8	23.1	19.2	25.1	28.1	32.1	0	27.9
01/07/2015 15:00	29.9	23.1	19.2	25.1	28.1	32.1	0	28.1
01/07/2015 16:00	29.6	23.1	19.2	25.1	28.1	32.1	0	28.2
01/07/2015 17:00	29.7	23.1	19.2	25.1	28.1	32.1	0	28.5

house UK51-bedroom 2 was used most of the time during the monitoring period. Not only did the occupancy here changed, but also the category of the building should have been changed (even though briefly) for part of the period, e.g. during the pregnancy of an occupant, after the baby was born and when an occupant was temporarily confined in bed. This consideration would affect the maximum acceptable temperature (T_{max}) and upper limit temperature (T_{upp}), cautiously restricting these thresholds.

Furthermore, house UK55 presented the case of a vulnerable occupant due to their lack of thermal sensation which exposed them to a higher risk to heat stress. In other words, the fact that in two out of four houses occupants turned out to be vulnerable (one temporarily and the other permanently) raises questions regarding the appropriateness of considering category II when throughout the life cycle of an occupant there will be stages of vulnerability.

Building regulations Part O

As shown in the previous paragraphs, some low-energy homes can overheat. These findings can also be used to evaluate the new requirement concerning overheating (Part O). One may wonder, for instance, whether the new standards introduced by Part O could have prevented overheating in the case studies. For this purpose, the four case studies were assessed against the simplified method outlined in Part O. All the monitored homes were considered to have cross ventilation and be located in 'moderate risk' locations. This meant they did not require a shading strategy (as outlined in paragraph 1.9 of Part O, requirement 2a.2C), which would have been mandatory for houses in high-risk areas. The compliance checklist with requirements and calculations for all houses is shown in Table 8.

When considering whether Part O could have prevented overheating in low-energy homes, two key considerations emerge based on the cases studied. The first consideration is that refurbished buildings fall outside the scope of Part O. In terms of Part O compliance, house UK51, as a retrofitted dwelling, would normally be excluded. Interestingly, house UK51 exhibited severe overheating, particularly in the bedrooms. This suggests that the current requirement fails to apply to a large portion of the existing building stock. The relevant building stock can thus be potentially susceptible to overheating even after it has undergone deep energy renovations. Notably, House UK51 incorporates Passivhaus principles, particularly in its focus on fabric energy efficiency. However, it would not have met the requirement for the maximum glazing area in the room with most windows – the living room – as that requirement is set out in Part O. UK51 fails to meet the requirement as it is a Victorian house, and Victorian houses were designed to maximize daylight. Additionally, the house's windows would not have passed the shading requirement set out in Part O, because their G-value is above the required maximum. Finally, in terms of removing excess heat, house UK51 failed to achieve the total minimum free area requirement at the house level because traditional sash windows were replaced with hinged windows that have a lower free area value.

The second consideration concerns the buildings – new homes – subject to Part O regulations. Consider House UK52, which would comply with Part O, insofar as the simplified method is used. Designed with input from a sustainability consultant and incorporating certain Passivhaus design principles inherently focused on summer comfort, this house nonetheless experienced occasional overheating according to its occupant. This discrepancy between predicted and actual performance highlights a potential limitation of Part O. Notably, the bungalow's restricted window opening due to safety concerns and the occupant's physical limitations (difficulty reaching the kitchen window handle), combined with the location of a hot water cylinder in the hallway, exacerbated overheating, as confirmed by the occupant. It is essential to recognize that hallways are typically excluded from overheating assessments as transition spaces. A crucial question is whether this hallway overheating influenced temperatures in adjacent occupied rooms. This factor should be considered in future research to better understand the impact of hallway heat sources on overall indoor comfort.

House UK54 is another case where the simplified method produced inaccurate results. While house UK54 met the minimum free area requirement in the bedrooms, as this minimum is indicated in Part O, it failed to meet the total minimum free area requirement for the entire house. Despite this failure, the data collected in this study showed that house UK54 did not overheat possibly because the combination of the house's north–south orientation, the thermal mass exposure of the building, and the occupants' adaptive behavioural strategies, in particular the window opening strategies to manage the temperature – in line with advice provided in the UK heatwave plan (Beat the Heat, n.d.) – helped to keep overheating at bay. So, here we have a house that does not overheat even if it falls short of the requirements imposed by Part O.

In conclusion, the introduction of Part O represents a significant step forward in preventing overheating in

Table 8. Part O compliance check list for all case studies (simplified method).

Part O – Compliance checklist	reference values		UK51	UK52	UK54	UK55
Part 1 – Building details and declarations						
1.1 Building and site details						
Town			Leicester	Sandiacre	York	York
Proposed building use/type of building	(a) residential dwelling/flat, (b) residential institutional (school, living accomodation) (c) residential other (student accomodation)		(a) residential dwelling – because is retrofit, it does not apply	(a) residential dwelling	(a) residential dwelling	(A) residential dwelling
Are there any security, noise or pollution issues?			noise: residential street urban noise closer (row of terrace houses)	security: bungalow ground floor	temporary pollution and noise from nearby construction works	not declared
Part 2 – Design details – Part 2a – Simplified method						
2a.1 Site details						
Site location	High-risk/moderate risk area		moderate risk	moderate risk	moderate risk	moderate risk
Building category	with cross ventilation/without cross ventilation		with cross-ventilation	with cross-ventilation	with cross-ventilation	with cross-ventilation
2a.2 Designed overheating mitigation strategy						
(A) Maximum area of glazing (% of floor area)	North	18	–	7.7%		
	East	18	5.7%	–		
	South	15	–	–	6.9%	9%
	West	11	–	–		
(B) Maximum area of glazing in the most glazed room (% of floor area of the room) with cross-ventilation	North	37	–	24.7%		
	East	37	**38%**	–		
	South	22	–	–	15.8%	**28%**
	West	22	–	–		
(C) Shading strategy not applicable as not high risk location	(a) external shutters with means of ventilation (b) glazing G-value max. 0.4 (c) overhangs with 50 degree altitude cut-off on due south-facing facades only		(a) no external shutters (b) G-value 0.72 (c) no overhangs in south-facing facades	(a) no external shutters (b) G-value 0.57 (c) no overhangs in south-facing facades	(a) no external shutters (b) G-value 0.63 (c) partially overhangs with 50 degree altitude cut-off on due south-facing facades	(a) no external shutters (b) G-value 0.63 (c) no overhangs in south-facing facades
(D) Total minimum free area	9% of the floor area/55% of the glazing area		**4%/54%**	6%/58%	**8%/45%**	**6%/35%**
(E) Bedroom minimum free area	4% of the floor area of the room		5%/3%	5%	11%	6%
Part 3 – Completion details Has the residential building been constructed and completed according to the specifications set out in Parts 1 and 2 of this checklist?			**No**	Yes	**No**	**No**

Note: Shaded cells indicate criteria not required due to building type or site location. In red are the failed criteria.

low-energy houses, since the requirement (1) provides clear guidance on limiting solar gains and removing excess heat and (2) considers other non-thermal factors that can impact occupant well-being, such as acoustic comfort, security, and the urban heat island effect. However, based on the case studies considered in this research, it can be stated that, on the one hand, Part O neglects at least some of the relevant overheating-enhancing factors, like roof pods (UK51), hot water cylinder placement (UK52), or sunspaces (UK55), and, on the other hand, it does not account for elements (such as orientation and thermal exposure of the house as well as the adaptive behaviour of the occupants) that can mitigate the risk of overheating.

Design considerations

In addition to the aspects already discussed in the previous section, there are some additional design considerations that can be brought together as learning points from these case studies. These considerations explore whether the chosen designs could have impacted the indoor temperatures.

Atypical architectural elements

1. Highly insulated roof pod (case UK51): The location of the MVHR outlet extract (on the lower floor to the roof pod) in combination with the warm roof construction, may have contributed to stratification, where warm air accumulates and becomes trapped in the second-floor roof pod. This case emphasizes the critical role of designers in considering the impact of building layout, ventilation system design, and roof type on thermal performance. This applies to both newly built as retrofitted buildings where established guidelines (or rules of thumb) are still evolving and their use for home extensions should be carefully considered. Several recommendations can be made, including equipping roof pods with a dedicated extract system to improve ventilation, installing external shading devices for roof pod windows to prevent solar heat gain, and using low-G-value glazing.
2. Sunspace (case UK55): Originally designed to create buoyancy and optimize natural ventilation, the sunspace in this case was not used as intended. Instead of its intended purpose, it functioned as a greenhouse with no window opening, leading to the highest recorded temperatures. This highlights the critical need for designers to provide clear instructions (house manuals) to occupants. To fully harness the symbiotic relationship between building performance and occupant behaviour inherent to low-energy homes, such guidance must be integral to the design process.

Thermal mass

The case studies demonstrate the effectiveness of thermal mass in providing resilience to high indoor air temperatures, provided that it is combined with an adequate window opening strategy and solar control strategy. Case UK54 exemplifies this successful combination. Here, the occupants understood cooling techniques (unlike the occupants of UK55). Additionally, house UK54 offered features such as effective cross-ventilation and some solar control, further facilitating cooling. What case UK54 shows, then, is that, for optimal performance, thermal mass needs to be paired with (a) occupant behaviour – i.e. window opening at the coolest hours and (b) external shading. Conversely, case UK55, despite very similar building specifications to UK54 (including exposed thermal mass), serves as a cautionary tale, highlighting the severe overheating resulting from the absence of these factors.

MVHR

The three cases that experienced overheating were all equipped with MVHR systems but lacked a summer bypass. These homes also lacked house manuals providing guidance on ventilative cooling strategies through window opening. This could lead to misconceptions about cooling homes (e.g. occupants in house UK55 believed ventilative cooling occurred via the MVHR).

Additionally, it is noteworthy that house UK52, despite meeting Part O regulations, experienced overheating. While other factors contributed to this, the absence of a summer bypass may have partially negated occupant efforts to cool the home. This suggests a need for further research into mandating summer bypasses in MVHR systems under Part O regulations.

Secure and accessible windows

Part O rightly emphasizes the importance to secure the possibility of window opening for effective heat removal. However, case UK52 illustrates a potential pitfall. Thick walls and the placement of kitchen furniture can make window opening difficult, or even, impossible for some residents. This constitutes a lost opportunity for purging heat and odours through ventilation that designers need to address.

No external shading

The case studies are located in an area considered at ‘moderate risk’ according to Part O. Consequently, there was no requirement for solar control measures, such as (a) external shutters (b) glazing with a G-value of 0.4 or lower and (c) overhangs with a 50-degree altitude cut-off. However, considering the overheating experienced in some cases and considering a warming climate, it might be advisable to revisit these requirements, using recent weather data, especially for new and highly insulated homes in similar climates.

Conclusions

This paper investigates overheating in low-energy homes in England. It employs a multi-method approach for post-occupancy evaluation, combining monitored data, standardized overheating assessments, and seasonal occupant questionnaires. By integrating data from these diverse approaches, the study reveals that each element complements the others, filling gaps in the overall understanding of overheating in low-energy homes. Accordingly, this study is oriented to a pragmatic philosophy that combines diverse approaches valuing both objective and subjective knowledge. The data analysis embraces an interpretivist perspective, as it acknowledges the transactional relationship between environment and behaviour, where occupants and their surroundings are constantly interacting within a dynamic reality, as defined by Takahashi (2000).

While the research has some limitations due to its relying on a small number of case study buildings in different locations, it also shows that CIBSE-TM52 assessment could underestimate overheating. In addition, considering that occupancy (and its vulnerability) can change, it introduces the notion of 'temporary vulnerable occupants', which designers should carefully consider when they assess the risk of overheating of the buildings they set out to design. The user perspective insights adopted in this study further shows that the reliance on window opening evidenced by the seasonal questionnaire provides an initial indication that adaptive measures are enacted by occupants to achieve comfort. Further research is needed to understand the drivers behind window opening practices in low-energy homes (thermal comfort, personal preference, contextual factors, etc.).

In terms of methodology, taken as single methods, all the overheating assessments, the seasonal questionnaires appear inconclusive (not statistically significant) and intricate (reliability on responses). Nonetheless, the integration of such methods enables one to appreciate that low-energy homes are environments prone to overheat (in certain contexts) and that building adaptive capacities and human adaptive behaviour are key to avoid present-day overheating. Accordingly, the results should be considered a reasoned prediction of how the different factors involved affect the overall phenomenon of overheating in dwellings.

The use of roof pods as a solution to regain floor space lost during deep retrofits constitutes an interesting and potentially viable option for retrofitting a large portion of the UK residential stock. However, the consistent overheating in UK51-bed 2, despite open windows, strongly suggests fundamental design issues in the roof pod and ventilation design requiring further investigation.

Finally, the retrospective examination of compliance with the building regulation Part O suggests that the new overheating requirements set by Part O may be inadequate. The case studies reveal the limitations of Part O in addressing specific factors, such as roof pods, hot water cylinder placement, and sunspaces. Not only does the standard's exclusion of refurbished buildings create a significant gap but also the discrepancies between overheating assessments based on simplified methods (like Part O) and real-world monitoring data suggest a need for more nuanced approaches that may be capable of considering factors beyond basic design elements. While low-energy design is clearly needed, this work demonstrates a deficit in the collective current knowledge of design and management of low-energy homes and, importantly, that it is crucial for occupants to be given additional non-energy intensive means and advice to keep the heat out and remove excess heat. Relatedly, the findings of this study can be reasonably expected to apply to other heating-intensive countries where similar strategies of low-carbon design are applied.

Acknowledgements

The authors would like to acknowledge the sponsorship of the Global Innovation Initiative (GII) project (2014–2016) 'Reducing global energy use in buildings while improving occupant comfort and well-being: reversing the growing trend toward energy-intensive air-conditioning', funded by the British Council as part of an international partnership between the University of Loughborough (UK), UC Berkeley (USA), CEPT University (India), De Montfort University (UK); the Faculty of Technology within De Montfort University to fund the PhD scholarship; and the Autonomous Province of Bolzano-Bozen for financing the project '*ADAPTIVE HOUSING – Solutions for Adaptive and Resilient Low-Energy Housing under Climate Change Scenarios*' through the Seal of Excellence funding scheme (Decree 13190/2022). Authors would like to express their outmost gratitude to the very patient and helpful volunteers of the houses surveyed. The first author would like to express her deepest gratitude to Stefano Bertea for his meaningful insights into the logical argumentation of this paper. The authors would also like to thank the editor and reviewers of this special issue for their valuable contributions to the paper's coherence and readability. Any shortcomings, however, remain the responsibility of the authors. Details of the seasonal questionnaire are available on reasonable request to the corresponding author.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by British Council: (Grant Number Air motion for maintaining thermal comfort); Provincia autonoma di Bolzano - Alto Adige: (Grant Number Decree 13190/2022).

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References

Attia, S., Benzidane, C., Rahif, R., Amaripadath, D., Hamdy, M., Holzer, P., Koch, A., Maas, A., Moosberger, S., Petersen, S., Mavrogianni, A., Maria Hidalgo-Betanzos, J., Almeida, M., Akander, J., Khosravi Bakhtiari, H., Kinnane, O., Kosonen, R., & Carlucci, S. (2023). Overheating calculation methods, criteria, and indicators in European regulation for residential buildings. *Energy and Buildings*, *292*, 113170. https://doi.org/10.1016/j.enbuild.2023.113170

Beizaee, A., Lomas, K. J., & Firth, S. K. (2013). National survey of summertime temperatures and overheating risk in English homes. *Building and Environment*, *65*, 1–17. https://doi.org/10.1016/j.buildenv.2013.03.011

Buguet, A., Radomski, M. W., Reis, J., & Spencer, P. S. (2023). Heatwaves and human sleep: Stress response versus adaptation. *Journal of the Neurological Sciences*, *454*, 120862. https://doi.org/10.1016/j.jns.2023.120862

CIBSE. (2006). *CIBSE Guide A: environmental design*. Chartered Institution of Building Services Engineers.

CIBSE. (2013). *TM52: The limits of thermal comfort: Avoiding overheating in European buildings*. Chartered Institution of Building Services Engineers.

CIBSE. (2015). *CIBSE Guide A: environmental design*. Chartered Institution of Building Services Engineers.

CIBSE. (2017). *TM59: Design methodology for the assessment of overheating risk in homes*. Chartered Institution of Building Services Engineers.

Colclough, S., & Salaris, C. (2024). Quantifying overheating in nZEB Irish residential buildings. An analysis of recorded interior temperatures of Irish newbuild and retrofit residential buildings against CIBSE, passive house and WHO overheating criteria and recorded occupant satisfaction. *Energy and Buildings*, *303*, 113571. https://doi.org/10.1016/j.enbuild.2023.113571

Crilly, M., Lemon, M., Wright, A. J., Cook, M. B., & Shaw, D. (2012). Retrofitting homes for energy efficiency: An integrated approach to innovation in the low-carbon overhaul of UK social housing. *Energy and Environment*, *23*(6), 1–30.

Dartevelle, O., Van Moeseke, G., Mlecnik, E., & Altomonte, S. (2021). Long-term evaluation of residential summer thermal comfort: Measured vs. perceived thermal conditions in nZEB houses in Wallonia. *Building and Environment*, *190*, 107531. https://doi.org/10.1016/j.buildenv.2020.107531

GOV.UK. (n.d.). Beat the heat: Staying safe in hot weather. (n.d.). *GOV.UK*. Retrieved June 9, 2024, from https://www.gov.uk/government/publications/beat-the-heat-hot-weather-advice/beat-the-heat-staying-safe-in-hot-weather

HM Government. (2021a). *Net zero strategy: Build back greener*.

HM Government. (2021b). *The building regulations 2010. Conservation of fuel and power requirement. Approved document L. Volume 1: Dwellings*. www.gov.uk/guidance/building-regulations-

HM Government. (2021c). *The building regulations 2010. Requirement O1: Overheating mitigation. Regulations: 40B*. https://assets.publishing.service.gov.uk/media/6218c5aad3bf7f4f0b29b624/ADO.pdf

HM Government. (2021d). *The building regulations 2010. Ventilation. Approved document F. Volume 1: Dwellings*. (Vol. 1).

Howieson, S. G., Sharpe, T., & Farren, P. (2014). Building tight—Ventilating right? How are new air tightness standards affecting indoor air quality in dwellings? *Building Services Engineering Research and Technology*, *35*(5), 475–487. https://doi.org/10.1177/0143624413510307

Hubbard, D. (2011). Ventilation, infiltration and air permeability of traditional UK dwellings. *Journal of Architectural Conservation*, *17*(3), 59–73. https://doi.org/10.1080/13556207.2011.10785097

Jang, J., Natarajan, S., Lee, J., & Leigh, S.-B. (2022). Comparative analysis of overheating risk for typical dwellings and passivhaus in the UK. *Energies*, *15*(10), 3829. https://doi.org/10.3390/en15103829

Kim, J., Xiong, J., De Dear, R., Parkinson, T., Jeong, B., Wu, Z., Sadeghi, M., & Chen, D. (2023). Testing the applicability of CIBSE overheating criteria to Australian subtropical residential contexts. *Building and Environment*, *246*, 110987. https://doi.org/10.1016/j.buildenv.2023.110987

Lomas, K. J., & Kane, T. (2013). Summertime temperatures and thermal comfort in UK homes. *Building Research & Information*, *41*(3), 259–280. https://doi.org/10.1080/09613218.2013.757886

Mavrogianni, A., Pathan, A., Oikonomou, E., Biddulph, P., Symonds, P., & Davies M. (2017). Inhabitant actions and summer overheating risk in London dwellings. *Building Research and Information*, *45*(1–2), 119–142. https://doi.org/10.1080/09613218.2016.1208431

McGill, G., Sharpe, T., Robertson, L., Gupta, R., & Mawditt, I. (2017). Meta-analysis of indoor temperatures in new-build housing. *Building Research & Information*, *45*(1–2), 19–39. https://doi.org/10.1080/09613218.2016.1226610

Mourkos, K., McLeod, R. S., Hopfe, C. J., Goodier, C., & Swainson, M. (2020). Assessing the application and limitations of a standardised overheating risk-assessment methodology in a real-world context. *Building and Environment*, *181*, 107070. https://doi.org/10.1016/j.buildenv.2020.107070

Ndlovu, N., & Chungag, B. N. (2024). Impact of heat stress on cardiovascular health outcomes of older adults: A mini review. *Aging and Health Research*, *4*(2), 100189. https://doi.org/10.1016/j.ahr.2024.100189

Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive thermal comfort: Principles and practice*. Routledge.

Palmer, J., Godoy-Shimizu, D., Tillson, A., & Mawditt, I.. (2016). *Building performance evaluation programme:*

Findings from domestic projects making reality match design. Innovate UK.

Preiser, W. F. E. (1995). Post-occupancy evaluation: How to make buildings work better. *Facilities*, *13*(11), 19–28. https://doi.org/10.1108/02632779510097787

Project Cottesmore. (2009). *Proposal for retrofit for the future-phase 2 application* [unpublished].

REHVA. (2021). CO_2 monitoring and indoor air quality. *REHVA Journal*, *58*(1), 54–59. https://www.rehva.eu/rehva-journal/chapter/co2-monitoring-and-indoor-air-quality

Retrofit for the Future: Project Cottesmore. (2010). *Retrofit for the future*. https://retrofitforthefuture.blogspot.com/p/project-cottesmore.html

Sharpe, T., Farren, P., Howieson, S., Tuohy, P., & McQuillan, J. (2015). Occupant interactions and effectiveness of natural ventilation strategies in contemporary new housing in Scotland, UK. *International Journal of Environmental Research and Public Health*, *12*(7), 8480–8497. https://doi.org/10.3390/ijerph120708480

Tabatabaei Sameni, S. M., Gaterell, M., Montazami, A., & Ahmed, A. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, *92*, 222–235. https://doi.org/10.1016/j.buildenv.2015.03.030

Takahashi, T. (2000). Sympathetic methods in environmental design and education. In S. Wapner, J. Demick, C. T. Yamamoto, & H. Minami (Eds.), *Theoretical perspectives in environment-behavior research: Underlying assumptions, research problems, and methodologies* (pp. 229–236). Springer US.

WHO. (2024). *Heat and health*. Retrieved December 29, 2023, from https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health

Appendix A. Loggers list

HOUSE CODE	location HOBO	floor level	location HOBO	serial 1st HOBO	variable measured	log interval (minutes)	start log	set up at home	battery level	log duration (days)	HOBO blinking (yes/no)	Light covered (yes/no)	Height (Head, Chest, mm)	Heat & Sun source re location	Picture taken
UK51	side gate	0	external	1272 666	air temperature	10	22/06/2015 12.00	22/06/2015 14.00	96%	1.5 years	y		above head	n	y
UK51	living room	0	front side	1272 651	air temperature	10	22/06/2015 12.00	22/06/2015 14.00	100%	1.5 years	y		head	n	y
UK51	kitchen	0	rear side	1272 638	air temperature	10	22/06/2015 12.00	22/06/2015 14.00	83%	65	y		head	n	y
UK51	bed 1	1	front	1272 659	air temperature	10	22/06/2015 12.00	22/06/2015 14.00	100%	1.5 years	y	y	head	n	y
UK51	lounge	1	rear side	1272 620	air temperature	10	22/06/2015 12.00	22/06/2015 14.00	70%	65	y		above head	n	y
UK51	bed 2	2	throughout	1272 643	air temperature	10	22/06/2015 12.00	22/06/2015 14.00	96%	1.5 years	y	y	head	n	y
UK55	hall	0	front side	1272626	air temperature	10	6/12/2015 12:00	12/06/2015 19.00	100%	100	y		head	n	y
UK55	kitchen	0	throughout	1272631	air temperature	10	6/12/2015 12:00	12/06/2015 19.00	100%	100	y		head	n	y
UK55	living room	1	throughout	1272635	air temperature	10	6/12/2015 12:00	12/06/2015 19.00	100%	100	y		head	n	y
UK55	bed 1	2	throughout	1272630	air temperature	10	6/12/2015 12:00	12/06/2015 19.00	100%	100	y	y	head	n	y
UK55	office	1	front side	1272637	air temperature	10	6/12/2015 12:00	12/06/2015 19.00	100%	100	y		head	n	y
UK55	bed 2	2	throughout	1272657	air temperature	10	6/12/2015 12:00	12/06/2015 19.00	100%	100	y	y	head	n	y
UK55	sunspace	2	throughout	1272628	air temperature	10	6/12/2015 12:00	20/06/2015 12.00	100%	100	y		above head	n	y
UK54	office	1	front side	1272664	air temperature	10	6/12/2015 12:00	12/06/2015 15.00	63%	100	y		head	n	y
UK54	bed 3	1	front side	1272662	air temperature	10	6/12/2015 12:00		100%	100	y	y	waist	n	y

(*Continued*)

Continued.

HOUSE CODE	location HOBO	floor level	location HOBO	serial 1st HOBO	variable measured	log interval (minutes)	start log	set up at home	battery level	log duration (days)	HOBO blinking (yes/no)	Light covered (yes/no)	Height (Head, Chest, mm)	Heat & Sun source re location	Picture taken
								12/06/ 2015 15.00							
UK54	bed 1	2	throughout	1272669	air temperature	10	6/12/2015 12:00	12/06/ 2015 15.00	83%	100	y	y	waist (100 cm)	n	y
UK54	external	0	external	1272668	air temperature	10	6/12/2015 12:00	12/06/ 2015 15.00	90%	100	y		knee	n	y
UK54	bed 2	1	rear side	1272667	air temperature	10	6/12/2015 12:00	12/06/ 2015 15.00	90%	100	y	y	waist high (120 cm)	n	y
UK54	bed 1	3	throughout	1272627	air temperature	10	08/10/ 2015 12.00	13/08/ 2015		43	n	y	waist high (120 cm)	n	
UK52	living room	0	front side	1164623	air temperature	10	6/30/2015 12:00	6/30/2015 12:00	100	362	y	Y	waist (100 cm)	n	Y
UK52	hall	0	throughout	1272641	air temperature	10	6/30/2015 12:00	6/30/2015 12:00	100	362	y	Y	head	n	Y
UK52	kitchen	0	front side	1272634	air temperature	10	6/30/2015 12:00	6/30/2015 12:00	100	362	y	Y	above head	n	Y
UK52	bed 2	0	rear side	1272670	air temperature	10	6/30/2015 12:00	6/30/2015 12:00	100	362	y	Y	above head	n	Y
UK52	bed 1	0	rear side	1272650	air temperature	10	6/30/2015 12:00	6/30/2015 12:00	100	362	y	Y	above head	n	Y