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Article

Addressing Overheating Risk in Zero Energy Buildings

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Abstract: Buildings in Europe represent a significant portion of energy use, necessitating an optimal balance between thermal comfort and efficiency. BedZED set a pioneering example of zero energy design in the early 2000s, yet recent assessments reveal limitations in maintaining its performance over time. This study employs simulation models to examine BedZED's current and future performance, investigating its response to targeted interventions aimed at enhancing thermal comfort, providing insights for adapting older energy-efficient designs to evolving climate and energy needs. The findings demonstrate that adding a sunspace increases temperatures, though higher airtightness values did somewhat reduce this effect. Looser infiltration reduced overheating but did not meet TM52 criteria without the removal of the sunspace. Solar control and shading emerged as effective solutions, along with reduced glazing and roof-level ventilation, especially under future climate scenarios.

Keywords: energy efficiency; overheating; passive strategies; infiltration rates; future weather

1. Introduction

The UK government aims for zero carbon in new buildings by 2030 and near-zero carbon emissions in existing buildings by 2050 (BEIS, 2021). While these targets are achievable, strategies differ, as only 120,000 new homes are built annually compared to 27 million existing dwellings, 80% of which are expected to remain in use by 2050. Buildings are responsible for nearly 40% of energy consumption and around 33% of total CO_2 emissions in Europe, making them the largest contributors to energy use in the region (Ionescu et al., 2015, Baek and Park, 2012). One of the most severe consequences of climate change is the rising frequency and intensity of heatwaves, which pose a significant threat to public health. These extreme events contribute to approximately 2,000 deaths annually, primarily affecting older adults with preexisting health conditions (Hajat et al., 2007, Gasparrini et al., 2012). While short periods of extreme heat can result in high mortality, research suggests that prolonged warm conditions are the primary drivers of heat-related deaths, rather than isolated hot days (Hajat et al., 2006). This upward trend in overheating will necessitate active cooling systems to maintain thermal comfort and protect public health. Air conditioning, already the fastest-growing energy use in buildings, is expected to see further growth (Viguié et al., 2020, McLeod et al., 2013). This increased demand for space cooling is projected to significantly raise energy consumption, contributing to higher greenhouse gas emissions and placing immense strain on electricity grids globally. Recent regulations, such as Part O (HMG, 2021), aim to tackle this issue. To mitigate overheating risk and adapt buildings to climate change, it is crucial to minimise internal heat gain.

To tackle this issue, governments and institutions are focusing on improving energy efficiency as a key strategy to mitigate global warming and reduce reliance on fossil fuels. The UK's Committee on Climate Change (CCC) has identified the country's existing housing stock as poorly equipped to handle these future climate challenges. To address this, the CCC recommends integrating passive cooling measures into both retrofitting projects and the construction of new residential buildings (Khosravi et al., 2023). Passive measures, which require no energy use, can cut overheating risks in up to 80% of UK homes under 2 °C warming (Bouhi et al., 2022, Howarth et al., 2024, Nicol and Stevenson, 2013).

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Strategies such as building orientation, shading, and material choices are considered equally effective and more sustainable (DEFRA, 2018, Taylor et al., 2014, Ozarisoy, 2022, Colclough et al., 2018, Gupta and Gregg, 2018, Beizaee et al., 2013, Lomas et al., 2024). However, research indicates that even with passive measures, homes in parts of England are projected to overheat by the 2050s, especially under a high emissions scenario (Gupta et al., 2015). Furthermore, low-energy homes represent a growing, though still nascent, segment of the UK housing market. However, limited Post-Occupancy Evaluations (POEs) have been conducted, leaving gaps in understanding their thermal performance and risks of overheating (Jones et al., 2016). Preliminary studies indicate that even under current climatic conditions, homes designed to higher thermal performance standards are experiencing indoor temperatures exceeding typical summer levels. This highlights potential vulnerabilities and the need for further investigation into their overheating risk (Jones et al., 2016, Liu and Coley, 2015, Ozarisoy and Elsharkawy, 2019).

2. Climate Change and Its Growing Impact on Building Resilience

Global warming's impact in the UK is clear, as highlighted in the State of the UK Climate 2020 report (Kendon et al., 2021). In July 2022, heatwaves hit Europe, North Africa, the Middle East, and Asia, with the UK recording an unprecedented 40.3 °C, breaking previous temperature records ((UKHSA), 2022). While there is no universally accepted definition of a heat wave in the UK, one study defines it as a continuous period when the average temperature exceeds 20 °C (Hajat et al., 2002). The UK Health Protection Agency defines it as daily mean temperatures above the 98th percentile of the year's temperature distribution for three or more consecutive days. By this definition, present-day heat waves in London would see mean daily temperatures above 22.6 °C (McLeod et al., 2013). The 2003 heat wave exceeded baseline temperatures by 8 °C, with London experiencing a maximum of 37.9°C and overnight lows as high as 26–27 °C (Johnson et al., 2005). Extreme events like the 2003 heatwave, which caused 2,091 deaths in the UK (Johnson et al., 2005) and 70,000 across Europe, and the 2018 heatwave are becoming more frequent (Tabatabaei Sameni et al., 2015), with the Met Office predicting heatwaves 30 times more likely due to climate change and a regular feature of UK summers by 2040 (Davies and Belcher, 2022, Khosravi et al., 2023, Brimicombe et al., 2021). The past decade (2011–2020) was 0.5°C warmer than the 1981–2010 average and 1.1 °C warmer than 1961–1990 (Office, 2021). Met Office predictions suggest that by the 2080s, under a high emissions scenario, summer daytime temperatures in lowland England could exceed 42 °C as frequently as once a decade (Office, 2021). This warming is expected to be accompanied by a decrease in summer cloud cover by up to 18%, leading to increased solar radiation by 16 W/m² in southern parts of the UK (Jenkins et al., 2009). This increase in extreme weather events and higher summer temperatures could necessitate active cooling systems to maintain thermal comfort and protect public health. As heatwaves intensify and temperatures rise, the demand for cooling through fans and air conditioning is growing to mitigate the impacts on comfort and health (Viguié et al., 2020). This increased demand for space cooling is projected to significantly raise energy consumption, contributing to higher greenhouse gas emissions and placing immense strain on electricity grids globally. By 2050, electricity consumption for cooling is expected to more than triple, driven by anthropogenic climate change and the growing need for indoor comfort (IEA, 2018). Most studies on cooling demand focus on hot regions, but climate change also threatens cooler western countries, where homes are designed for milder climates and often lack cooling systems (Velashjerdi Farahani et al., 2021). These countries, including the UK, will face increasing overheating risks as they adapt to warmer conditions, despite their historical lack of reliance on cooling infrastructure.

The papers within Table 1 emphasize the emerging overheating challenges in energy-efficient UK housing, particularly in response to climate change and rising global temperatures. Notably, super-insulated homes and Passivhaus apartments face heightened overheating risks, especially during heatwaves, due to increased thermal gains and limited ventilation options. Multiple studies highlight the vulnerability of specific dwelling types (such as top-floor apartments), high-rise buildings, and lightweight structures- which exacerbate internal temperature rises. Occupant behaviour, particularly regarding ventilation and system control, emerges as a critical factor affecting overheating. Furthermore, the research underscores that traditional retrofits may fail or even worsen overheating in energy-efficient homes unless tailored to future climate scenarios, which indicate decreasing heating needs but rising cooling demands. Solutions proposed across studies include shading, enhanced ventilation strategies, and mechanical cooling; however, these measures may only partially mitigate overheating, with significant variability based on dwelling typology and occupancy patterns.

Table 1. Literature review.

Year	*Main Findings*	*Typology*	*Reference*
2008	The BASF house meets the 15 kWh/m² Passivhaus standard. Further optimizations improved performance by 35%. Overheating was minimal, except in the sunspace, which exceeded 25°C for 24% of the year.	Dwellings	(Schiano-Phan et al., 2008)
2010	Simulations show low thermal mass homes, common in the UK, face high overheating risk and urban heat island effects, especially in cities like London. A "cooling tipping point" for passive methods hasn't been clearly identified yet.	Dwellings	(Peacock et al., 2010)
2012	Overheating risks arise from occupant activities, communal heating, and inadequate ventilation, with increased insulation worsening the issue.	-	(Foundation, 2012)
2013	High overheating in post-1990 dwellings and flats- 80% of bedrooms was found surpassing the 5%/24°C threshold. Assessments indicate that older solid-wall and detached houses remained cooler than modern cavity wall constructions.	UK Housing stock	(Beizaee et al., 2013)
2013	Super-insulated UK homes face overheating risks. By 2050, London homes could exceed 25°C for 5–10% of the year, increasing the need for active cooling.	Dwelling	(McLeod et al., 2013)
2015	In-use data shows 72% of UK Passivhaus flats face overheating risks, driven by occupant behaviour, with vulnerable occupants experiencing twice the overheating risk.	Apartment s	(Tabatabaei Sameni et al., 2015)
2015	By 2080, UK homes may need mechanical cooling as cooling seasons expand, while Zero Carbon homes risk overheating year-round despite lower heating demand.	Dwellings	(Gupta et al., 2015)
2015	In a highly insulated timber structure, concrete reduced overheating most effectively but was impractical for lightweight construction. PCM boards performed well, yet overheating persisted, emphasizing the need to combine thermal mass with passive cooling strategies.	Dwelling	(Rodrigues et al., 2015)
2016	By mid-century, heating demand may drop 17–26%, while cooling demand could rise 31–73% under RCP8.5, with massive-frame buildings at higher overheating risk. By 2090, shading and increased ventilation may not prevent overheating.	Apartment s	(Dodoo and Gustavsson, 2016)
2017	Severe overheating in 20% of apartments could have been prevented with blinds, window fixes, and proper MEV use, but occupants lacked awareness.	High-rise apartments	(Baborska-Narozny and Grudzinska, 2017)
2018	Energy-efficient retrofits combined with shutters can reduce heat-related mortality risk by 30–60% in summer, while complete retrofits alone may increase mortality risk by 1–14%.	-	(Taylor et al., 2018)
2019	Monitoring during the 2018 heatwave revealed significant overheating and thermal discomfort in a lightweight terraced house in southeast England, with all occupied spaces exceeding comfort levels, particularly on the first floor.	Semi-detached terrace house	(Ozarisoy and Elsharkawy, 2019)
2020	Many Passivhaus occupants seek greater control over system operation without compromising energy efficiency, highlighting the difficulty of creating a thermal environment that meets diverse needs.	-	(Zhao and Carter, 2020)
2020	In future climates, well-insulated buildings without mechanical cooling may overheat for 360–6,140 hours annually as passive cooling becomes inadequate.	Single-family house	(Grygierek and Sarna, 2020)
2020	Future climate scenarios indicate decreased heating demand but a significant rise in cooling demand while energy-efficient measures reduce heating needs but increase cooling demands.	Multi-storey residential building	(Ayikoe Tettey and Gustavsson, 2020)
2021	Overheating intensity depends on natural ventilation, but varying occupant behaviour complicates standardized ventilation assessment.	Apartment s	(Schünemann et al., 2021)
2021	Climate assessments predict more extreme weather will increase cooling needs and reduce heating demand across regions; in Sweden, future heating demand reductions are smaller under new IPCC AR5 scenarios compared to AR4.	Building stock	(Yang et al., 2021)
2022	Top-floor Homes 1 and 2 face higher temperatures due to increased solar gains, while higher air change rates in Homes 2 and 3 suggest potential for reducing heat gains via infiltration.	Multifamil y Dwellings	(López-García et al., 2022)
2022	The 2060 climate change scenario predicts Milan's heating decreasing by up to 54%; cooling could account for 34% of total HVAC energy	Dwelling	(D'Agostino et al., 2022)

	due to internal heat gains, making efficient low-energy appliances and lighting essential.		
2024	Traditional retrofitting methods may worsen overheating as climate change increases cooling demand and reduces heating needs, requiring climate-specific evaluations.	Retrofit Dwellings	(Liyanage et al., 2024)
2024	Overheating varies by typology, higher energy efficiency ratings result in warmer living rooms; Evidence shows internal wall insulation raises room temperatures, and high-efficiency homes are more prone to overheating due to occupant.	Apartment s	(Lomas et al., 2024)

3. Evaluating BedZED: Lessons from a Pioneering Sustainable Development in the Face of Modern Climatic Challenges

The past century has seen a significant rise in global temperatures, posing challenges to the ability of buildings once considered "efficient" to meet modern performance standards. Developed in the early 2000s, the Beddington Zero Energy Development (BedZED) (seen in Figure 1) was introduced as a pioneering effort to combat climate change and serves as an important case study in this regard. Although many energy-efficient housing projects have been created since, BedZED is particularly notable for its innovative approach at the time, as it was among the first developments to focus on energy efficiency before reducing operational energy consumption became a widespread priority. This research investigates the thermal comfort performance of BedZED, considering recent evaluations (BioRegional, 2009, Downie, 2023) that have highlighted certain limitations and a decline in its effectiveness over time. With global temperatures continuing to rise, this study reevaluates BedZED's initial design features (such as its sunspace concept) to determine their relevance and adaptability to current and future climatic challenges.

Figure 1. South-facing image of BedZed (BioRegional, 2009).

3.1. How BedZED Redefined Sustainable Building Standards

BedZED comprised of three terraces containing 82 housing units, supplemented by 1,500m² of live-work and commercial spaces tailored primarily for small to medium-sized families. The third level included studio apartments specifically designed to accommodate young professionals and couples. A core objective of the development was the integration of a combined heat and power (CHP) system to supply energy efficiently, necessitating a substantial reduction in energy demand compared to prevailing standards of the time. To enhance energy efficiency, the buildings were equipped with 300mm-thick insulation, which significantly surpassed the building regulations of that era. The design also featured argon-filled, north-facing triple-glazed windows and glass-enclosed winter gardens to optimize solar heat gain during colder months (Downie, 2023). The homes were positioned with unobstructed, south-facing glass facades to maximize sunlight exposure. This arrangement enabled the sunspaces to absorb and retain heat effectively, even during winter, facilitating the transfer of warmth into the living areas through simple actions such as opening doors and windows. By stabilizing indoor temperatures and reducing energy loss, this design contributed significantly to thermal efficiency (Williams, 2023). Notably, BedZED achieved an impressive U-value of 0.11 W/m² (Young, 2015), far exceeding the minimum required U-value of 0.45 W/m² at the time (Office, 1991). This performance aligns with contemporary Passivhaus standards, underscoring the project's forward-thinking approach to sustainable building design (Johnston and Siddall, 2016). The project aimed for a 60% reduction in energy demand and successfully achieved a 90% decrease in heat requirements compared to homes built under the 1995 building regulations in place at the time of its design (Downie, 2023). Finally, designed for natural ventilation through heat exchange, the development's vibrant rooftop wind cowls are a key feature, effectively supporting ventilation during hot summers.

3.2. The Challenges of Bed-ZED

The southern facades of the building, characterized by a high window-to-wall ratio and quadruple glazing (due to sunspace), have contributed to overheating during the warmer months. This design feature has led to a significant accumulation of excess heat within the building. According to a post-occupancy assessment by BioRegional, concerns were raised regarding discomfort caused by both temperature and noise. Survey results indicated that 39% of residents resorted to alternative cooling methods, while 56% reported experiencing considerable heat during summer (BioRegional, 2009). Further analysis of data collected between 2003 and 2005 (Young, 2015) examined average summer temperatures in various apartments, with particular attention to bedrooms and living rooms. Onsite monitoring found that one living room surpassed the 28 °C threshold, with two others nearing it. Similarly, three bedrooms exceeded the 26 °C threshold, and five others approached this limit under the same external conditions. When external temperatures rose to 25 °C, 15 out of 21 bedrooms exceeded 26°C, and five out of 22 living rooms surpassed 28 °C. In addition, the upper floors of the BedZED development experience overheating, primarily attributed to the sunspace design, which lacks operable roof-level windows. BedZED's architect, Bill Dunster, acknowledged that this design decision was influenced by cost-cutting measures. Although the sunspaces include roof-level windows, opening mechanisms were omitted. If these windows were operable, it would allow for improved cooling in the sunspaces without compromising security (Lane, 2009).

3.3. Impact of Infiltration Rates on BedZED

Onsite testing and POE of BedZED reveal two infiltration rates: with the wind cowls open, the infiltration rate was 0.16, and with the cowls closed, it was 0.12 (Young, 2015). Various studies have explored the impact of airtightness, particularly in modern buildings, on indoor overheating during summer, generally finding a positive correlation. Although worse (higher) infiltration rates do not necessarily lead to improved ventilation, this paper aims to assess whether infiltration rates are a limiting factor in summer overheating. Additionally, it examines whether retrofitting to modern infiltration standards could exacerbate summer overheating without significantly improving winter comfort in the near future.

3.4. Gap Analysis

Despite extensive research on building energy efficiency and overheating risks, significant gaps remain in understanding the long-term thermal performance of low-energy and Passivhaus homes under future climate scenarios. While studies highlight the vulnerability of highly insulated dwellings to overheating, there is limited empirical data to assess how these buildings perform across different typologies and occupant behaviours. Additionally, existing research predominantly focuses on short-term overheating events during extreme heatwaves, overlooking the cumulative impact of prolonged warm periods on indoor thermal comfort and health. Furthermore, the effectiveness of passive cooling strategies in mitigating overheating remains unclear, particularly in dense urban environments where external shading and natural ventilation may be constrained. This research gap is particularly evident in pioneering developments like BedZED, where initial design strategies aimed at energy reduction may no longer align with current and future climatic conditions.

4. Methodology

The building's low U-value fabric allowed for a shift in focus toward optimizing thermal comfort through strategic design adjustments. Drawing on insights from literature and an understanding of passive design principles (Omrany and Marsono, 2016), attention was directed at managing and controlling solar gains. Given the extreme temperatures recorded in the United Kingdom, especially from May to August (as shown in Figure 2), careful attention to the sunspace design was critical. The primary objective was to retain heat during colder months while maximizing solar gain. To evaluate the building's performance in its specific climate, data was sourced from an ASHRAE EPW file for London Gatwick, obtained via Ladybug. The UK experiences four distinct seasons, with winter temperatures typically cold, while summers have increasingly been marked by heatwaves (Brimicombe et al., 2021). Throughout the year, temperatures in London ranged between 6–17 °C, with rare occurrences of temperatures falling below -3 °C or exceeding 27 °C.

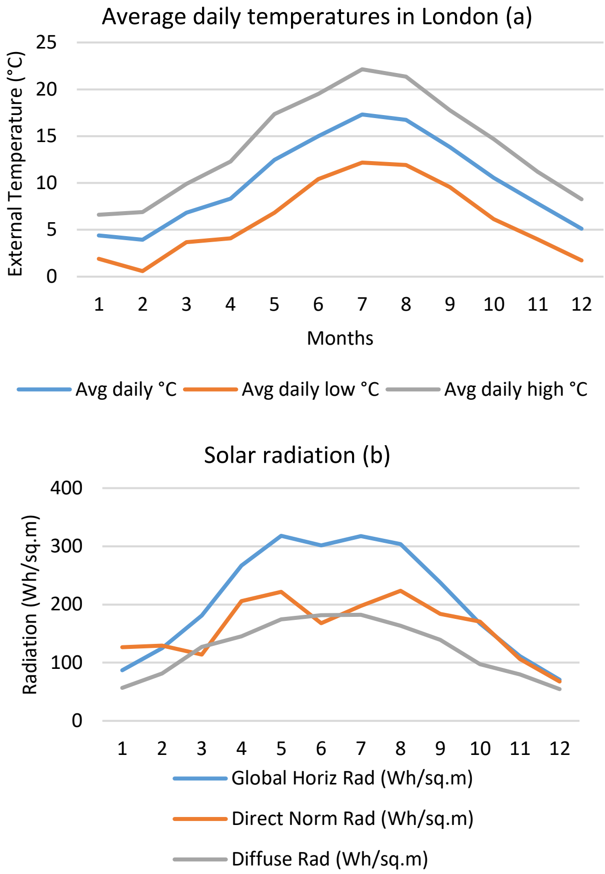

Figure 2. The climate of London: (**a**) temperature change (**b**) solar radiation.

The building's digital twin was created using the simulation software Integrated Environmental Systems: Virtual Environments (IES VE), which is frequently utilized for Building Energy Simulation (BES) to generate abstract representations of real-world conditions (Petrou et al., 2017). IES VE is accredited by the U.S. Department of Energy and adheres to ASHRAE Standard 140, primarily due to its robust thermal simulation tool, ApacheSim (Qays et al., 2019, Attia and Herde, 2011). The reliability of IES VE results has been corroborated by several studies (Ben and Steemers, 2014, Pollock et al., 2009). The digital twin, as illustrated in Figure 3a, was developed and scaled based on the architectural plans and sections that were publicly available online (Downie, 2023). This process entailed replicating key components of the building envelope, incorporating elements such as brick-and-block cavity construction, insulation materials like Rockwool, and ground floors utilizing expanded polystyrene. The simulation model incorporated key parameters, including U-values, glazing specifications, and detailed exterior construction elements. Data for the model's replication was sourced from Bioregional's material report (Lazarus, 2002). The research focused on a single block, with one side exposed to external conditions and the other adjoining a neighbouring block. This block was divided into two sections: the south-facing live unit and the north-facing work unit. While the work unit was included in the model to account for its impact on the live unit, the internal temperature data presented in the subsequent tables is limited to the live unit, as illustrated in Figure 3b.

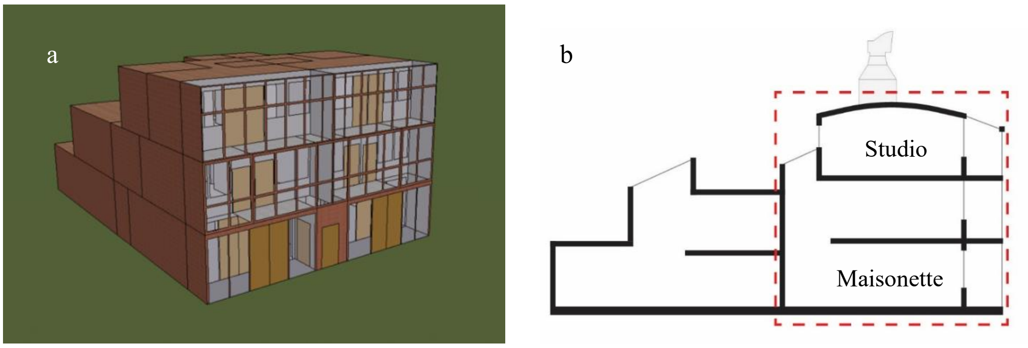

Figure 3. (**a**) Digital twin on IES VE, (**b**) Part considered for simulation.

The live unit's tested floor areas measured 64 m² each for the first and second floors, and 52 m² for the third floor. Initially, the model was evaluated in its base state before implementing minor iterative modifications. The indoor thermal conditions were simulated and analysed over the period from January 1st to December 31st, using a 10-minute simulation time step and a 60-minute reporting interval. Rising temperatures prompted an assessment of whether past and current strategies would remain viable in the future, considering overheating and its impact on thermal comfort. The EPW weather file was processed using CCWeatherGen (Jentsch et al., 2008), an Excel-based tool for generating climate-adjusted weather files for building simulations. It used data from the IPCC Third Assessment Report's HadCM3 A2 experiment, available from the IPCC Data Distribution Centre (IPCC, 2001).

4.1. Assumptions

The Chartered Institution of Building Services Engineers (CIBSE) introduced Technical Memorandum 59 (TM59) to support the development of thermally comfortable homes, outlining a new approach for utilizing BES software to assess the risk of overheating (CIBSE, 2017). In order to achieve precise results, the TM59 profiles were integrated into a comprehensive testing framework that focused on key factors contributing to overheating, particularly during high-risk periods. This framework accounted for variations in occupancy patterns across different homes, ensuring that the performance of the evaluated units was thoroughly assessed both during the day and night. The following assumptions were applied in the testing process:

- A standard occupancy of two people per room, with each individual contributing 75W of sensible heat and 55W of latent heat.
- A lighting power density set at 2W/m², with specific details provided in Table 2.
- Customized appliance and equipment profiles for each room, reflecting varying activity levels as specified in TM59.
- Window operation based on internal and external temperatures: windows were opened when internal temperatures exceeded 24°C, closed during winter, and remained shut in summer when external temperatures rose above 26°C. The window configurations were modelled in accordance with the project specifications, utilizing a combination of fixed and top-hung windows with a 20% openable area.

Table 2. TM59 Schedules and gains; adapted from (CIBSE, 2017).

	Sensible	*Latent*	*00-08*	*08-09*	*09-18*	*18-20*	*20-22*	*22-23*	*23-24*
Double bedroom occupancy	150	110	0.7	1	0.5	0.5	0.5	1	0.7
Double bedroom equipment	80	-	0.13	1	1	1	1	1	0.13
One bed: living- kitchen occupancy	75	55	0	0	1	1	1	0	0
Three bed: living- kitchen occupancy	225	165	0	0	1	1	1	0	0
Living- kitchen equipment	450	-	0.19	0.19	0.24	1	0.44	0.24	0.24
Lighting	2 (W/m^2)		0	0	0	1	1	1	0

While the existing building included wind cowls to aid ventilation, the software limitations prevented their precise modelling. The wind cowls, being highly dynamic in their operation by rotating and orienting themselves according to wind direction, posed significant challenges for accurate representation. Additionally, to the best of the authors' knowledge, the wind cowls lack mechanical components apart from the heat exchanger (Young, 2015), primarily relying on natural ventilation. Since summer overheating is the primary concern, the model excludes heat recovery during this period and does not focus on winter indoor temperatures- when considered, the closed vent infiltration rate was adopted. Part L (2021) stipulates that building envelopes must achieve an air permeability of 8 $m^3/hr/m^2$ at 50 Pa. By using equation 1 and equation 2, more accurate estimates of ACH infiltration rates were determined for input into the IES VE software. In the UK, the Standard Assessment Procedure (SAP) adopted the divide-by-20 rule for converting q50 values to infiltration rates as the official method for predicting infiltration in dwellings (BRE, 2013). While the original American studies used n50, the UK applied this rule to q50 ($m^3/h/m^2$), assuming a typical volume-to-envelope area ratio of approximately 1, which was common in UK houses. However, for greater accuracy in this study, Equation 1 was used to convert q50 values measured at 50 Pa (as per building regulations) into n50 values, as was standard in Passivhaus assessments. Since the software used in this analysis considered infiltration at natural pressure, it was necessary to adjust the q50 values from their pressurized state (at 50 Pa) to natural conditions, for which Equation 2 was employed. However, this paper relied on n-values derived from technical publications, as several studies (Pasos et al., 2020) have shown that the n-value used in SAP may not be fully representative of actual conditions. For this research, an adjusted value of 25.4 was applied (Building Research Establishment (BRE), 2023), reflecting the largely sheltered, urban environment surrounding the BedZED development. While these values are approximations, they provide valuable insights into how infiltration rates impact overheating in buildings. The analysis considered air permeability rates: 8 $m^3/h\cdot m^2$ (Part L) and 0.6 ACH (Passivhaus), all at 50 Pa. These standards were compared with on-site testing at the BedZED development, where closed vents achieved an infiltration rate of 0.12 ACH, and passive vents open yielded 0.16 ACH (Young, 2015).

Equation 1: q50 to n50 conversion formulae.

$$q_{50}=n_{50}\times\left(\frac{\text{Volume}}{\text{Surface Area of Envelope}}\right)$$

q_{50} = Air exchange rate (Used in building standards; air leakage in relation to exposed surface)
n_{50} = Air exchange rate (Used by Passivhaus; air leakage in relation to building volume

Equation 2: Average infiltration rate formulae.

$$\text{Average infiltration rate (ACH)}=\left(\frac{n_{50}}{n}\right)$$

n_{50} = Air changes per hour @ 50 Pa
ACH = Air changes per hour @ Natural ventilation
n = n factor

4.2. Thermal comfort and overheating criteria

According to the ISO standard 7730 (ISO, 2005) thermal comfort is the "condition of mind which expresses satisfaction with the thermal environment". According to CIBSE Guide A, the benchmark peak summer temperatures indicating overheating are 28 °C for living rooms and 26 °C for bedrooms (CIBSE, 2017, Engineers, 2006). While the traditional method for calculating overheating has been based on the number of hours a space exceeds a comfort threshold by K°C, this study also calculates the average K°C of spaces to provide a broader assessment of overheating throughout the summer. This quantitative approach enables a comparative analysis of cumulative temperature differences across the summer period (May–September) among the various tested iterations. This paper also applies TM52's dynamic overheating criteria (Engineers, 2013), focusing on Category II, as recommended by CIBSE. The categories are defined as: Category I for spaces occupied by vulnerable individuals, Category II for new buildings and renovations, and Category III for existing buildings. Each category is assessed by three criteria, with failure to meet two or more indicating unacceptable overheating risk. These criteria are:

Criteria 1: The number of hours the operative temperature exceeds the comfort threshold (by 1 °C or more) between 1 May and 30 September.

Criteria 2: Defines a daily limit on how long and how intensely operative temperatures can surpass comfort levels. The operative temperature (T_{op}) must not exceed the maximum threshold (T_{max}) by more than 6 degree-hours.

Criteria 3: The maximum allowable daily temperature beyond which overheating is considered unacceptable. The upper temperature limit (T_{max}) must not be exceeded by more than 4 °C at any time.
The following tables highlight any failures to meet the TM52 criteria, specifying the hours during which internal operative temperatures exceeded the defined Tmax thresholds, as outlined in each criterion.

4.3. Hypothesis Development

Building on insights from the literature review, four key hypotheses were formulated to investigate factors influencing overheating and ventilation performance. These hypotheses shaped the simulation strategies for sunspace design, ventilation configurations, and user behaviour, providing a structured framework to assess overheating risks and mitigation measures.

- Hypothesis 1: examined the impact of increased air exchange rates resulting from open passive wind cowls during warmer periods. Comparisons were drawn between scenarios with vents open and closed to assess their influence on internal temperatures.
- Hypothesis 2: explored the role of sunspaces and extensive glazing in contributing to summer overheating. Previous studies indicate that large areas of south-facing glazing significantly increase solar gain (Omrany and Marsono, 2016), raising internal temperatures, particularly in summer. To evaluate this, the removal of the second glazing layer was tested to determine its impact on overheating and winter performance.
- Hypothesis 3: investigated the effectiveness of single-sided ventilation and whether the addition of windows could mitigate overheating. By modifying ventilation openings, the study assessed changes in thermal conditions and airflow efficiency.
- Hypothesis 4: addressed the influence of occupant behaviour on overheating. Factors such as window operation habits and unintentional heat sources, including towel rail usage, were examined to determine their contribution to indoor temperature increases.

4.4. Framework

This section examines different strategies to assess the performance of sunspaces, ventilation, and user behaviour in mitigating overheating. By comparing the base case with multiple interventions, the study evaluates how these factors influence thermal comfort and energy efficiency under present and future climate scenarios. Additionally, a broader framework is established to quantify their impact across different airtightness levels and time periods. The findings contribute to understanding the long-term viability of sunspaces, the effectiveness of ventilation strategies, and the role of user behaviour in shaping indoor thermal conditions.

a. Sunspace

This section explores the effectiveness of using a sunspace and its relevance in future scenarios. To assess its benefits, the base case was compared with Strategy 1, which removed the sunspace (Figure 4). This comparison helps determine if sunspaces will remain useful over time. Strategy 2 added shading to evaluate its role in preventing unwanted solar gains and overheating. Strategy 3 involved a 20% reduction in external sunspace glazing to analyse the effect of excess trapped solar gains within the space. Lastly, since omitting roof-level openings was expected to increase overheating, Strategy 4 analysed how this cost-cutting decision impacted overall overheating. Strategies studied within this section include *BC: Base case, S1: No sunspace, S2: No sunspace with shading, S3: Base case with lower external glazing ratio, S4: Base case with a roof-level opening*

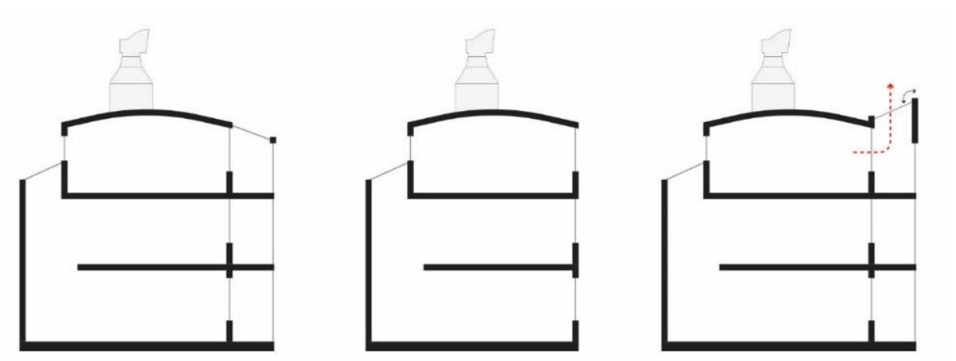

Figure 4. Strategies analyzed; (Left) Base-case, (Middle) S1, (Right) S4.

b. Ventilation

A key issue identified in the BedZed study was the lack of ventilation (aside from the passive heat exchanger). Ventilation and heat purging during summer mostly came from the sunspace openings, with only the first floor having a north-facing bedroom window. This section focused on ventilation strategies, testing three approaches together to measure changes (S5, S6 & S7). The roof level (S4) opening was adopted for S5-7. S5 and S6 explored ventilation for the second-floor studio (Figure 5). In S5, a north-facing window was added to bring fresh air into the living room using the standard window opening profile. In S6, the sunspace glazing was closed, and the roof glazing was opened to test if heated air in the sunspace would rise, similar to a Trombe wall or solar chimney, improving thermal conditions. S7 focused on the ground-floor maisonette; a west-facing window was added with the standard window opening profile. Strategies studied within this section include *S5: 2nd floor with a north opening, S6: 2nd floor with closed external glazing (open top-level opening), S7: West opening in the ground floor living room*

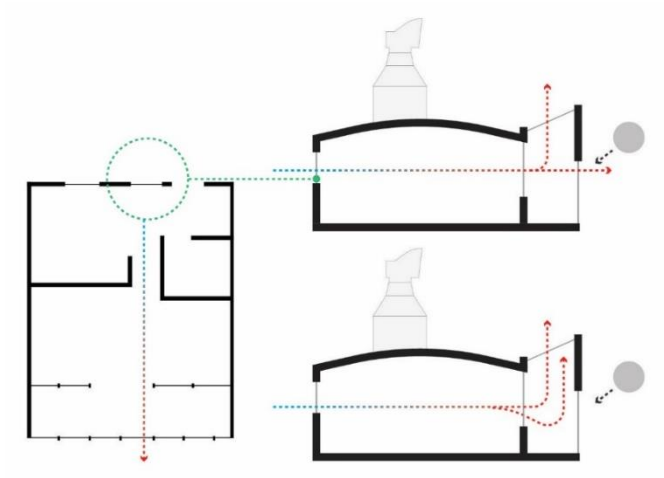

Figure 5. Ventilation strategy (S5-6). Top is S5, bottom is S6.

c. Impact of user

As observed in various studies (Tabatabaei Sameni et al., 2015) (Baborska-Narozny and Grudzinska, 2017) (Foundation, 2012), user behaviour is highly unpredictable. Even highly efficient systems can fail if not used correctly. This study aims to assess how user actions may contribute to overheating. Reports indicate that users found it difficult to open windows, leading S9 to examine the impact of keeping the sunspace external glazing closed in Building Case (BC) on overheating. Additionally, reports noted confusion over operating the towel rail heating, which was often left "on" during summer. S10 used values from previous reports (Young, 2015) to analyse the effect of this added heat source (towel rail heating) on internal overheating. Strategies studied within this section include *S8: Base case with all glazing closed, S9: Base case with towel rail heating left on.*

d. Framework

A total of 120 simulations were analysed, focusing on average temperatures around the sunspace/glazing and average floor temperatures. Ten different strategies were tested against four levels of airtightness across three time periods: 2020, 2050, and 2080. These diverse parameters (refer to Table 3) facilitated a parametric analysis of various strategies, enabling the quantification of their impact across different climatic conditions and levels of airtightness. 4 strategies focused on sunspace variations, 3 on ventilation, and 2 on the impact of user choices on overheating.

Table 3. Various parameters tested.

		2020				**2050**				**2080**			
		BC O	**BC C**	**PL**	**PH**	**BC O**	**BC C**	**PL**	**PH**	**BC O**	**BC C**	**PL**	**PH**
-	BC												
H2	S1												
H2	S2												
H2	S3												
H3	S4												
H3	S5												
H3	S6												
H3	S7												
H4	S8												

H4 S9			

[1] Where BCO: Base case open, BCC: Base case close, PL: Part L, PH: Passivhaus

While all strategies explored hypothesis 1, H2-4 indicate the hypothesis each strategy aimed to test.

5. Analysis and Results

This study investigates the long-term viability of sunspaces as a design strategy, particularly in relation to overheating risks. It also evaluates the influence of air infiltration, user behaviour, and ventilation strategies on the thermal performance of the building, offering a comprehensive assessment of both passive design elements and occupant-driven factors.

5.1. Evaluating the Thermal Performance and Overheating Risks of Base Case

To accurately assess the severity of overheating, various spaces were tested across the structure, including the ground-floor living room, first-floor living area and bedroom, and second-floor living area and north bedroom. This selection of rooms provided insight into which areas experienced the most significant overheating and the underlying causes. Utilizing the BCO infiltration rate, the simulation results indicated that internal temperatures increased with elevation, with the ground floor maintaining the lowest temperatures. As illustrated in Figure 6, summer internal temperatures exceeded 20% in south-facing bedrooms, approximately 18% in north-facing bedrooms, and around 10% in living rooms. Overheating is most severe on the first floor, with higher peaks in the second-floor studio. The fact that such high temperatures are observed across an extended period highlights the severity of future overheating risks. Additionally, under TM52 testing, all living rooms and bedrooms fail two or more criteria in the 2020 scenario (see Table 4). When applying the more lenient Category III, looser ventilation rates allow some rooms, particularly non-sunspace-facing rooms, to pass. While the primary focus of the study was summer overheating, the paper also examined the impact of the sunspace during winter. As heat recovery could not be modelled, the closed vent infiltration rate was used. Average floor temperatures of 17.4 °C were observed, with projected increases of up to 1.5 °C by 2080. Areas near the sunspace were warmer by 0.76 °C, demonstrating its effectiveness during winter periods.

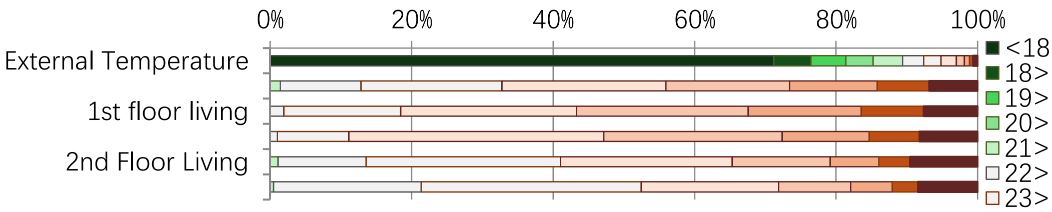

Figure 6. Temperature Variations Across the Structure.

Table 4. TM52 assessment (Category II) of Base-case.

Room Name	Criteria 1	Criteria 2	Criteria 3	Criteria failing
G floor living	3.3	24	3	1 & 2
1st floor bed north	3.6	27	3	1 & 2
1st floor bed south	4.2	56	7	1 & 2 & 3
1st floor living	3	33	3	1 & 2
2nd floor living	14.9	94	11	1 & 2 & 3
2nd floor bedroom	6.3	83	10	1 & 2 & 3

An analysis of two spaces within the structure under various weather scenarios and infiltration rates indicates that opening the vents reduces overheating from 7.8% to 6.9%, as shown in Figure 7. Additionally, variations in infiltration rates demonstrate that as infiltration decreases (i.e., the building envelope becomes tighter), internal temperatures increase, as expected, ranging from 5.5% in the PL scenario to 10.3% in the PH scenario. BedZED exhibits lower overheating levels compared to typical low-energy or Passivhaus-designed structures due to its passive vent infiltration; however, it experiences greater overheating than a standard Part L-compliant building. Furthermore, projections for 2080 indicate that the living room is expected to overheat by 27.5% in the PL scenario and 34.99% in the PH scenario. Notably, as external temperatures rise, the ground floor exhibits higher overheating levels during the summer months compared to the upper floors, reaching up to 6.1%. For model validation, data from prior research (Young, 2015) was referenced. The actual mean internal temperature recorded in the living room was 25.4 °C, whereas the simulation, which applied climatic data from a similar period (May to September), produced an average temperature of 25.15 °C (as seen in Appendix A). This resulted in a minor deviation of 0.98%.

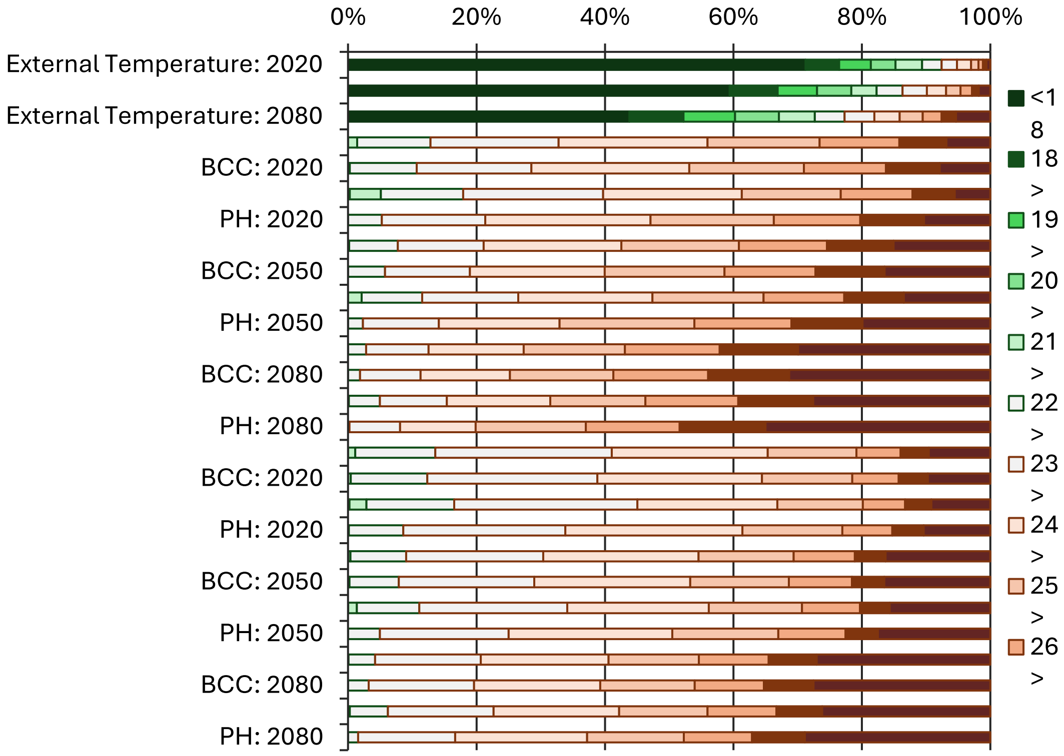

Figure 7. Temperatures Range Across the Years and Infiltration Rates.

5.2. Impact of Sunspace on Thermal Comfort: A Comparative Analysis

To fully assess the role of the sunspace in both overheating and winter benefits, a model iteration (S1) was tested without the sunspace. In the 2020 weather scenario, the removal of the sunspace resulted in an 8.4% drop in temperatures over comfort. Looking at future scenarios, this temperature gap widens to approximately 17.41% (see Table 8). This suggests that while the sunspace may offer some thermal benefits, its long-term suitability is questionable. The removal of the sunspace allowed the structure to meet TM52 criteria (seen in Table 5), with only the south-facing first-floor bedroom failing. However, under projected future climate conditions, additional rooms fail even without the sunspace, with all rooms failing by 2080. Notably, in the 2050 scenario, the first rooms to fail were south-facing, as shown in Table 6. The removal of the sunspace resulted in a reduction of internal temperatures below the comfort threshold by 22.91%. Notably, the influence of the sunspace diminishes over time, with the temperature difference between cases decreasing to 10.72% by 2080, indicating a decline in effectiveness. This corresponds to an average annual reduction of approximately 0.20%. Testing across various infiltration rates indicates that higher infiltration allows for cooler summer temperatures. However, the difference between Part L and BedZED's open-vent configuration is minimal, even under future climate projections. TM52 testing similarly shows no substantial changes between the two infiltration rates.

Table 5. TM52 assessment (Category II) of S1 (2020).

Verdict	Room Name	Criteria 1	Criteria 2	Criteria 3	Criteria failing
Passed	G floor living	1.3	13	2	2
Passed	1st floor bed north	0.6	10	1	2
Passed	1st floor living	0.6	13	2	2
Passed	2nd floor living	1.6	21	3	2
Passed	2nd floor bedroom	0.8	17	2	2
Failed	1st floor bed south	2	40	6	2 & 3

Table 6. TM52 assessment (Category II) of S1 (2050).

Verdict	Room Name	Criteria 1	Criteria 2	Criteria 3	Criteria failing
Passed	1st floor bed north	1.9	20	2	2
Passed	1st floor living	1.6	25	3	2
Passed	2nd floor bedroom	2.4	29	3	2
Failed	G floor living	3.8	24	3	1 & 2
Failed	1st floor bed south	4.1	55	7	1 & 2 & 3
Failed	2nd floor living	5.4	34	4	1 & 2

In winter, infiltration rates significantly affect internal temperatures (as seen in Table 7). The Part L infiltration results in a 26.32% increase in temperatures falling below comfort levels compared to the base case, decreasing to 21.42% by 2080 due to projected warming. In contrast, the stricter Passivhaus standard maintains warmer interiors, with discomfort levels at 4.65%, dropping to 0% in future climates. TM52 analysis indicates that buildings with tighter infiltration rates fail the overheating criteria earlier.

The structure's failure in the TM52 overheating assessment likely results from limited control over solar gains. To address this, the study evaluated shading designed for peak summer conditions (S2). Analysis revealed a 0.92% reduction in temperatures outside comfort for S2 (Table 8 & Figure 8) compared to the base case (S1), increasing to 3.65% by 2080. Applying the TM52 criteria, which considers overheating at peak levels, shows that S2 meets requirements, unlike S1, even under projected 2080 climate conditions. Excessive south-facing glazing is a known contributor to increased solar gains and overheating. Scenario S3 analysed the impact of reducing the glazing ratio on overheating within the base-case structure. A 20% reduction in glazing resulted in a 2.94% improvement in temperature under current climatic conditions, though this effect diminished to 1.72% by 2080. Lower glazing ratios were found to mitigate overheating in airtight structures, as shown in Figure 9, though the effect was less pronounced under future climate scenarios. Scenario S4 examined the potential overheating implications of cost-saving fixed roof openings. Since the base-case structure featured fixed roof windows, this scenario evaluated the impact of operable openings designed to expel hot air opposite the prevailing wind direction. This modification led to an immediate 7.08% reduction in average summer temperatures by 2020, increasing to 13.13% by 2080. Furthermore, in airtight structures (PH infiltration), the implementation of operable roof openings resulted in a 14.27% reduction in overheating by 2080.

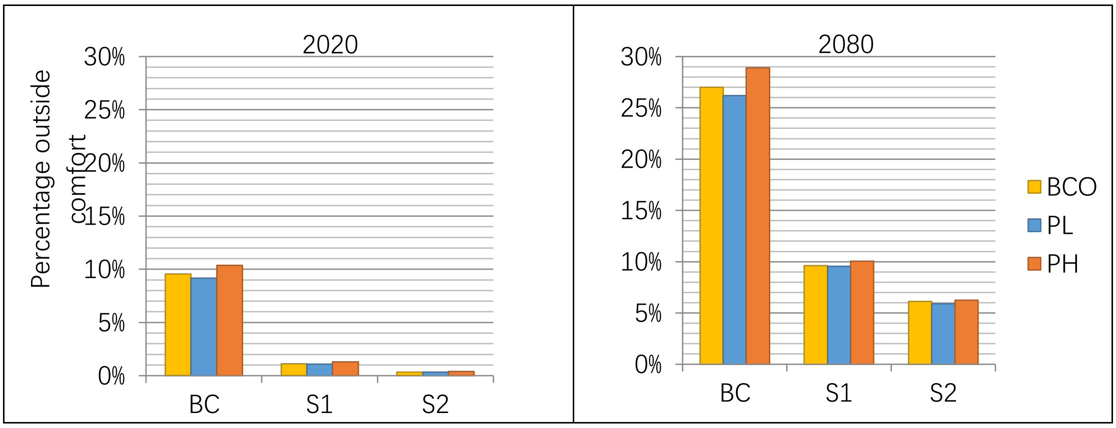

Figure 8. Impact of strategies S1-2 through the years when considering infiltration rate.

Table 7. Percent under comfort (18 °C) for BC & S1 (2nd floor living room) during winter.

	2020			2050			2080		
	BCC	**PL**	**PH**	**BCC**	**PL**	**PH**	**BCC**	**PL**	**PH**
BC	25.87	52.19	4.65	16.04	42.26	1.49	6.88	28.30	0
S1	48.78	71.49	16.25	34.58	59.31	4.65	17.60	44.38	0.21

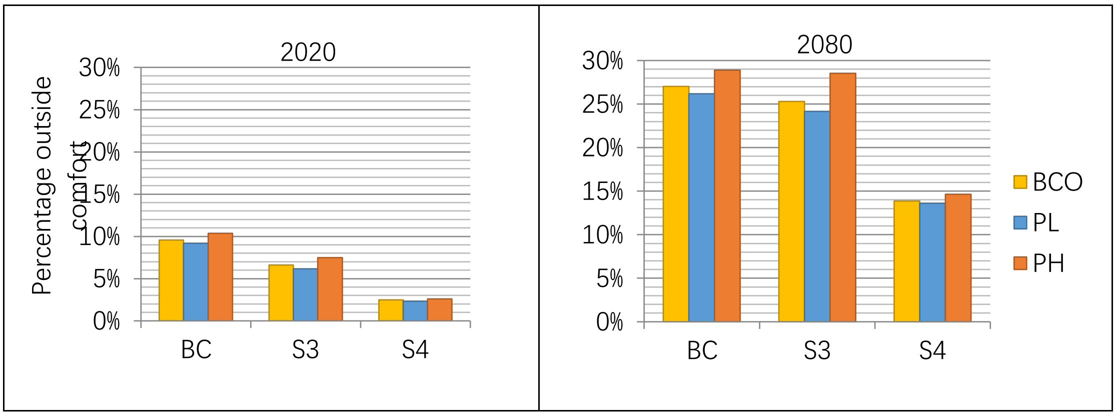

Figure 9. Impact of strategies S3-4 through the years when considering infiltration rate.

Table 8. Percent over comfort (28 °C) for various strategies (2nd floor living room) during summer.

	2020				**2050**				**2080**			
	BCO	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**
BC	9.56	9.75	9.18	10.38	16.31	16.50	15.66	17.48	27.02	27.51	26.20	28.89
S1	1.12	1.25	1.09	1.31	3.7	3.73	3.62	3.84	9.61	9.78	9.56	10.05
S2	0.33	0.33	0.33	0.38	1.28	1.28	1.23	1.33	6.13	6.18	5.91	6.24
S3	6.62	6.81	6.15	7.49	13.26	13.67	12.58	14.65	25.30	26.39	24.16	28.54
S4	2.48	2.51	2.34	2.59	5.96	6.05	5.66	6.48	13.89	14.05	13.62	14.62

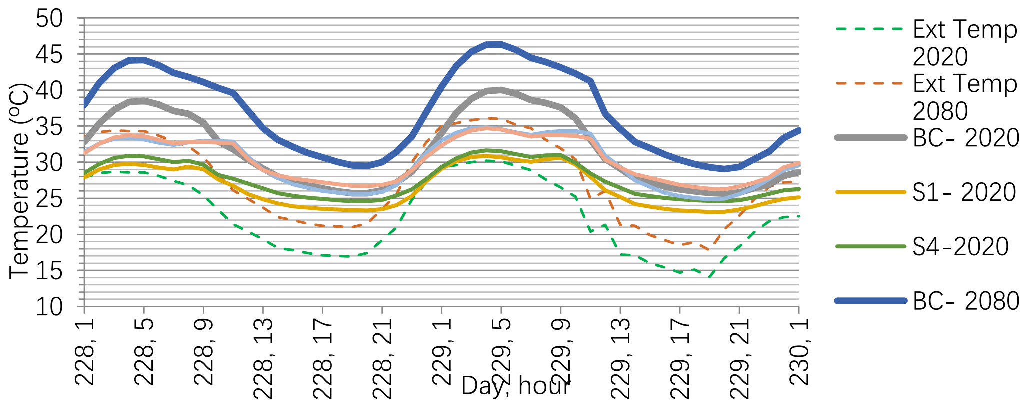

Figure 10. Temperatures on the warmest day for BCO (2020, 2080).

Analysis of peak temperatures on the hottest day of the year indicates that by 2080, implementing either S1 or S4 results in thermal performance comparable to the current base case. However, despite these mitigation strategies, the building consistently exceeds the comfort threshold, even under present-day conditions. This trend is particularly evident in the second-floor living room, as illustrated in Figure 10.

5.3. Impact of Modified Ventilation Strategies on Thermal Comfort

Ventilation is a well-established method for reducing summer overheating. To examine the effectiveness of minor ventilation interventions, strategies S5 to S7 were implemented. Strategies S5 and S6 focused on improving the thermal environment of the top studio floor. S5 introduced an additional north-facing window in the living room with a standard opening profile, allowing airflow from the sunspace to the north window. In contrast, S6 kept all sunspace glazing closed except for the roof glazing, creating a solar chimney effect where cooler air entered through the north window, heated up in the sunspace, and exited through roof openings. As shown in Table 9, the addition of an extra window in S5 significantly improved thermal comfort on the second floor, reducing temperatures by 7.54% from base case and 0.46% from S4, with a more pronounced effect under tighter infiltration conditions (Figure 11), reaching up to 8.12%. By 2080, this intervention led to a 14.68% temperature improvement under standard infiltration rates and 16.25% under tighter infiltration. In comparison, S6 resulted in a 7.03% improvement over the base case but was consistently less effective than S5 across all scenarios, suggesting that the airflow strategy employed may not have been optimally effective. S7 introduced a west-facing window in the ground-floor living room to assess if incoming wind could effectively cool the space using a standard window opening profile. The strategy saw the ground floor of the maisonette cool by up to 8.31% (as seen on Table 9), with improvements decreasing to 5.83% by 2080. While the base case failed all TM52 criteria in current conditions, S7 reduced overheating failures to two rooms- the first-floor sunspace-facing bedroom and the second-floor sunspace-facing studio- demonstrating the thermal benefits of well-chosen ventilation strategies.

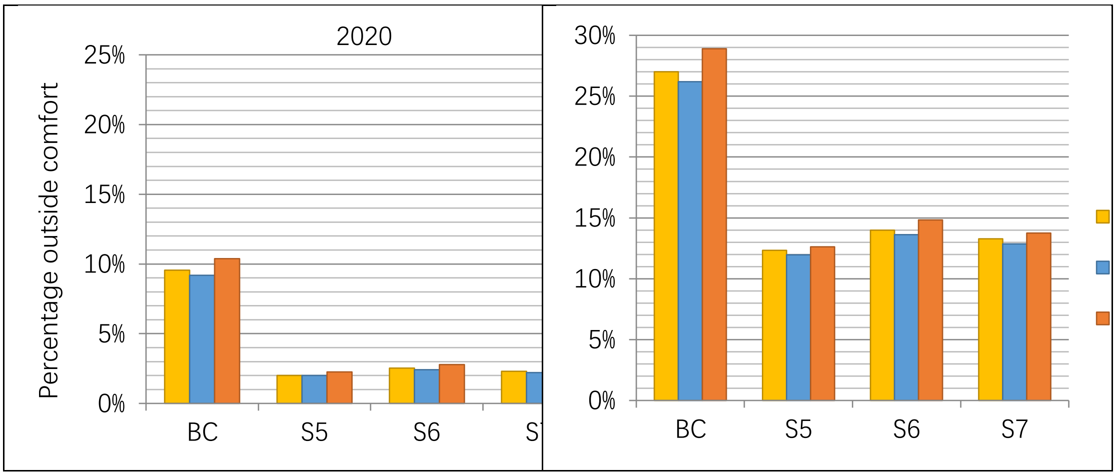

Figure 11. Impact of ventilation opening through the years when considering infiltration rate.

Table 9. Percent over comfort (S5-7).

	2020			2050			2080		
	BCO	**PL**	**PH**	**BCO**	**PL**	**PH**	**BCO**	**PL**	**PH**
BC	9.56	9.18	10.38	16.31	15.66	17.48	27.02	26.20	28.89
S5	2.02	2.02	2.26	4.96	4.85	5.34	12.34	11.96	12.64
S6	2.53	2.42	2.78	6.24	5.99	6.75	14.00	13.62	14.84
S7	1.25	1.23	1.50	3.89	3.81	4.17	9.83	9.61	10.27

5.4. Impact of Occupant Choices on Overheating

To assess the impact of occupant choices on overheating, two tests (S8 and S9) were conducted. Improper use of sunspace windows or ventilation can lead to temperature increases exceeding over 55.80%. Additionally, when towel rails are left on, overheating rises by 0.76% above the base case. These findings highlight the critical need for occupant education on ventilation practices and system usage within buildings, as misuse or lack of awareness can significantly worsen overheating. This issue is further intensified in airtight structures, where S8 and S9 result in overheating increases of 67.13% and 0.92%, respectively as seen on Table 10.

Table 10. Percent over comfort for the second floor living room (8-9).

	2020			2050			2080		
	BCO	**PL**	**PH**	**BCO**	**PL**	**PH**	**BCO**	**PL**	**PH**
BC	9.56	9.18	10.38	16.31	15.66	17.48	27.02	26.20	28.89
S8	65.39	59.15	77.51	84.29	75.87	85.95	92.18	81.24	98.19
S9	10.32	9.83	11.30	18.52	16.56	18.63	30.36	27.40	29.78

5.5. Discussions

This paper analyses and evaluates various strategies to address overheating within the structure. The purpose of these subsections was to investigate the multiple factors contributing to increased internal temperature. The first section examined the base-case structure, highlighting its limitations, while the second section evaluated the effect of incorporating a sunspace. Results indicate that the sunspace contributed to overheating by an additional 8.5% over comfort. However, due to the structure's looser airtightness- when compared to Passivhaus standards, its level of overheating is less pronounced than in more airtight buildings. Furthermore, the study shows that the degree of overheating varies based on infiltration rates; looser infiltration rates are associated with reduced overheating. Upon removal of the sunspace however, looser infiltration had a smaller difference on internal temperatures across summer. Despite lower internal summer temperatures, the structure still failed the TM52s overheating criteria. S2 emphasizes the importance of solar control and shading as effective measures to manage overheating, enabling the structure to meet TM52's criteria. Additional methods, such as reducing glazing ratios and introducing roof-level ventilation, were identified as effective strategies, particularly in future climate scenarios. While the roof-level opening was designed as non-operable due to cost-cutting measures; this modification could have been anticipated as a necessary adjustment to enhance the building's resilience to future overheating risks.

The second stage of the study focused on ventilation, given its significant impact on reducing overheating. It quickly became evident that relying solely on south-facing windows, with only one additional window on the north side, was insufficient to cool the space effectively and make use of strategies such as cross ventilation. Adding windows in conjunction with the roof opening led to an reduction of 7.54% over comfort when compared to the base case. Further optimization of ventilation strategies, such as adjusting window opening schedules, could yield additional improvements. However, this approach is limited by the likelihood that most occupants may not adhere to optimal opening schedules consistently. Consequently, the third stage of the analysis examined overheating influenced by occupant behaviour. Reports indicated that users often left towel rail heating on during the summer and struggled to maintain appropriate window opening schedules in the sunspace due to usability challenges. These behaviours were found to substantially increase internal temperatures, with improper window operation in particular posing a risk of severe overheating under future climate conditions.

While the sunspace enhances winter comfort, providing a 22.91% increase in comfort hours during the winter period in the 2020 scenario, its effectiveness is expected to decline to 10.72% by 2080. By that time, the base case will exhibit 6.88% discomfort, while S1 will reach 17.60% outside the comfort range. This highlights the need for a careful trade-off between winter benefits and potential overheating risks. The study suggests that an alternative to the sunspace could be the implementation of low infiltration rates. Although the sunspace appears to be a logical short-term solution, overheating is already an issue. One important consideration is that the model does not account for heat exchange, leading to warmer temperatures than those analysed in the project. Future studies may necessitate a more comprehensive analysis in this regard, as the inclusion of this mechanism could indicate significantly higher winter temperatures in the base case and documented strategies within the paper. While tightly sealed buildings may require some heating for the short-term, they generally perform well under both climate scenarios when paired with well-designed ventilation strategies and effective solar control measures. However, future projected temperatures suggest summer averages around 24.5°C, which would likely cause the structure to fail the TM52 overheating assessment. Additionally, literature frequently identifies user behaviour as a critical factor in overheating. Simpler systems may improve adherence compared to more complex designs, as relying on users to follow specific window-opening schedules introduces significant variability, given that most occupants do not adhere strictly to these routines. Accordingly, the insights gained from this study allow us to draw key conclusions regarding the previously stated hypotheses:

a. Hypothesis 1 (Impact of Passive Wind Cowls on Overheating): The investigation into the impact of increased air exchange rates through open passive wind cowls showed effectiveness in reducing summer overheating. While looser infiltration lowered internal temperatures, the difference between the Part L standard and the BedZED open-vent configuration remained minimal across all climate scenarios. TM52 results confirmed that both configurations performed similarly under stress conditions. This suggests that, although passive wind cowls may support minor temperature reductions, their impact alone is insufficient to mitigate overheating, particularly under future climate projections.
b. Hypothesis 2 (Influence of Sunspaces and Glazing on Overheating): Sunspaces and extensive glazing were found to substantially contribute to summer overheating, validating Hypothesis 2. The removal of the sunspace in S1 led to a reduction in temperatures exceeding the comfort threshold under current conditions. This modification enabled most rooms to meet TM52 criteria in 2020,

although performance deteriorated by 2080. Similarly, reducing south-facing glazing (S3) resulted in modest reductions in overheating, more pronounced in highly airtight configurations. However, benefits diminished over time due to overall climate warming. These findings affirm that while sunspaces may offer winter gains, their long-term thermal performance is detrimental in summer, especially in future climates. Consequently, design strategies should critically assess the use of large glazed areas and incorporate responsive solar control.

c. Hypothesis 3 (Effectiveness of Single-Sided Ventilation Strategies): Modifications to single-sided ventilation, particularly through the introduction of new openings (S5–S7), demonstrated significant potential to mitigate overheating, supporting Hypothesis 3. S5, which introduced an additional north-facing window, proved effective, reducing temperatures in 2080 under Passivhaus conditions. S6 (solar chimney effect) was slightly less effective, while S7 (ground-floor west-facing window) achieved % reduction under present-day conditions. These interventions improved compliance with TM52, with fewer rooms failing under modified ventilation layouts. This underlines the importance of strategic window placement and operability in enhancing natural ventilation and maintaining thermal comfort in increasingly warm climates.

d. Hypothesis 4 (Impact of Occupant Behaviour on Overheating Risk): Hypothesis 4 is strongly supported by the results, revealing that occupant behaviour can drastically influence thermal conditions. Scenario S8, representing poor ventilation habits (e.g., sunspace windows closed), caused a staggering increase in overheating. Similarly, leaving towel rails on (S9) led to modest but consistent overheating increases. These results emphasize the critical role of occupant education in the effective operation of ventilation systems and thermal management, especially in airtight buildings where errors are less forgiving. Long-term overheating mitigation strategies must therefore pair passive design improvements with behavioural guidance and user-friendly control systems.

6. Conclusions

Recognizing the relationship between climate change and energy consumption is crucial for developing effective mitigation strategies. In Europe, buildings are a major source of energy consumption and CO_2 emissions, highlighting the importance of energy efficiency in shaping policy initiatives. This study examines the BedZED development, showing that rising temperatures have compromised its initial success, with sunspaces now contributing to overheating. It evaluates the long-term viability of this passive design strategy amid future climate challenges. By analysing temperature variations across multiple spaces and assessing various design interventions, the findings highlight both the benefits and limitations of sunspaces in maintaining thermal comfort. Key results indicate that overheating risks increase significantly over time, with internal temperatures rising across all tested spaces. Notably, upper floors experience the highest temperature peaks, emphasizing the need for targeted cooling strategies. Under the TM52 criteria, most rooms in the base-case scenario fail to meet acceptable comfort thresholds, even under current climate conditions. The sunspace contributes to overheating, particularly in summer, although it provides measurable thermal benefits during winter by raising internal temperatures by an average of 0.76 °C. However, these benefits diminish over time, suggesting that the sunspace's effectiveness will decline as external temperatures continue to rise. The study also explored a range of mitigation strategies, including shading, glazing modifications, enhanced ventilation, and adaptive occupant behaviours. Shading (S2) and operable roof openings (S4) were found to be the most effective in reducing overheating, with temperature reductions of up to 13.13% by 2080. Strategies that improved cross-ventilation (S5-S7) also demonstrated significant potential in enhancing thermal comfort, particularly for upper floors. In contrast, tighter infiltration rates, while beneficial in winter, were found to exacerbate summer overheating. Occupant behaviour (S8-S9) was a critical factor, as improper use of ventilation systems or sunspace openings led to overheating increases.

This study emphasizes the necessity of ongoing adaptation in building design to respond to changing climate conditions, especially with the rise in global temperatures. Energy-efficient buildings must strike a careful balance between maintaining thermal comfort and minimizing energy consumption. The results reveal discrepancies in the assessment of overheating risks based on comfort standards, as well as differences in the intensity and frequency of overheating events. These findings highlight the need to reassess older energy-efficient designs and to standardize risk evaluation methods, ensuring that both present and future environmental challenges are adequately addressed. Future research should explore the impact of different strategies during the heating seasons more thoroughly. While winter effects have been studied, a more comprehensive analysis of trade-offs between strategies is needed. Additionally, the study used 2002 IPCC A2 scenario data for future weather projections in 2050 and 2080. A limitation of the SRES scenarios (including A2), is their lack of explicit carbon emissions controls, although they consider broad sustainability themes. The newer Representative Concentration Pathways (RCPs) from the Fifth Assessment Report provide more nuanced projections, incorporating potential climate mitigation policies. Comparing RCP 2.6 (optimistic) and RCP 8.5 (worst case) could yield significantly different overheating outcomes, as A2 broadly aligns with RCP 6.0 and 8.5.

Appendix A

Table A1. Variations in the average temperatures of BC through the years- expanded.

	2020				2050				2080			
Ground Floor												
	BCO	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**
Near sunspace	24.99	25.15	24.7	25.48	25.75	25.88	25.48	26.21	26.9	27.03	26.65	27.35
Avg. floor	24.6	24.82	24.24	25.27	25.43	25.6	25.09	26.05	26.65	26.81	26.33	27.24
First Floor												
	BCO	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**
Near sunspace	25.5	25.65	25.24	25.97	26.25	26.37	26	26.69	27.42	27.55	27.19	27.88
Avg. floor	25.57	25.77	25.21	26.2	26.36	26.53	26.04	26.96	27.58	27.74	27.27	28.17
Second Floor												
	BCO	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**	**BCO**	**BCC**	**PL**	**PH**
Near sunspace	24.98	25.05	24.83	25.22	25.77	25.84	25.63	26.01	27.11	27.18	26.96	27.37
Avg. floor	24.4	24.51	24.2	24.76	25.25	25.35	25.06	25.59	26.63	26.73	26.44	26.99

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