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TECHNICAL ARTICLE

Operational Carbon Impacts of Fabric Retrofits in Victorian Housing: An Assessment Under Future Climate Scenarios

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ABSTRACT

The UK's housing stock is among the oldest and least energy-efficient in Europe, with most homes built before the introduction of energy regulations in the 1990s. Improving their performance is therefore important for meeting national net-zero targets. While insulation, airtightness and glazing can substantially reduce heating demand, their long-term performance under future climate conditions remains less well understood, particularly when overheating and cooling demand are considered. This study evaluated the long-term operational carbon and thermal performance of five retrofit strategies applied to a typical mid-terrace Victorian house. Dynamic thermal simulations were undertaken for shaded and unshaded models using current and future weather files, with mechanical cooling introduced where overheating thresholds were exceeded. The results showed that deeper fabric retrofit substantially reduced heating-related emissions, with the most comprehensive strategy reducing them by approximately 80.7% relative to the base case. However, highly insulated and airtight configurations also increased summertime overheating and cooling demand. By 2080, cooling demand in the most advanced retrofit scenario became comparable to heating demand. External shading reduced cooling-related emissions by approximately 13-25% across the retrofit scenarios, although its effect on total operational carbon was more modest. Cooling setpoint assumptions also had a strong influence. Overall, the findings show that future retrofit performance should be assessed not only in terms of winter heating reductions, but also in relation to overheating risk, passive solar control and future cooling demand.

KEYWORDS Energy efficiency, Overheating, Passive strategies, Airtightness, Future weather

1. Introduction

The UK has one of the oldest and least energy-efficient housing stocks in Europe, with approximately 80% of existing homes already built, the majority of which predate the energy efficiency regulations introduced in the 1990s (Palmer and Lewis 2022). With global temperatures already 1.07°C higher than pre-industrial levels (2010-2019), the world risks exceeding the Paris Agreement's 2°C limit unless carbon emissions reach net zero by 2050 (Summary for Policymakers 2023; United Nations 2015). The building sector, responsible for approximately 38% of global carbon emissions (Hamilton *et al.* 2022), is therefore a critical focus for developing strategies that enable the transition to carbon-neutral buildings. The UK's emission reduction targets of 34% by 2020 and 80% by 2050 remain difficult to meet due to the strong correlation between building age and poor energy performance identified by the English House Condition Survey (CLG 2009; Moran *et al.* 2014). With a retrofit rate of only 2.9-5% per year, current progress is inadequate to achieve national goals (Eames *et al.* 2013). As a result, significant attention has been directed toward upgrading these homes to improve their energy performance and align with the country's net-zero targets. Increasing energy efficiency is regarded as an "essential plank" in this transition, with reports estimating that around 26 million homes will

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require retrofits by 2050 (BEIS 2021; IET 2020). Key strategies for achieving this include reducing household energy demand, transitioning to electric heating as the grid decarbonizes, and increasing the adoption of renewable energy sources. Retrofitting buildings to improve thermal performance during the heating season involves several key strategies, with insulation and airtightness being paramount.

1.1. Retrofit strategies often adopted

Effective insulation is crucial in minimizing heat transfer through the building envelope. Studies that have evaluated English dwellings before and after implementing energy-efficient retrofit measures (cavity wall and loft insulation) indicate that combined measures could potentially reduce infiltration rates by 24%, thereby enhancing the thermal efficiency of the buildings (Hong *et al.* 2004). Common insulation methods used in UK retrofits include cavity wall insulation and external wall insulation. Cavity wall insulation involves filling the gap between a building's external and internal walls with insulating material to minimize heat loss. External wall insulation, on the other hand, consists of applying an insulating layer to the outside of a building, which helps reduce heat loss and enhances overall energy efficiency. Two insulation materials most frequently discussed in the literature are glass wool and expanded polystyrene (EPS). Glass wool is consistently reported as having one of the shortest carbon payback periods among conventional insulation materials (Li and Densley Tingley 2023; Li and Densley Tingley 2021), while EPS is noted for its extensive application in both research and practice (Loucari *et al.* 2016; Arslan *et al.* 2023; Ramli Sulong *et al.* 2019). An important consideration in selecting insulation is the thickness required to achieve a target thermal transmittance. For example, to attain a U-value of 0.15 W/m^2K, glass wool requires approximately 199 mm of material, compared with 248 mm for EPS. This disparity highlights the spatial implications of insulation choice in retrofit design (Li and Densley Tingley 2021). Traditional insulation materials such as mineral wool, expanded polystyrene and polyurethane foams often present challenges including increased structural weight and greater wall thickness (Zhao *et al.* 2025). These limitations reduce the overall effectiveness of the building envelope and restrict their suitability for deep retrofitting or space-constrained applications. Next-generation insulation and façade materials (such as aerogels, vacuum insulation panels (VIPs), advanced thermal plasters, and waste-based composites) are slowly gaining importance. Aerogel-based renders, panels, etc. exhibit ultra-low thermal conductivities and provide excellent thermal resistance with minimal thickness (Baetens *et al.* 2011). VIPs offer even lower conductivities, delivering 5-8 times higher thermal resistance than conventional insulation (Alotaibi and Riffat, 2014, Alam et al., 2022), though their long-term reliability depends on robust edge sealing, puncture resistance and vacuum stability (Baetens *et al.* 2010). However, widespread adoption remains limited due to the relatively higher embodied carbon and longer payback periods compared to conventional options such as mineral wool, which offers significantly faster returns on investment (Alam *et al.* 2022).

Improving airtightness involves sealing unintended gaps and cracks in the building envelope to prevent uncontrolled air leakage, which can account for significant heat loss in older dwellings. Research has demonstrated that applying conventional draught-proofing measures can achieve a reduction in air permeability of over 30% compared to the baseline (Gillott *et al.* 2016). Further sealing of service penetrations and floors reduced air permeability to as low as 4.74 $m^3/(h \cdot m^2)$ at 50 Pa. These improvements contributed to an approximate 9% reduction in space heating energy requirements. Windows are essential components of the building envelope, and upgrading them plays a crucial role in reducing heat loss with research indicating that replacing single-glazed windows with triple glazing can reduce space-heating energy demand by 14.58% during winter and achieve an overall annual energy savings of 15.31% (Memon 2014). Options often considered when retrofitting include double glazing and triple glazing. Double glazing uses two glass panes with a gap to reduce heat transfer, while triple glazing adds a third pane for improved thermal performance and energy efficiency.

1.2. Overheating and cooling

A study examining overheating in London revealed that homes built after 1996 (which adhere to higher energy efficiency standards) experienced significantly longer periods of elevated indoor temperatures compared to older properties. This finding suggests that modern-day retrofits should be carefully evaluated in the context of a rapidly warming world (Pathan *et al.* 2017). Furthermore, in addressing overheating in retrofitted residential buildings, it is imperative to evaluate mitigation strategies such as the implementation of shading devices and air-conditioning (AC) systems. External shading devices, particularly overhangs, have been demonstrated to significantly reduce indoor overheating by limiting solar heat gain. Research has indicated that overhangs contributed to a 9.2% reduction in cooling loads, with potential savings increasing to 15.5% when design and length variations were applied (Mohammed *et al.* 2022). Conversely, the adoption of AC as a cooling strategy presents both benefits and challenges. Currently, the prevalence of AC in UK homes is estimated to be less than 3%, expected to rise to 5-32% by 2050 (Ferguson *et al.* 2023; Crawley *et al.* 2020). Simulation studies indicate that continuous HVAC operation (24 hours per day per room) could increase energy consumption by approximately 14% between 2015-2065, highlighting the importance of dynamic assessments that account for climate change, rather than relying on static models. The analysis also found that electricity demand for cooling increases by approximately 8% for every 1 °C rise in outdoor temperature, demonstrating the strong link between climate and energy use (Lira *et al.* 2025). While AC provides immediate relief from high indoor temperatures, its growing use can substantially boost energy consumption and greenhouse gas emissions (Hoggett et al., 2024, Lizana et al., 2022). This highlights the importance of a balanced retrofit strategy that prioritizes passive cooling solutions to effectively manage overheating without exacerbating environmental impacts. While AC offers immediate relief from high indoor temperatures, its increased use can significantly raise energy consumption and greenhouse gas emissions, highlighting the importance of a balanced retrofit approach that integrates passive cooling strategies to mitigate overheating effectively.

1.3. Retrofitting Solid-Wall Homes: Challenges and Opportunities in Preserving the UK's Historic Housing Stock

Masonry construction remains one of the most characteristic and enduring forms of building in the UK. In particular, many homes constructed before the 1930s, such as those from the Victorian and Georgian eras, typically feature solid brick walls, a defining feature of pre-war English housing (Hunt 2022). Due to the UK's exceptionally low housing demolition rate (Boardman *et al.* 2005), a large proportion of these older buildings remain in use today. Specifically, pre-1919 Victorian dwellings-known for their poorer thermal performance and higher energy demand to maintain comfort. These dwellings continue to represent a significant portion of the English housing stock (Li and Densley Tingley 2021). Solid brick walls are a key feature of these older homes (Turner and Partington 2015) and are estimated to contribute to 35% of their overall heat loss (Li and Densley Tingley 2021). Although the UK government has set a national target to retrofit 2 million solid-wall homes with insulation by 2030, progress has been notably limited (Stark and Thompson 2019). One major barrier is that insulating solid walls is more costly and intrusive than insulating cavity walls or lofts, making it a less appealing option for both homeowners (Milsom 2014). Despite these challenges, insulating solid walls offers a range of benefits, including enhanced energy efficiency, improved thermal comfort during winter, and positive outcomes for health, wellbeing, and fuel poverty mitigation as often seen in literature (Vadodaria *et al.* 2010). Research on retrofitting Victorian houses (as seen in Table 1) has highlighted the effectiveness of various measures, particularly insulation and glazing, in reducing energy consumption and CO_2 emissions. Solid wall retrofits, offer rapid carbon payback and substantial emission reductions, with faster retrofit rates leading to significant stock-level reductions. However, while insulation improvements such as double vacuum glazing and airtightness measures can result in more than 66% savings, increased insulation may raise the risk of summer overheating, particularly in top-floor flats and poorly ventilated spaces.

Table 1. Studies on Retrofits of Victorian Homes.

Findings	Carb. [1]	Insu/ Air[2]	FW[3]	Glazing	Ref.
Double vacuum glazing and airtightness measures delivered > 66.8% savings, though increased insulation posed some risk of summer overheating.		●		●	(Qu *et al.* 2021)
Solid wall retrofits significantly reduce operational emissions; carbon payback times are under 6 years (often <1 year for PIR, EPS, glass wool, and wood fibre), with faster retrofit rates yielding larger stock-level reductions up to 268.3 $MtCO_2e$.	●	●			(Li and Densley Tingley 2021)
Living rooms remain comfortable until 2050, while bedrooms may overheat as early as 2020 under future climate scenarios.			●		(Ji *et al.* 2014; Swan *et al.* 2017)
Draught proofing was the most effective low-risk measure. Loft insulation was less effective when pre-existing insulation was present.		●			(Menconi *et al.* 2024)
A study of 3,456 London dwellings found that building form, age, insulation, and floor level significantly affect overheating, with top-floor flats and poorly ventilated spaces being most at risk. Internal wall insulation sometimes raised temperatures, particularly in solid wall constructions.		●	●		(Mavrogianni *et al.* 2012)
Measures like internal insulation, PV panel, floor and roof insulation, and secondary glazing can yield substantial reductions in energy consumption and CO_2 emissions.		●		●	(Sevim *et al.* 2025)
A combination of low, medium, and high-risk interventions, along with boiler upgrades, can significantly reduce CO2 emissions. Effective retrofit options were identified, such as internal wall insulation, secondary glazing, and ground floor insulation.	●	●		●	(Menconi *et al.* 2025)
Improving insulation and glazing in pre-1919 homes to meet building regulations is cost-effective, reducing heating bills by 46% and improving the SAP rating from band F to D, with an estimated cost of GBP 15,000.		●		●	(Ogunrin *et al.* 2024)

[1] Carbon considered, [2] Insulation/ Airtighness, [3] Future Weather

1.4. Aims and novelty

Taken together, the studies reviewed demonstrate that substantial attention has been given to the individual effects of insulation, glazing, airtightness, and other retrofit measures on energy demand and carbon emissions in older UK dwellings. Several studies have also examined overheating risk or the implications of future climate conditions. However, these factors are generally considered independently or within a limited set of combined variables. Relatively little attention has been given to how progressively deeper fabric retrofit strategies interact with future climate change, overheating thresholds, the subsequent introduction of mechanical cooling, and external shading when evaluating operational carbon over the building life cycle.

This creates an important research gap, as measures that reduce heating-related emissions under present-day conditions may produce different long-term outcomes once increasing overheating risk and cooling demand are considered. The study therefore addresses this gap by comparatively evaluating five progressive retrofit strategies under current and future climate conditions, with both

shaded and unshaded configurations, while accounting for the operational carbon implications of mechanical cooling where overheating thresholds are exceeded. Accordingly, the study addresses the following research questions:

- How do progressively deeper fabric retrofit strategies influence operational carbon emissions over the building life cycle under current and future climate conditions?
- To what extent does increasing overheating risk alter the operational carbon benefits of these retrofit strategies when mechanical cooling is introduced?
- How does external shading influence overheating risk, cooling demand, and the resulting long-term operational carbon performance of different retrofit strategies? The novelty of the study lies in addressing these questions within a single comparative framework. Rather than examining retrofit measures, overheating, future climate, shading, and cooling independently, the study evaluates their combined influence on long-term operational carbon performance. This enables the analysis to determine whether retrofit strategies that perform favourably under present-day heating-dominated conditions retain their carbon benefits as the climate warms and cooling demand emerges.

2. Methodology

Terraced housing represents a substantial component of the existing UK housing stock and is particularly prevalent in England. Recent English Housing Survey data indicate that terraced dwellings account for approximately 25.8% of the English housing stock (HMRC 2026). Furthermore, previous studies (Beizaee et al., 2013, Cherian et al., 2026) have shown that mid-terrace dwellings can exhibit lower heat-loss rates than semi-detached or end-terrace properties due to their reduced external surface area and shared party walls. A mid-terrace Victorian dwelling was therefore selected as the basis for this study. Victorian housing also represents a substantial proportion of the UK's older residential stock and is particularly relevant to retrofit research because such dwellings commonly feature solid masonry walls, relatively poor airtightness and limited levels of original thermal insulation. These characteristics make Victorian terraces both vulnerable to high operational energy demand and an important target for energy-efficiency retrofit, while also raising potential trade-offs between winter energy savings and future overheating risk.

The analysis was conducted using architectural plans of a representative house located in Watford, UK, obtained from publicly available online sources (Cotton 2020). In the absence of original construction documentation, various building details were inferred based on common characteristics of Victorian-era housing. For example, the external walls were assumed to be solid masonry without insulation, while windows were considered to have been retrofitted with double glazing. Additional construction features were derived and adapted from established literature on solid wall Victorian dwellings (Qu *et al.* 2021). A mid-terrace dwelling was selected to provide a controlled environment with windows oriented along a single axis, enabling a focused assessment of solar gains from the south. Additionally, the adjoining properties on either side act as thermal buffers, reducing heat loss through shared walls contributing to elevated internal temperatures when compared to detached dwellings (Beizaee *et al.* 2013). The building featured an overall glazing ratio of approximately 25%, with 24% on the south façade and 27% on the north. The living spaces and bedrooms were oriented southward, incorporating windows solely on the north and south elevations. A comprehensive summary of the construction assumptions employed in this study is provided in Table 2. It is also worth noting that no adjacent buildings blocked solar gains/ shadowed the structures glazing.

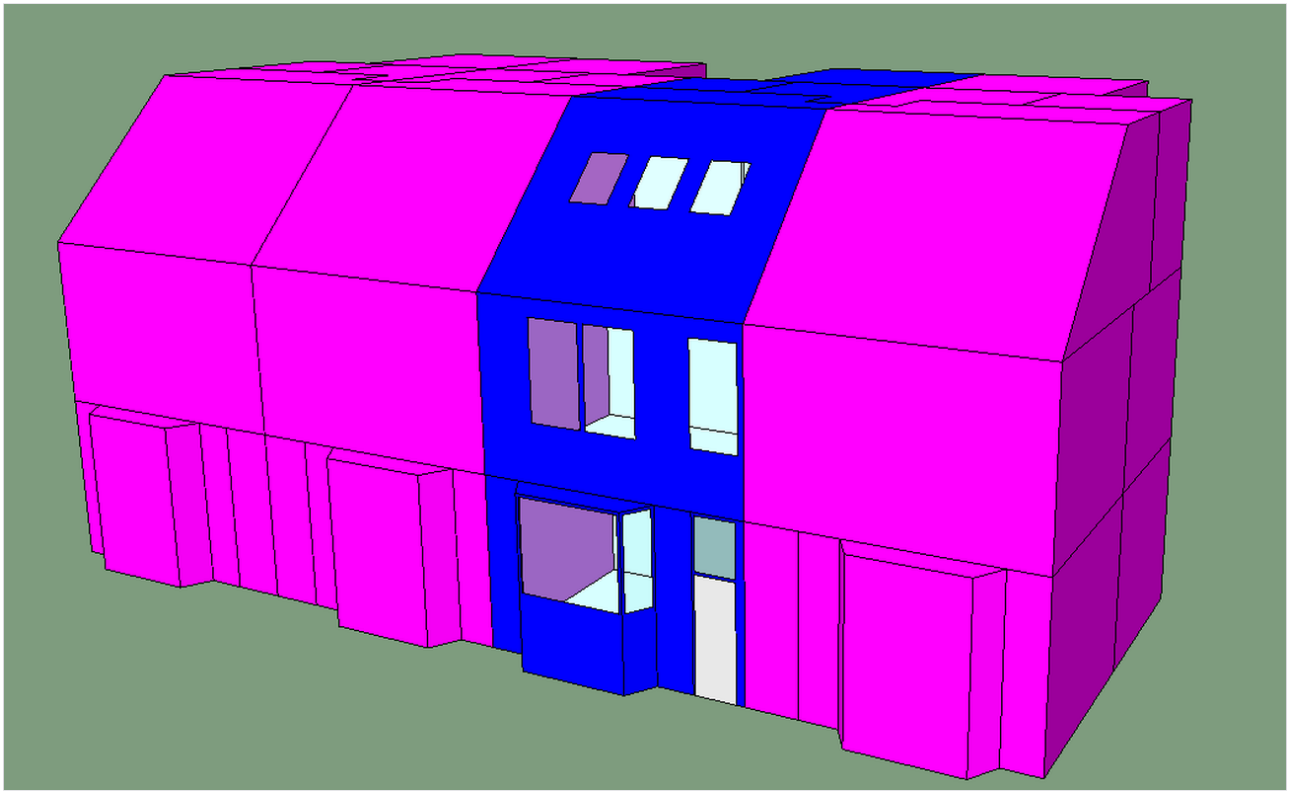

Figure 1. The Base-case house (in blue) with surrounding context.

Table 2. Base-case construction and assumptions.

Building Components	Materials	Conductivity (W/mK)	Density (kg/m³)	Heat Capacity (J/kgK)	U-Value (W/m²K)
Ground floor	400 mm cast concrete	1.13	2000	1000	0.97
	100 mm air cavity	Thermal resistance: 0.15 m2K/W			
	20 mm timber floor	0.14	650	2300	
	10 mm carpet	0.06	186	1360	
Wall	300 mm brick	0.84	1700	800	1.77
	5 on the north. 19 mm gypsum	0.50	1300	1000	
Roof	19 mm Clay tiles	0.84	1900	800	1.22
	100 mm timber joist	0.16	650	1600	
	19 mm gypsum	0.42	1200	837	
Glazing	6mm clear glass	1.06	-	-	3.17 (including frame)
	Cavity	-	-	-	
	6mm clear glass	1.06	-	-	

The generic Victorian house was developed using Integrated Environmental Solutions: Virtual Environment (IESVE) (as seen in Figure 1), a widely used tool for Building Energy Simulation. Its reliability has been validated in multiple peer-reviewed studies (Ben and Steemers 2014; Pollock *et al.* 2009). Two identical digital models were developed, differing only in the inclusion of external shading. Model A served as the baseline without external shading, while Model B incorporated a fixed overhang derived using a rule-of-thumb sizing approach based on representative summer solar

conditions (Equation 1). This resulted in an overhang approximately 0.9 m in depth, positioned above the window to reduce peak summer solar gains.

$$\text{Overhang} = \frac{\text{height of window}}{\tan(\textit{degrees of elevation of sun})} \tag{1}$$

2.1. Weather analysis

To evaluate the building's performance under local climatic conditions, weather data was obtained from an ASHRAE EPW file for London Gatwick (the nearest available location to Watford) using the Ladybug tool. The climate dataset was subsequently analysed within the IESVE simulation environment using VistaPro. The UK experiences four distinct seasons, with winters typically characterised by cold temperatures and summers increasingly affected by heatwaves (Brimicombe *et al.* 2021). In London, average annual temperatures generally range between 6°C and 17°C, with extreme values rarely dropping below -3°C or rising above 27°C. Figure 2 illustrates the projected monthly average external daily temperatures for the years 2025, 2050 and 2080, based on climate data for the London region. A clear upward trend is evident, with each subsequent time slice showing a consistent increase in average temperatures across all months. Notably, peak summer temperatures in July and August rise from just under 20°C in 2025 to over 22°C by 2080, indicating a heightened risk of overheating in future decades. Winter months also see a modest but significant warming, which may reduce heating demand but increase the potential for cooling requirements during extended warm periods. These shifts highlight the importance of climate-responsive retrofit strategies when designing for long-term thermal comfort and energy performance.

Future EPW weather files were generated using CCWeatherGen (Jentsch *et al.* 2008), an Excel-based tool designed to produce climate-adjusted weather data for building performance simulations. The tool relied on projections from the HadCM3 A2 scenario of the IPCC Third Assessment Report (IPCC 2001). The results are based on the medium (50th percentile) climate scenario and should therefore not be interpreted as representing worst-case or heatwave conditions. Higher-emission or 90th-percentile scenarios could produce substantially greater temperatures, overheating risk and cooling demand, as indicated by previous research (Cherian *et al.* 2026b).

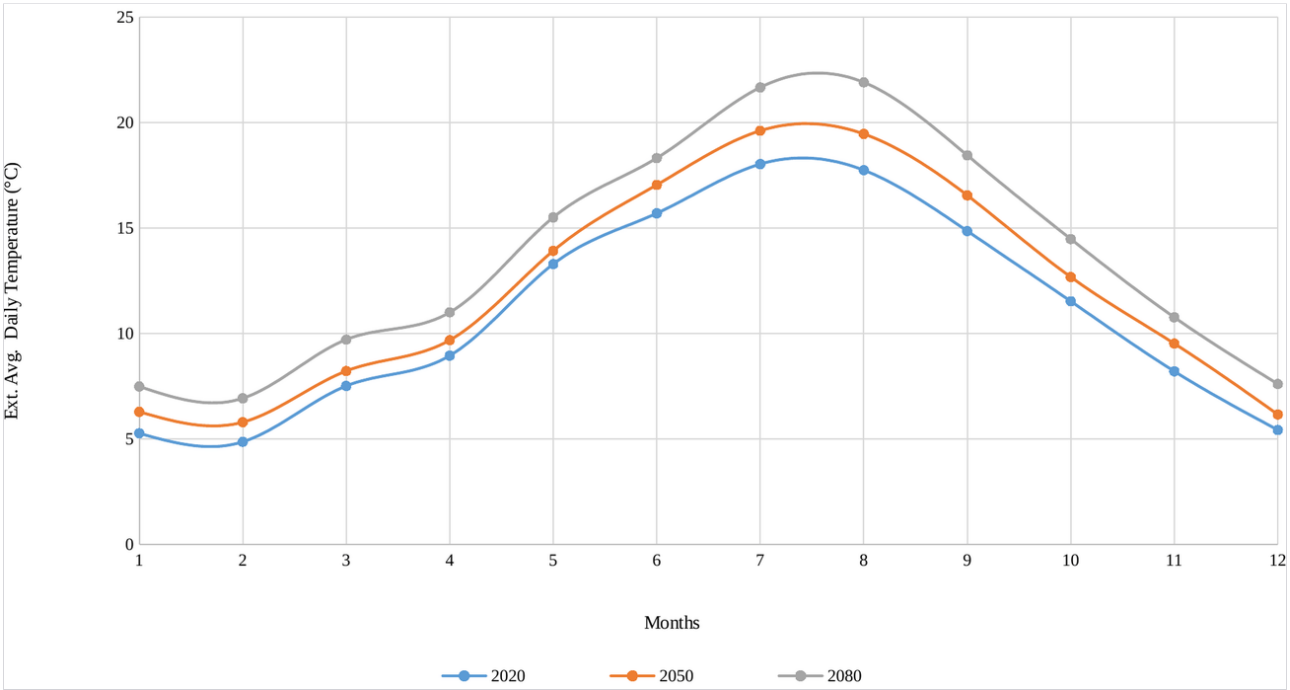

Figure 2. External Temperature through the years.

2.2. Assumptions

CIBSE Technical Memorandum 59 (TM59) establishes a standard approach for assessing the risk of overheating in residential buildings through the use of BES tools (CIBSE 2017). In this study, TM59 occupancy profiles (as seen in Table 3) were integrated into the simulation framework to represent realistic usage patterns and account for conditions associated with elevated overheating risk. The simulation assumed standard occupancy conditions, with individuals generating 75 W of sensible heat and 55 W of latent heat. Two occupants were assigned to each double bedroom, and three occupants were assumed to occupy the living room and kitchen areas, following the occupancy schedules and internal load profiles presented in Table 3. Internal heat gains from lighting were modelled using a power density of 2 W/m^2. Appliances and equipment were defined using room-specific profiles aligned with activity levels outlined in TM59. Window operation followed a binary control logic when AC was not considered: windows opened when internal temperatures exceeded 24°C, remained closed in winter, and stayed shut during summer if external temperatures rose above 26°C.

Table 3. Schedules, gains (adapted from (CIBSE 2017)) and Assumptions.

Space	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
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/m2)		0	0	0	1	1	1	0
Parameter	**Description**			**Assumption**					
Weather	London Gatwick			Typical weather year					
Air Permeability	Base-case			Air Permeability of 10 m3/hr/m2					
Heating Profile	Model setpoint			18°C					
	Technology			Gas Boiler					
	Seasonal efficiency			0.9200					
	SCoP kW/kW			0.8820					
Cooling Profile	Model setpoint			22°C					
	Technology			Standard Air-conditioning Unit					
	Nominal EER kW/kW			3.6800					
	Seasonal EER kW/kW			6.8000					

In this study, carbon emissions were evaluated using two approaches. The first employed a static emission profile, applying the latest BEIS conversion factors to the annual operational consumption derived from IESVE, expressed in kgCO_2e. This method assumes a constant emission intensity over time. It should be noted that kgCO_2e accounts for multiple greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O). The second approach (applied where specified) incorporated a dynamic grid decarbonisation profile based on the Committee on Climate Change's (CCC) Seventh Carbon Budget pathway (CCC 2025). Under this method, the projected emission factors (shown in Figure 3) were applied to the modelled electricity demand of the building to estimate operational carbon emissions over time. In contrast, a static emission factor was retained for natural gas, as its carbon intensity is assumed to remain relatively stable across the analysis period. Historical trends over the past decade support this assumption, with only minor fluctuations observed between 2021 and 2024 (as seen in Figure 4 with data extracted from DESNZ yearly carbon conversion factors over the last 10 years (DESNZ 2025)).

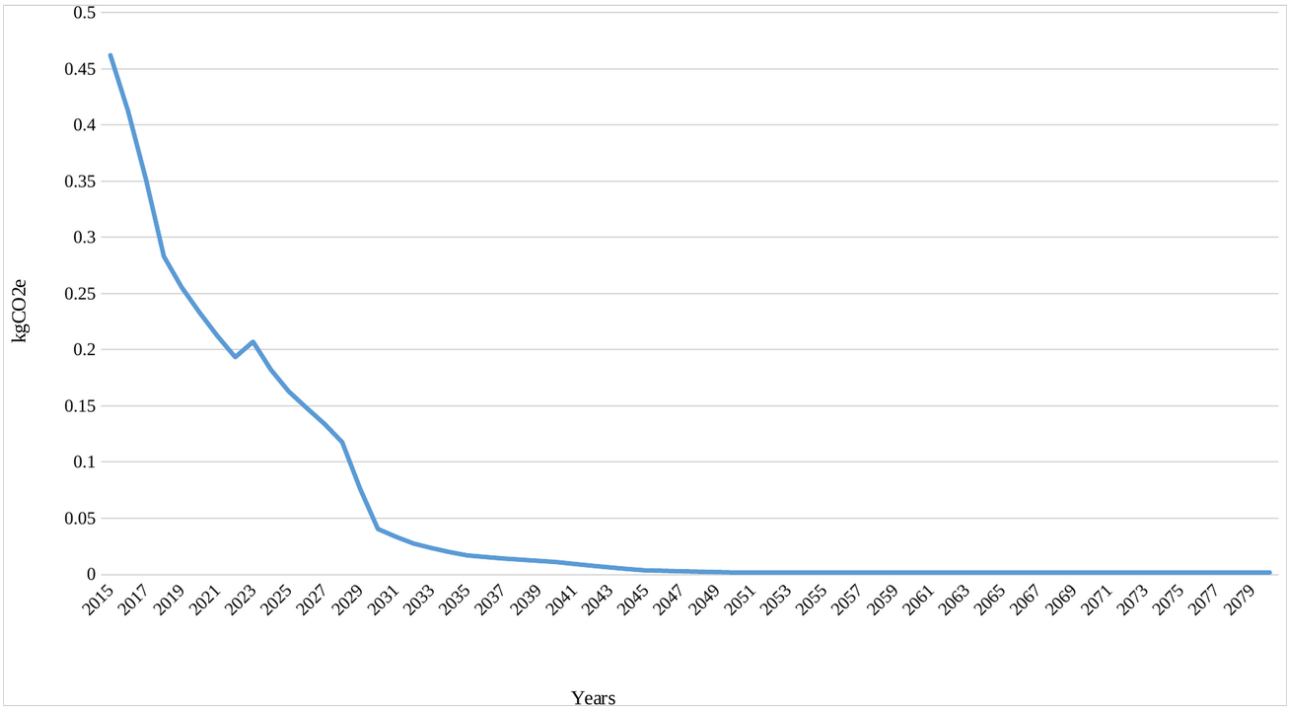

Figure 3. Projected emission factor over the years.

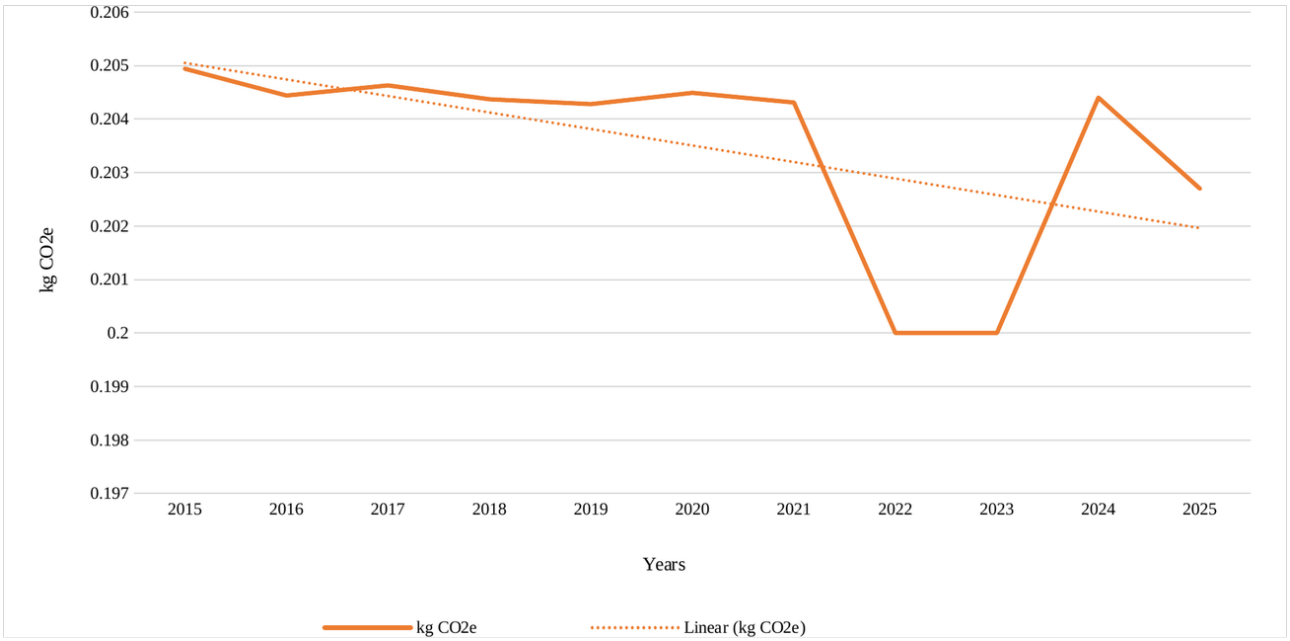

Figure 4. Natural gas emission factor over the last decade.

2.3. Thermal comfort and overheating criteria

As residential AC adoption increases, thermostat setpoints and operating patterns become increasingly important in influencing cooling energy demand. Although setpoints in the range of 24-26°C are generally considered sufficient to achieve thermal comfort, lower temperature setpoints or extended operation periods may significantly increase cooling-related energy use, highlighting the sensitivity of emissions to thermostat temperature settings (LG 2025; Hoggett and Lowes 2024a). By contrast, UK offices, where AC is far more common, offer a richer source of data. Surveys of facility managers indicate that most offices maintain summer cooling setpoints at or below 22°C, with over 60% reporting setpoints of 22°C or lower (Lakeridou *et al.* 2014). While this has traditionally been

standard practice, industry guidelines have begun shifting to encourage higher setpoints to improve energy efficiency. The British Council for Offices, for example, historically recommended 22 ± 2°C for cooling, but more recent guidance has suggested raising setpoints by 2°C (Lakeridou *et al.* 2014). In other words, UK offices could be kept at 24 ± 2°C without significantly compromising comfort or productivity.

Traditionally, overheating assessments are based on the number of hours a space surpasses a defined threshold. In line with guidance from CIBSE Guide A, overheating in residential spaces is typically associated with indoor temperatures exceeding 28°C in living rooms and 26°C in bedrooms during peak summer periods (CIBSE 2017; CIBSE 2006). Thermal comfort is then evaluated using two criteria: Criterion A applies to living rooms, kitchens and bedrooms, requiring that indoor temperatures exceed the comfort threshold by no more than 1°C for less than 3% of occupied hours between 1st May-30th September. Criterion B applies to bedrooms only, limiting temperatures above 26°C between 10 pm and 7 am to no more than 1% of total annual hours (CIBSE 2017). In this study, a study-specific sensitivity criterion was applied, whereby all retrofit strategies were assessed against an upper indoor temperature threshold of 26°C between 1st May-30th September. Where temperatures in two or more bedrooms exceeded 26°C for more than 3% of the year, a multi-split air-conditioning system serving the three bedrooms and living room was assumed to be installed. This simplified assumption was adopted because occupant decisions regarding whether to install air conditioning, and in which individual rooms, cannot be determined with confidence. Modelling room-specific installation behaviour would therefore introduce additional uncertainty into the analysis. All subsequent references to overheating percentages in this study refer to the percentage of the annual occupied period during which indoor temperatures exceeded the defined 26°C threshold.

2.4. Analysis Framework

A total of five retrofit strategies (C1 to C5) were tested in addition to the base case (with no retrofit interventions), which served as the control. Each strategy applied a measure or combination of measures. As seen on Table 4 and Table 5, the insulated wall construction was applied in retrofit strategies C2-C5, while triple glazing was used in strategies C1, C4, and C5. The base case assumed an airtightness level of 10 $m^3/hr/m^2$, which aligns with older Part L regulations and represents a moderately leaky building- typical of older UK housing stock. In scenarios where airtightness was included as part of the retrofit (C3 and C5), a significantly tighter airtightness was assumed, consistent with Passivhaus standards at 0.6 air changes per hour at 50 Pascals. This approach reflects industry practice, as airtightness is typically implemented alongside other fabric upgrades rather than as a standalone measure.

Table 4. Retrofit Strategies.

Strategy ID	Retrofit Measures Applied
Base Case	No changes (Control model)
C1	Triple glazing
C2	Insulation
C3	Insulation + Airtightness
C4	Insulation + Triple glazing
C5	Insulation + Triple glazing + Airtightness

Table 5. Construction Specifications for Retrofit Strategies.

Building Components	Materials	Conductivity (W/mK)	Density (kg/m³)	Heat Capacity (J/kgK)	U-Value (W/m²K)
Wall (Insulated)	19mm plaster	0.50	1300	837	0.12
	250mm insulation	0.035	25	1400	
	300mm brick	0.84	1700	800	
	19mm gypsum	0.50	1300	1000	
Glazing	4mm clear glass	1.06	-	-	2.29 (including frame)
	Cavity	Argon			
	4mm clear glass	1.06	-	-	
	Cavity	Argon			
	4mm clear glass	1.06	-	-	

Carbon emissions were calculated based on simulated energy demand using three different future weather files (EPWs) representing the years 2025, 2050 and 2080. These files represent projected climate scenarios used to estimate the building's operational energy use and carbon emissions over the 55-year analysis period, offering a practical balance between accuracy and computational efficiency. In climate modelling, overheating metrics are typically evaluated at coarse time slices (e.g. years 2020, 2050, 2080). This is a deliberate trade-off: simulating every individual year would be computationally intensive and costly, especially when running ensembles of dozens or hundreds of scenarios. To reduce computational demands, models often simulate selected milestone years and interpolate between them. However, for this body of research, where the timing of threshold crossings (e.g. when overheating exceeds 3% of the year) is critical, relying solely on coarse slices is insufficient. Knowing exactly when a threshold is passed, even to the nearest year, is essential for impact forecasting. Running simulations for each year would offer ideal precision but would require enormous computational power, often beyond the scope of most studies. Thus, a computationally efficient interpolation approach is employed to estimate intermediate years with reasonable accuracy. This is done by linear interpolation between two known time slices. This approach was selected as a transparent and parsimonious method that preserves the simulated endpoint values without introducing additional assumptions regarding the form of the trajectory between them. Although nonlinear or spline-based interpolation could be applied, such approaches would require assumptions concerning the rate, curvature, or acceleration of change that are not directly supported by the discrete simulation outputs and could therefore introduce additional uncertainty into the analysis.

Whole-life operational carbon emissions from heating and cooling were then evaluated using statistical equations (presented in Equations 2 and 3). AC is assumed to remain unused until the threshold year (x_T), defined as the point at which overheating first exceeds the comfort threshold. From the first full year after this point, AC adoption is assumed. Cooling energy demand is then modelled to increase linearly until the next simulation year (2050), as represented in Equation 3. This approach allows us to estimate a gradual increase in cooling energy consumption following the onset of overheating discomfort.

$$E(x) = \begin{cases} E_0 + \left(\frac{x - 2025}{2050\text{-}2025} \right) \cdot (E_1 - E_0) \text{ if } x \leq x_T \\ E_2 + \left(\frac{x - 2025}{2050\text{-}2025} \right) \cdot (E_3 - E_2) \text{ if } x > x_T \end{cases} \quad (2)$$

x: year in question, E_0 and E_1 represent the modelled energy use in the years 2025 and 2050, respectively, under scenarios without AC. Conversely, E_2 and E_3 denote the energy use in 2025 and 2050 with AC enabled, x_T: year when overheating threshold is crossed

For the period between 2050 and 2080, a simplified linear interpolation approach is applied. This is justified by the fact that, across all simulated permutations, overheating levels have already exceeded the critical threshold by 2050. Therefore, it is assumed that AC is in use during this period, and energy demand for cooling increases linearly from the modelled value in 2050 to 2080 (denoted as E_{2080}).

$$E(x) = E_1 + \left(\frac{x - 2050}{2080\text{-}2050} \right) \cdot (E_4 - E_3) \quad (3)$$

The methodological process began with the development of two IESVE simulation models: one incorporating external shading and one without. Both models were then evaluated across the defined retrofit scenarios using dynamic thermal simulations with future weather files. Annual heating and cooling energy demands were extracted from the simulation outputs, and Equations 2 and 3 were used to estimate yearly heating and cooling energy consumption over the 55-year analysis period. The corresponding annual carbon emission factors were then applied to these energy values to account for grid decarbonisation over time. The resulting annual emissions were summed across the full analysis period to determine the cumulative whole-life operational carbon emissions associated with heating and cooling.

2.5. Limitations

While this study offers valuable insights into the long-term carbon implications of various retrofit strategies, several limitations should be acknowledged to contextualize the results and highlight areas for future improvement:

- The IESVE models are not calibrated to any specific dwelling or measured energy use, which limits real-world precision.
- This study focuses solely on operational emissions. Embodied carbon from materials, installation, maintenance, or end-of-life disposal is not included. Deeper retrofit options (e.g. C5) are likely to involve greater material use and construction intensity and therefore may carry higher embodied emissions. As a result, the inclusion of embodied carbon in a full whole-life carbon assessment could influence the comparative ranking of retrofit strategies.
- Component lifespans and replacement cycles (e.g., for glazing) are not accounted for.
- Only three EPW weather files are used to approximate 55 years of performance. A more accurate approach would involve year-by-year weather simulations using a continuous climate change projection, but this was deemed infeasible due to time and computational constraints.
- Gas boilers were assumed throughout. While typical of UK housing, this excludes potential carbon savings from low-carbon heating options like heat pumps. If it had been considered within some retrofit strategies, particularly those that significantly improve thermal efficiency, the associated heating-related emissions would likely have been lower.

3. Operational Carbon Outcomes and Cooling Implications

The analysis was divided into four main components. The first focused on evaluating the overheating impact of each retrofit strategy over the 55-year period. The second part examined the influence of AC and the effect of different retrofit scenarios on carbon output. The third examined the influence of different cooling setpoints on carbon output. Finally, the fourth scenario examined the impact of grid decarbonisation on overall emissions.

Prior to evaluating the retrofit parameters, the base case model was assessed to establish a performance benchmark. The analysis revealed that higher south-facing glazing ratios substantially increased the risk of overheating, particularly in south-facing bedrooms, where the proportion of occupied hours above 26°C rose from approximately 8% in 2025 to 24% by 2080 (Figure 5). All south-facing rooms exceeded the 3% overheating threshold, with the living room experiencing approximately 3.6% of hours above 26°C and 2% above 28°C. In contrast, north-facing rooms (including the kitchen) remained below the threshold in 2025 but began to exceed it by 2050, with the kitchen surpassing it only by 2080, reaching 9.1% of hours above 26°C and 3.5% above 28°C.

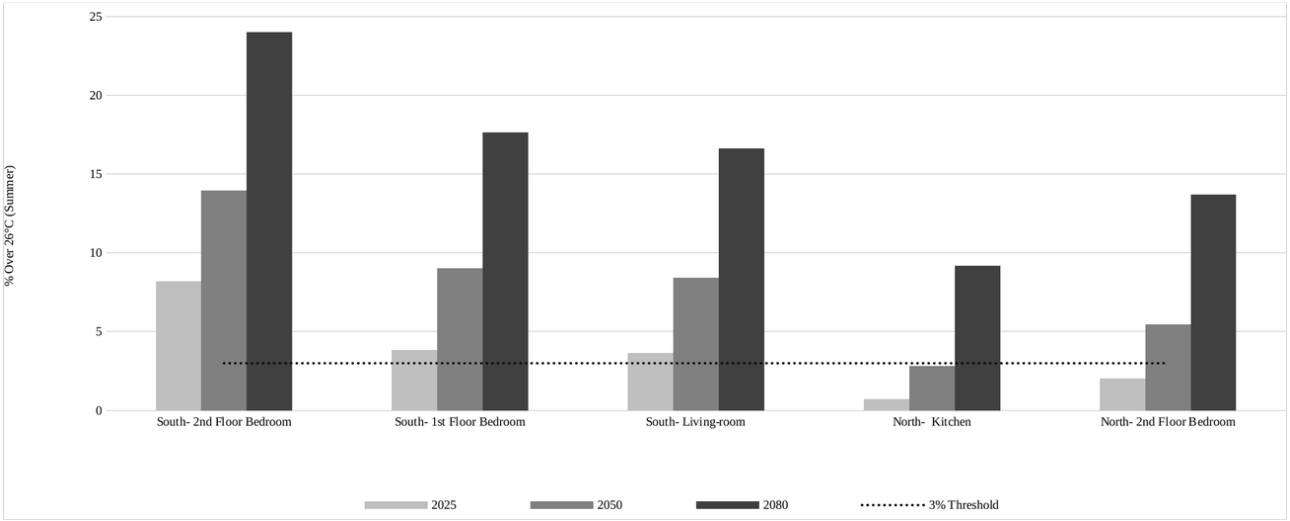

Figure 5. Percentage of hours Above 26˚C for Base-Case.

While the model was not explicitly calibrated against a single monitored study, its outputs were checked for plausibility against ranges reported in published large-scale monitoring studies. National monitoring campaigns using indoor temperature loggers during summer months report mean internal temperatures in terraced dwellings (mid-terrace, end-terrace and semi-detached) typically between 22.7-23.6°C from June-September, with evidence that newer construction types exhibit a greater tendency to overheat than older dwellings (Pathan *et al.* 2017). A further large-scale study monitoring dwellings across England reported mean summer temperatures of approximately 21.7°C in mid-terrace, end-terrace and semi-detached houses between late July and August, with marginally higher temperatures observed in older solid-brick constructions (21.9°C) and in southern regions (22.2°C) (Beizaee *et al.* 2013). These monitored temperature ranges were used as a plausibility check for the simulated outputs.

3.1. Thermal comfort and overheating criteria

The results presented in Figure 6 illustrate when indoor temperatures exceed 26°C for two versions of a typical mid-terrace Victorian house: Model A (unshaded) and Model B (shaded). Model A, exhibited the highest levels of overheating across all scenarios and projected time periods. Overheating increased substantially over time; however, all configurations exhibited overheating from the baseline year of 2025. In the base case, overheating approached 23% by 2080, indicating substantial vulnerability to rising future temperatures. Across the different strategies, retrofit interventions in

Model A did not reduce overheating risk. Most strategies showed similar or slightly increased levels of overheating compared to the base case. The triple glazing strategy (C1) provided no meaningful improvement, while more comprehensive approaches such as C4 and C5, which included insulation, airtightness, and triple glazing, tended to worsen overheating. This outcome was likely due to tighter airtightness measures and increased internal heat retention, without the benefit of solar shading. Figure 7 illustrates the temperature distribution for the projected 2080 period, showing that nearly half of the indoor temperatures exceeded 24°C.

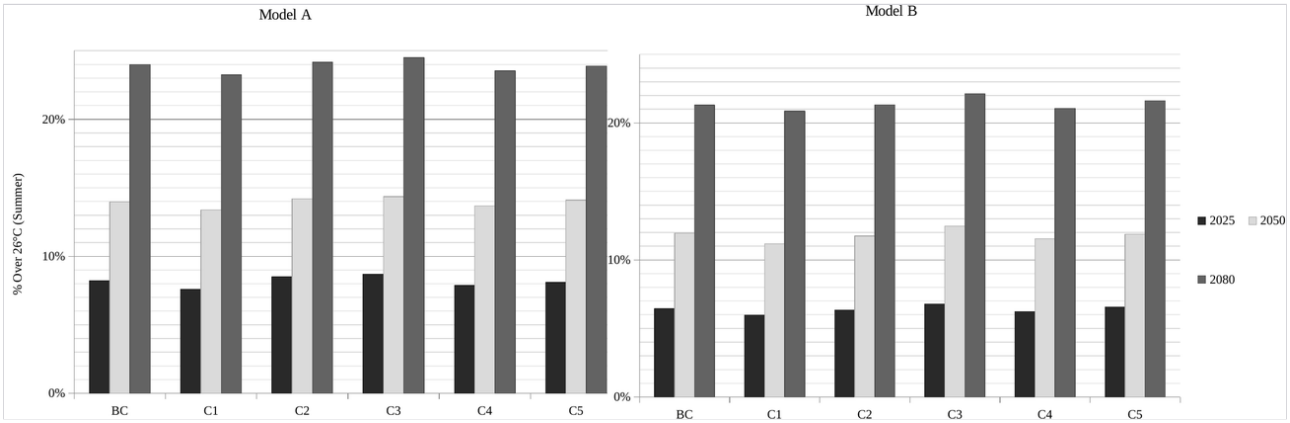

Figure 6. Percentage of Time Above 26°C: Model A & Model B for the 2nd Floor South Bedroom.

BC: Base Case; C1: Triple glazing; C2: Insulation; C3: Insulation + Airtightness; C4: Insulation + Triple glazing; C5: Insulation + Triple glazing + Airtightness.

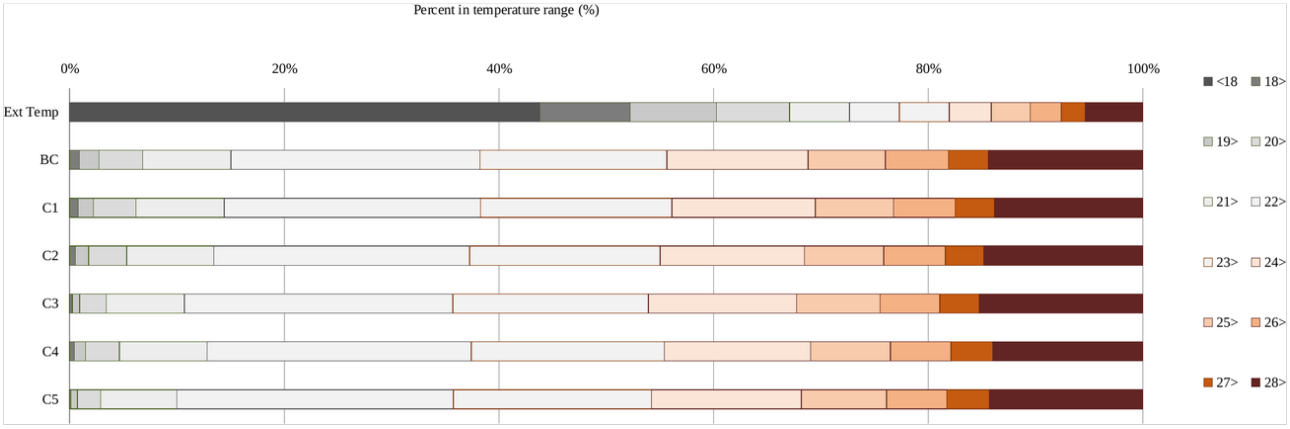

Figure 7. Temperature Range Model A for year 2080.

In contrast, Model B included the fixed external shading device and consistently demonstrated better performance in reducing overheating. Across all strategies and time periods, the percentage of time above the 26°C threshold remained lower in Model B than in the unshaded version. It is important to note that Model B did not eliminate overheating entirely. Even in the 2025 scenario, the percentage of time above 26°C exceeded 3% for most strategies. The presence of external shading helped to mitigate the more severe impacts observed in the unshaded model. Compared to Model A, most scenarios in Model B averaged up to a 2.5% reduction in annual overheating, suggesting that external shading played a stabilising role in supporting thermal comfort under future climate conditions. Several key observations emerged from this analysis. Shading proved to be an effective passive design measure that consistently reduced the risk of overheating across all retrofit scenarios. Conversely, insulation and airtightness, although beneficial for reducing winter heating demand, contributed to increased summertime overheating when not paired with appropriate ventilation or solar control strategies. By 2080, all scenarios exceeded the overheating threshold, reinforcing the

likelihood that mechanical cooling would become necessary in many future cases. The role of shading became increasingly important under warmer climate conditions.

It is important to note that the elevated overheating levels observed are largely attributable to the roof configuration and skylight glazing. Testing an alternative space, such as the first-floor south-facing bedroom, yielded different overheating characteristics and inferences (as seen in Figure 8). Analysis of the room indicated that overheating was substantially reduced and below the set limit across most retrofit strategies, except for C3, which remained above the overheating threshold in 2025. The inclusion of shading measures was essential to maintain compliance with this limit; without shading, all strategies exceeded the 26 °C threshold by approximately 4%. It was due to the higher temperatures consistently observed on the second floor that the second-floor bedroom was selected as the primary zone for overheating assessment. Upper floors are typically more susceptible to heat accumulation due to solar gains and the upward movement of warm air, making this space the most thermally vulnerable within the dwelling.

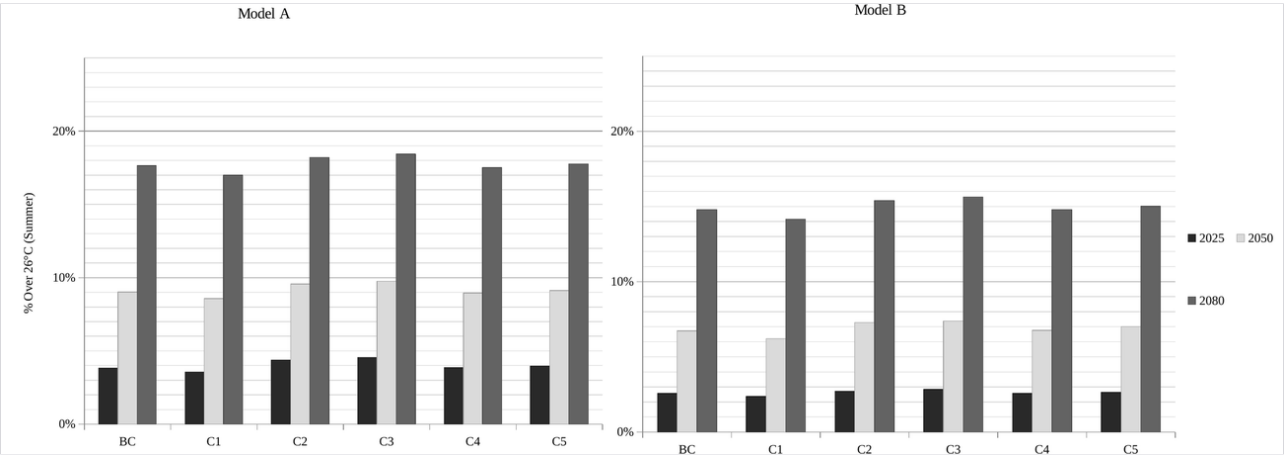

Figure 8. Percentage of Time Above 26°C: Model A & Model B for the 1st Floor South Bedroom.

3.2. When considering air-conditioning

Across both models, a consistent pattern was observed: heating demand decreased over time, while cooling demand increased, reflecting the warming climate projections. When considering Model A (unshaded), BC consistently recorded the highest heating demand across all three weather-file years, beginning at 10.99 MWh in 2025 and declining to 7.42 MWh by 2080. This reduction aligns with the warming climate trend, which progressively reduces the building's need for space heating. Cooling energy demand, though initially low (0.571 MWh), increased significantly to 1.017 MWh by 2080, highlighting a growing risk of overheating and cooling demand under future climate conditions.

- C1, which incorporated triple glazing, produced a modest reduction in both heating and cooling demand, as well as associated carbon emissions, relative to the base case. This improvement is likely attributable to the reduced air leakage and improved thermal resistance of triple glazing compared to the base case double-glazed configuration, limiting heat loss during winter while also reducing conditioned air loss during summer.
- C2 led to a substantial decrease in heating demand, cutting energy use by over 39.9% between 2025 and 2080. However, cooling demand increased over time, reaching 1.121 MWh by 2080, higher than both the base case and C1. This suggested that while insulation was effective in reducing winter energy use, it may trap excess heat during warmer months, thereby increasing reliance on cooling systems.
- Adding airtightness to insulation (C3) further improved performance. Heating energy dropped further to 1.657 MWh by 2080. Although this strategy resulted in slightly higher cooling demand than the base case, the overall operational carbon performance was significantly better.

- C4, which combined enhanced insulation with triple glazing, achieved substantial reductions in heating energy demand. Among the multi-parameter strategies, it exhibited the lowest cooling energy use, second only to C1 (which implemented triple glazing alone). This outcome suggests that the C4 configuration provided a more effective balance between winter efficiency and summer overheating resilience compared to strategies focused primarily on airtightness improvements.
- The most comprehensive retrofit strategy, C5, delivered the lowest energy use for heating across all three weather-file years. Heating energy consumption was reduced to 1.152 MWh by 2080, while emissions fell to 233.59 kgCO_2e. Cooling demand was also slightly lower than in C3, which employed a similar construction without triple glazing. This further indicates that triple glazing enhanced the retention of cooled indoor air, thereby reducing cooling energy consumption during the summer months.

As retrofit strategies were introduced, heating related emissions declined. For instance, C1 reduced emissions by approximately 9%, while C5 (insulation, glazing, and airtightness) achieved the greatest reduction, lowering emissions by 80.7% compared to BC. This outcome was neither unexpected nor unreasonable, as existing literature frequently highlights that such retrofit measures contribute to reduced overall emissions.

The addition of a fixed external shading device in Model B had a notable impact on cooling performance, especially under future climate scenarios. For example, in 2080, the base case cooling energy use was reduced from 1.0171 MWh (Model A) to 0.875 MWh (Model B). The implementation of shading across the different parameters and scenarios produced substantial reductions in cooling-related emissions, varying between 13% and 25%, depending on the retrofit configuration. However, the effectiveness of shading diminished under future climate scenarios, such as 2080. This decline is likely due to higher baseline outdoor temperatures, which reduce the relative influence of solar-control measures on total cooling loads. Furthermore, the inclusion of shading devices resulted in a modest increase in heating-related emissions, ranging from approximately 1.1% to 2% across all retrofit strategies. This outcome was observed despite the use of a parametrically modelled overhang to optimise seasonal solar control. The increase in heating demand can likely be attributed to the reduction of beneficial solar gains during winter, as the shading elements limited direct solar radiation that would otherwise contribute to passive heating.

It is worth noting that, all cases begin to experience overheating due to rising internal temperatures. Consequently, although cooling increases between 2025 and 2080, the performance gap between different parameter configurations and the base case narrows (as shown in Figure 9). This trend suggests that, in the future, most buildings are likely to overheat, shifting the design focus toward strategies that can delay the onset of overheating for as long as possible and thereby postpone the need for active cooling. It is also worth noting that the reduction in heating energy demand becomes more pronounced over time.

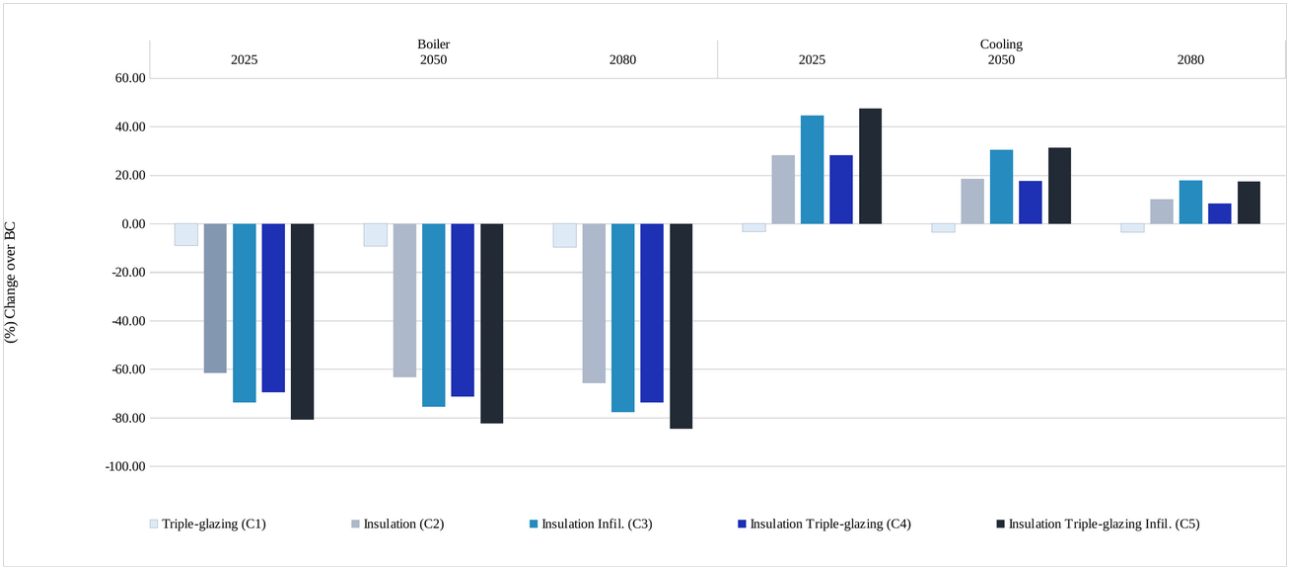

Figure 9. Percentage change over Base-case for C1-C5.

An additional key finding is the changing balance between heating and cooling demand under future climate scenarios. By 2080, cooling becomes nearly as significant as heating in highly retrofitted buildings (as seen in Table 6). In BC, the heating energy demand in 2025 was approximately 22 times greater than the cooling demand, indicating a predominantly heating-driven energy profile. However, in the most advanced retrofit scenario (C5), this ratio decreased substantially, with heating demand being only about 2.5 times higher than cooling. The divergence narrows even further under 2080 weather projections, where the base case heating demand is only 7.3 times greater than cooling, while in C5, cooling demand supersede heating by 1.04 times. This progressive convergence between heating and cooling requirements highlights the growing prominence of cooling loads in future climate conditions.

Table 6. Energy use for heating and cooling.

Parameters	Boiler (MWh)		AC energy consumption (MWh)			
			Model A		Model B	
	2025	2080	2025	2080	2025	2080
BC	10.994	7.428	0.571	1.017	0.456	0.875
C1	10.007	6.709	0.552	0.981	0.450	0.856
C2	4.241	2.549	0.732	1.121	0.605	0.973
C3	2.893	1.657	0.826	1.199	0.694	1.047
C4	3.364	1.955	0.733	1.102	0.619	0.970
C5	2.124	1.152	0.842	1.195	0.723	1.059

3.3. Analysis of cooling setpoint effects on energy use and carbon emissions

This section examines the sensitivity of operational energy use and associated carbon emissions to different cooling setpoint temperatures (26°C, 24°C and 22°C) across the two model configurations. The selected setpoints represent a range of plausible thermostat settings used to explore how variations in cooling temperature selection influence energy demand and emissions. The results (Table 7 and 8) demonstrate the degree to which cooling-related emissions respond to both

temperature selection and building design interventions, including retrofit measures and external shading.

1. Setpoint: 26°C

At the highest cooling setpoint of 26 °C, cooling energy use and associated emissions remained relatively low across both models, although Model A consistently exhibited higher cooling demand than Model B. For example, in 2080 the base-case cooling demand in Model B was reduced by approximately 24-36% compared with Model A. Among retrofit strategies, C1 and C4 consistently performed best, demonstrating that pairing shading with improved envelope performance leads to more stable internal conditions, even at minimal cooling demand.

2. Setpoint: 24°C

Lowering the setpoint to 24°C led to a substantial increase in cooling energy across all strategies and both models. However, the performance gap between shaded and unshaded models widened, reinforcing the role of passive shading under increased cooling demand. In Model A, the 2080 cooling demand for the base case increased to 0.437 MWh, whereas Model B recorded a lower value of 0.358 MWh. In both models, cooling demand increased noticeably for retrofit strategies C2-C5, with C3 exhibiting the highest levels. By contrast, strategies incorporating triple glazing, such as C1, C4 and C5, appeared to moderate this effect, potentially by better retaining conditioned air.

3. Setpoint: 22°C

At the lowest setpoint of 22°C, the cooling loads and emissions increased dramatically across all scenarios. The higher cooling setting amplified the thermal consequences of both insulation-heavy retrofits and the absence of shading. Additionally, retrofit strategies C3 and C5, which emphasized insulation and airtightness, saw the highest emissions overall at 22°C, particularly in Model A. These configurations appear to have required longer cooling periods to maintain the lower setpoint.

The results indicate that cooling-related carbon emissions were highly sensitive to the selected cooling setpoint across all model configurations. Model B consistently demonstrated lower cooling demand than Model A, highlighting the effectiveness of external shading in reducing cooling energy use across different temperature settings. Retrofit strategies incorporating higher levels of insulation and airtightness substantially reduced heating demand but also tended to increase cooling requirements at lower cooling setpoints. By comparison, configurations incorporating glazing upgrades generally moderated cooling demand relative to otherwise similar retrofit strategies without glazing improvements.

Table 7. Implications of set points (Model A) on cooling related Carbon (kgCO2e).

Parameters	Set point 26°C		Set point 24°C		Set point 22°C	
	2025	2080	2025	2080	2025	2080
BC	7.0	35.2	23.5	71.3	93.0	165.7
C1	7.6	35.8	26.4	72.7	119.2	182.6
C2	6.1	31.7	21.1	66.2	90.0	159.9
C3	7.7	36.0	27.3	73.3	134.6	195.4
C4	6.5	32.2	23.9	67.3	119.4	179.6
C5	6.7	32.3	24.7	67.8	137.3	194.7

Table 8. Implications of set points (Model B) on cooling related Carbon (kgCO2e).

Parameters	Set point 26°C		Set point 24°C		Set point 22°C	
	2025	2080	2025	2080	2025	2080
BC	4.4	26.5	16.7	58.4	74.3	142.6
C1	4.8	27.0	19.1	59.6	98.6	158.5
C2	3.9	24.3	15.4	54.9	73.4	139.4
C3	5.0	27.1	19.9	60.1	113.1	170.6
C4	4.3	24.7	17.7	56.0	100.9	158.1
C5	4.4	24.7	18.4	56.4	117.8	172.6

3.4. Importance of AC efficiency and its effect

The efficiency of AC systems strongly influences operational energy use and associated cooling-related carbon emissions. To investigate this effect, three representative efficiency levels were modelled: an inefficient legacy system, a typical modern efficient system (used throughout the baseline analysis), and a high-efficiency system exceeding current market norms. The detailed efficiency assumptions for each case are provided in Table 9.

The analysis confirmed that, as expected, higher-efficiency systems required less energy to achieve similar internal thermal comfort conditions (as seen on Table 10). While the relative performance trends across retrofit configurations remained broadly consistent with the baseline AC profile, absolute energy use varied substantially depending on system efficiency. On average, the baseline system performed approximately 1.9x more efficiently than the inefficient system, while the high-efficiency configuration delivered an additional 1.2x improvement compared with the baseline. These variations are particularly important when evaluating the sensitivity of retrofit outcomes to HVAC assumptions. Selecting an overly efficient or underperforming AC system could artificially amplify or suppress the perceived benefits of envelope-based retrofit measures. For instance, in the most comprehensive retrofit scenario (C5), annual cooling energy demand at a 22 °C setpoint reached approximately 1.017 MWh using the baseline system but increased to 1.976 MWh with the inefficient AC configuration and decreased markedly to 0.813 MWh when the high-efficiency system was applied. These contrasts highlight the critical role of AC system performance in determining both energy and carbon outcomes in future retrofit strategies.

Table 9. Efficiency assumptions.

Category	EER	SEER	Description
Inefficient system	2.8	3.5	Represents pre-2010 fixed-speed split systems or underperforming retrofits.
High-efficiency system	3.5	6.0	Reflects performance typical of the system used in the study
Very high-efficiency system	5.0	8.5	Represents best-available technology with high seasonal efficiency.

Table 10. Implications of AC efficiency (Model A) on energy consumption (MWh).

Variables	26°C		24°C		22°C	
	2025	2080	2025	2080	2025	2080
Base-case	0.043	0.216	0.144	0.437	0.571	1.017
Inefficient	0.084	0.420	0.280	0.850	1.109	1.976
Very efficient	0.034	0.173	0.115	0.350	0.456	0.813

3.5. Whole life operational carbon from heating and cooling

The study recognised that certain extreme retrofit scenarios could lead to greater overheating and consequently, higher carbon emissions. The research therefore sought to investigate whether the rise in cooling-related emissions could offset or even negate the carbon savings achieved through retrofit measures that primarily reduce heating demand. The analysis incorporated all tested parameters, including BC and retrofit configurations C1-C5, evaluated across three indoor temperature setpoints (22°C, 24°C and 26°C) and three AC efficiency levels: inefficient, high efficiency and very high efficiency. Given that both unshaded (Model A) and shaded models (Model B) exhibited overheating conditions by 2025, AC operation was assumed from the start of the analysis period to reflect realistic occupant comfort responses. The cumulative carbon emissions from combined heating and cooling demand for each configuration are presented in Figure 10. The results demonstrate a clear downward trend in overall carbon emissions as the retrofit depth increases.

BC consistently exhibited the highest overall carbon emissions when modelled with the baseline AC efficiency, followed closely by C1, representing the least extensive retrofit scenario. Although C1 achieved reductions in both heating and cooling-related emissions, the overall improvement was relatively modest, resulting in only an 8.8% decrease in lifetime carbon emissions compared to the base case. Additional insulation increased cooling-related emissions; however, overall carbon emissions still declined, highlighting the dominant contribution of heating-related emissions, particularly those associated with natural gas use. The C5 retrofit scenario consistently achieved the lowest total emissions, even when cooling was included. This pattern remained consistent across all three temperature setpoints, indicating that retrofit improvements provide robust carbon savings independent of internal comfort conditions.

The comparison between shaded and unshaded conditions reveals that the influence of shading on total carbon emissions is generally modest, particularly in mid-level retrofits such as C2, where differences remain marginal (refer Figure 11). However, at higher retrofit levels (C5) and higher cooling setpoints (26°C), shading exerts a more pronounced effect, reducing overall carbon emissions by approximately 4.2%. This finding suggests that shading becomes more effective in higher-load, high-performance building envelopes, where small reductions in solar gains yield proportionally greater energy savings. Although cooling-related energy use is projected to match or even surpass heating demand by 2080 (as shown in Table 6), the gradual increase in cooling energy consumption combined with the higher carbon intensity of natural gas means that total carbon emissions from cooling remain substantially lower than those from heating. This trend is clearly illustrated in Figure 12.

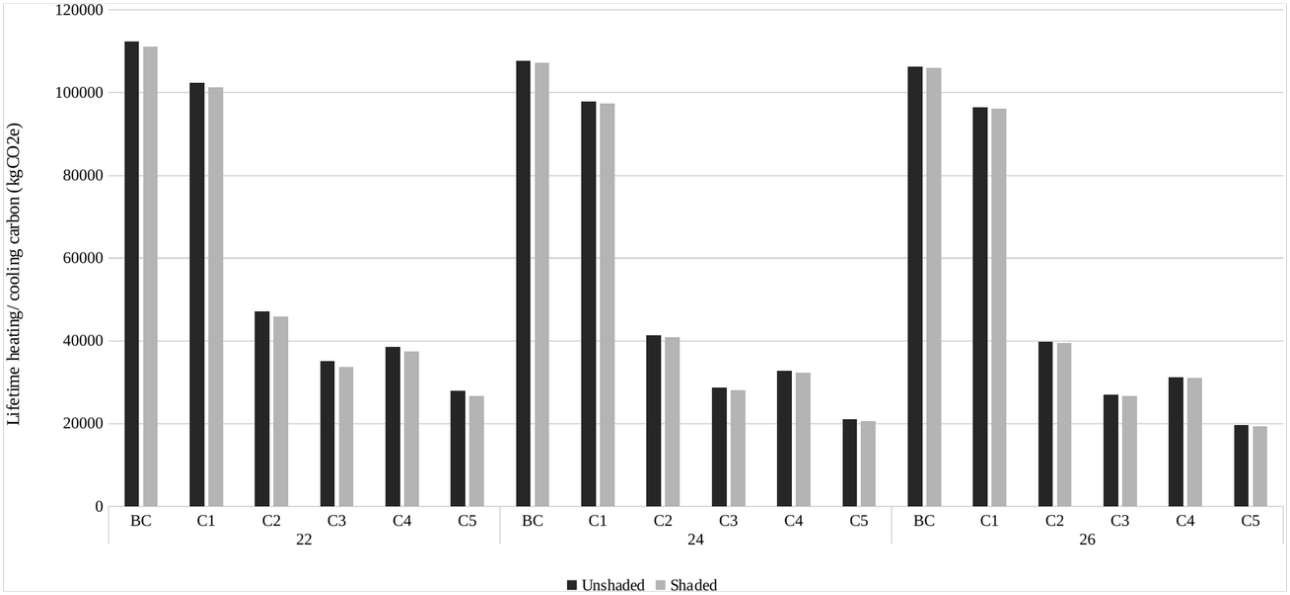

Figure 10. Whole-life operational heating and cooling carbon emissions: Comparison of Model A and Model B across setpoints.

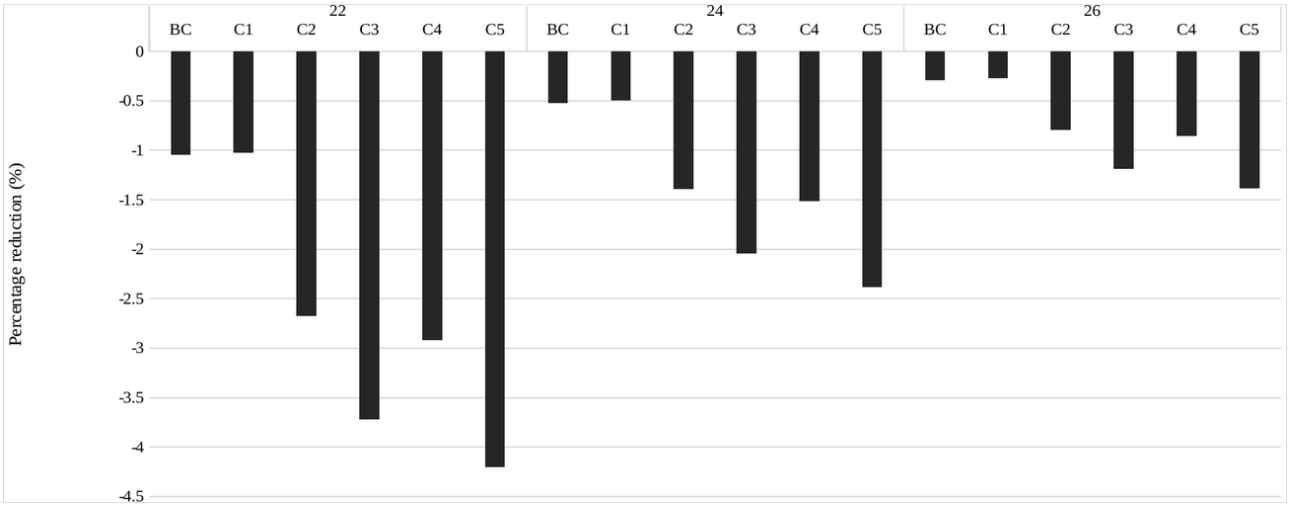

Figure 11. Percentage reduction between Model A and Model B (Shaded vs. unshaded).

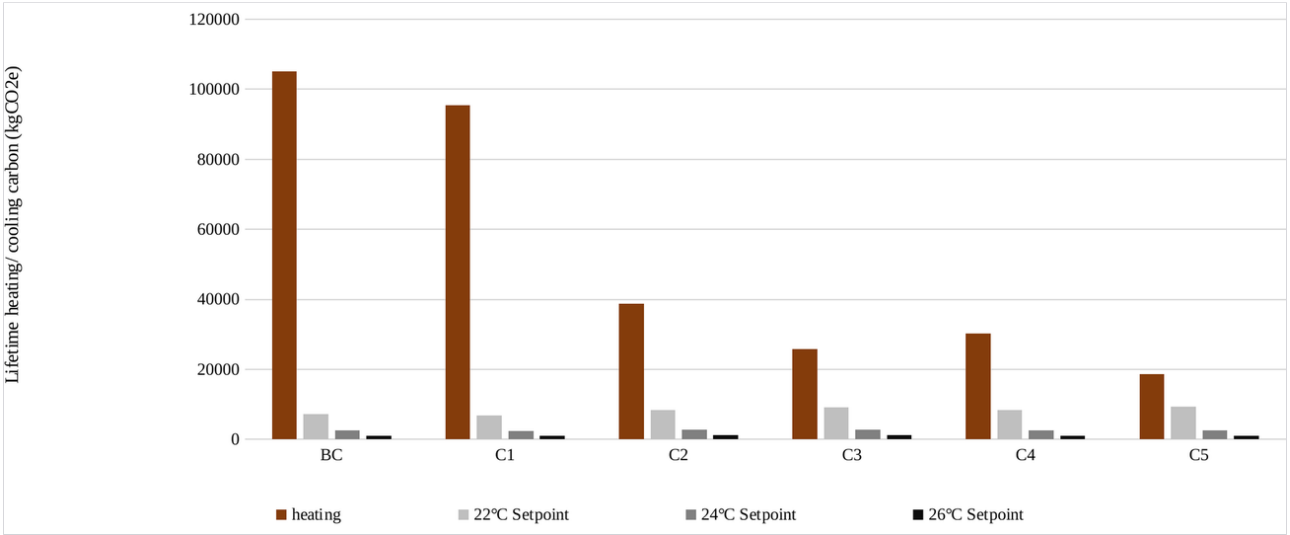

Figure 12. Lifetime emissions across different setpoints and retrofit options.

The previous analysis considered only the base-case AC efficiency, providing a limited view of how system performance influences overall emissions. When AC efficiency was varied to include both inefficient and very efficient systems, notable differences emerged across retrofit scenarios. The inefficient AC system resulted in significant increase in total carbon emissions, rising by up to 31% in the most advanced retrofit configuration (C5) compared with the base-case system. In contrast, minor retrofit options such as C1 exhibited only a modest increase of around 6%, consistent with the overall base-case trend. Conversely, the very efficient AC system produced a marginal reduction in total heating and cooling emissions, with decreases of up to 6% observed under the most extensive retrofit scenario (C5). The magnitude of variation between systems decreased as temperature setpoints increased. At a setpoint of 26°C, the difference between system efficiencies was relatively small, with the inefficient AC showing only about a 1% increase in emissions. All results were benchmarked against the base-case AC performance for consistency. A comparative bar chart illustrating these results at the 22°C setpoint is presented in Figure 13, highlighting the divergence between AC system efficiencies across the retrofit spectrum.

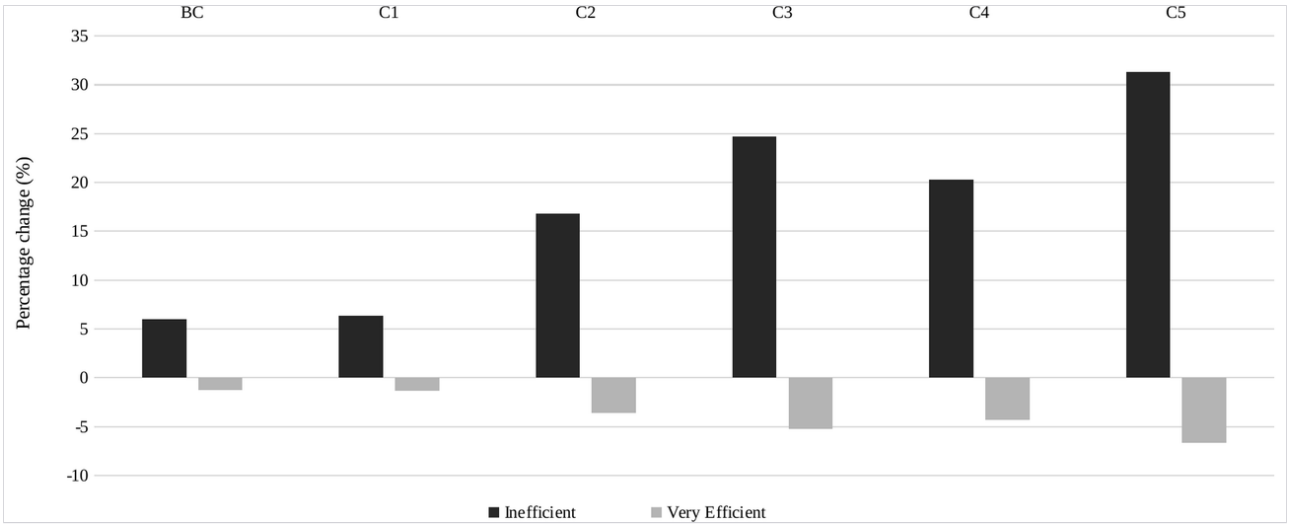

Figure 13. Variation in AC efficiency across different retrofit parameters assuming a 22°C cooling setpoint compared to the efficient AC efficiency.

3.6. Importance of carbon factors and a decarbonising grid

While the previous analysis assumed a static carbon factor, the grid is steadily decarbonising. As a result, the carbon impact of AC and other electricity-based technologies will be significantly lower than what is typically observed today. Using the CCC's projected UK grid carbon intensity to 2050 from the Seventh Carbon Budget report (CCC 2025), the following analysis examines how declining carbon factors influence cooling-related emissions. To assess the influence of a decarbonising UK electrical grid, whole-life operational emissions were recalculated using the previously discussed variable parameters. The results, summarised in Figure 14 and Figure 15, demonstrate that the progressive reduction in grid carbon intensity yields substantial decreases in total cooling/ heating-related emissions, particularly for highly retrofitted cases. Assuming a progressively declining grid carbon factor, the analysis revealed a consistent reduction in whole-life operational heating/ cooling-related carbon emissions, primarily due to lower cooling energy intensity. Using the 22°C setpoint, the shift from a static to a declining carbon factor reduced cumulative emissions by 6.2 % in the

unshaded base case and 5.2% in the shaded equivalent. The magnitude of reduction increased with retrofit depth:

- C2-C4 achieved reductions ranging from 19-31 % (unshaded) and 17-27 % (shaded).
- The C5 scenario exhibited the largest improvement, with emissions falling by 43.2 % (unshaded) and 38.0 % (shaded) relative to the static-grid baseline.

Across all AC setpoints, the difference between shaded and unshaded conditions remained small (typically less than 0.5 %) indicating that shading has only a marginal additional impact once the carbon factor trajectory is accounted for. Nevertheless, the relative ranking of retrofit configurations remained consistent under both static and declining scenarios, confirming that decarbonisation uniformly lowers the carbon footprint without altering the comparative performance of each retrofit option. Overall, assuming a declining carbon intensity results in whole-life operational carbon reductions of up to 43 % for advanced retrofit measures, emphasising the growing dominance of operational energy decarbonisation in shaping the long-term climate performance of buildings.

When accounting for different AC efficiencies, additional discrepancies and variations emerge. Larger reductions appear in the high-efficiency AC model, while smaller reductions occur in the low-efficiency configuration. The greatest variation is associated with the advanced retrofit cases, which outperform the base case and C1, where only minor differences are observed. As shown in Figure 15, this pattern is evident when Model A is evaluated with a cooling setpoint of 22 degrees.

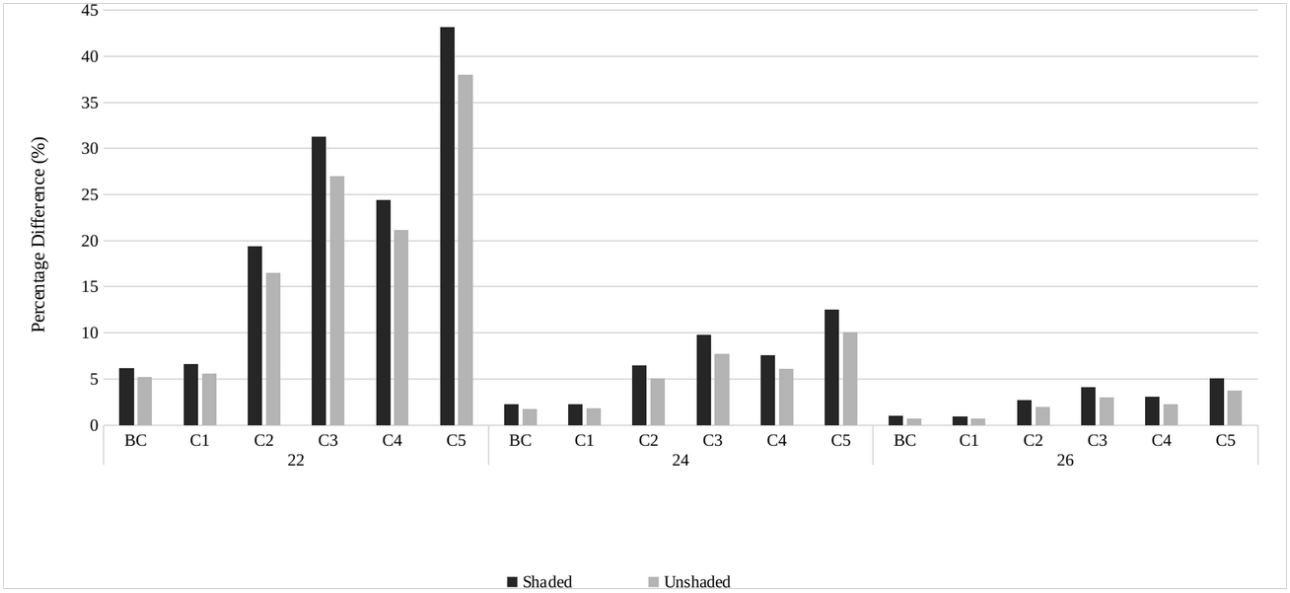

Figure 14. Percentage reduction in lifetime heating and cooling emissions under a dynamic decarbonisation grid scenario, evaluated across shaded and unshaded scenarios.

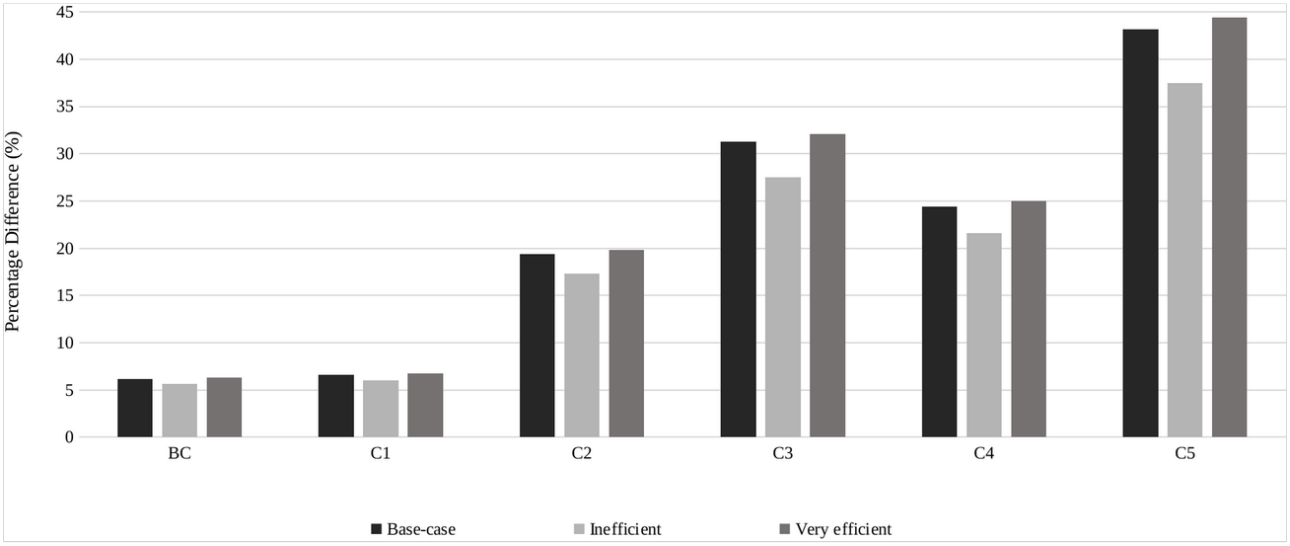

Figure 15. Percentage reduction in lifetime heating and cooling emissions under a dynamic decarbonisation grid scenario, evaluated across different AC efficiencies.

4. Discussion

The simulations demonstrate a clear interaction between retrofit depth, future climate conditions and overheating risk. Progressively deeper fabric retrofit reduced heating demand and associated operational carbon emissions but generally increased summertime heat retention, particularly where insulation and airtightness were combined without external solar control. The unshaded model consistently experienced greater overheating than the shaded model, and by 2080 all configurations exceeded the adopted overheating threshold. These results indicate that improvements in winter thermal performance do not necessarily translate into improved year-round thermal performance. This behaviour is consistent with previous studies identifying overheating as a potential consequence of improved envelope performance. For example, research has found that dwellings constructed to higher energy-efficiency standards experienced longer periods of elevated internal temperatures (Pathan *et al.* 2017), while others have identified insulation, building form and floor level as important determinants of overheating risk (Mavrogianni *et al.* 2012). The present study supports these observations but extends them by considering how the relationship changes under progressively warmer future climates and by incorporating the operational carbon consequences of introducing mechanical cooling. Previous studies of Victorian and older UK housing have similarly demonstrated that insulation and reduced infiltration can lower energy demand while increasing overheating risk.

Spatial variation was also evident within the dwelling. The second-floor south-facing bedroom experienced considerably greater overheating than the equivalent first-floor space (as seen in Figure 16). This is consistent with research, where upper-floor and poorly ventilated spaces have been identified as particularly susceptible to overheating, and with studies suggesting that bedrooms may become vulnerable under future climate scenarios even where other spaces remain comparatively comfortable (Mavrogianni *et al.* 2012). The present results therefore reinforce the importance of considering room-level characteristics, particularly orientation and vertical position, when evaluating overheating following retrofit.

External shading consistently reduced overheating and cooling demand across the modelled scenarios. This agrees with previous research identifying external solar control as an effective means of limiting summer heat gains. Research has reported cooling-load reductions of approximately 9.2%, increasing to 15.5% depending on shading configuration (Mohammed *et al.* 2022). The present study similarly found substantial reductions in cooling-related emissions, although direct numerical comparison should be treated cautiously because the previous study assessed cooling loads rather

than operational carbon. Importantly, shading had a much smaller influence on total operational carbon than on cooling demand because gas heating remained the dominant source of emissions over much of the analysis period. This distinction suggests that the value of shading in the present study lies primarily in mitigating overheating and reducing cooling requirements rather than providing large reductions in total operational carbon.

A similar distinction is evident when considering retrofit depth. The deeper retrofit configurations increased cooling requirements but still achieved lower total operational carbon emissions because reductions in heating-related emissions outweighed the additional emissions associated with cooling. This broadly agrees with previous studies showing substantial operational carbon benefits from insulation, glazing and tighter airtightness in older dwellings (Li and Densley Tingley 2021). However, the present analysis adds an important qualification: the retrofit option with the lowest operational carbon was not necessarily the option with the lowest overheating or cooling demand. Operational carbon and summer thermal performance should therefore be treated as related but distinct measures of retrofit performance. The results also showed a progressive shift in the balance between heating and cooling demand. Heating remained dominant in the earlier climate scenarios, but cooling became increasingly significant as external temperatures increased and fabric improvements reduced space-heating requirements. The present analysis suggests that this transition may be particularly important in highly retrofitted dwellings because reductions in heating demand increase the relative contribution of cooling to total building energy use.

Cooling setpoint selection introduced a further source of variation. Lower setpoints substantially increased cooling energy consumption and associated emissions, particularly in highly insulated and airtight configurations. Rather than representing a prediction of future occupant behaviour, these results demonstrate the sensitivity of operational carbon outcomes to assumptions regarding thermostat settings and comfort expectations. This is important when interpreting long-term simulations because the future carbon consequences of cooling depend not only on climate and building fabric but also on how cooling systems are operated. Furthermore, occupant behaviour and ventilation patterns remain critical factors in determining overheating outcomes. In this study, window operation was represented using a simplified binary control strategy based on internal temperature thresholds. In practice, however, occupants often limit window opening due to concerns related to security, privacy, noise, outdoor pollution, or insects (Cherian *et al.* 2026a; Baborska-Narożny *et al.* 2016). Such behaviour can exacerbate overheating, particularly in highly sealed and insulated buildings. This dynamic may partially explain why some retrofit configurations exhibited higher overheating exposure despite improved thermal performance. Without adequate ventilation strategies, fabric improvements alone may inadvertently increase overheating risk under future climate conditions.

When grid decarbonisation was incorporated into the analysis, overall emissions declined substantially across all scenarios. As electricity becomes progressively lower in carbon intensity, the relative contribution of cooling-related emissions decreases, while the long-term carbon benefit of electrified building systems becomes more pronounced. Grid decarbonisation also coincides with a period in which cooling demand is expected to increase as overheating becomes more frequent. Although this would ordinarily lead to higher cooling-related emissions, the declining carbon intensity of electricity substantially mitigates the associated increase in operational carbon.

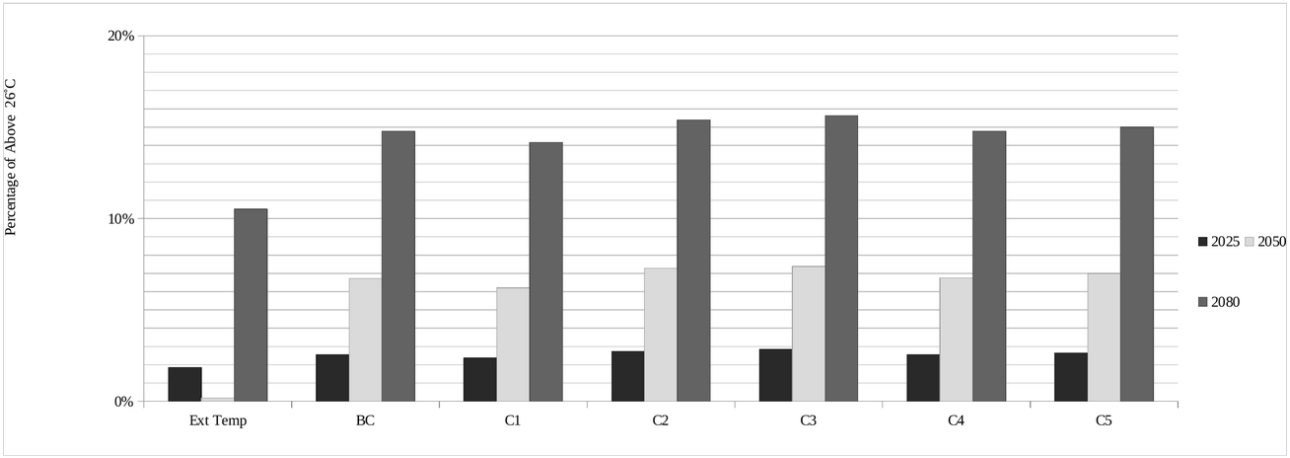

Figure 16. Overheating in the South-Facing Room on the Second Floor.

4.1. Future work

Future research should explore the integration of low-carbon heating technologies, particularly heat pumps, into retrofit scenarios. While this study focused on conventional gas boilers, reflecting their continued prevalence within the UK housing stock, the UK policy and regulatory landscape is increasingly oriented towards the decarbonisation of domestic heating. Government initiatives such as the Future Homes Standard and heat pump grant schemes aim to phase out fossil fuel-based heating systems (GOV.UK 2022). Heat pumps, with their higher efficiency and reduced operational carbon footprint, could significantly alter the outcomes presented in this study and offer a more sustainable long-term solution. In addition to heating systems, ancillary technologies such as solar photovoltaic (PV) panels should be considered in future analyses. The inclusion of on-site renewable energy generation may offset a substantial portion of operational energy demand and reshape the carbon performance of retrofit packages. In evaluating the technologies, the study assumed fixed efficiencies for both the boiler and AC systems. It is acknowledged that variations in these efficiencies could significantly influence the comparative trade-offs and overall performance outcomes.

Moreover, while this study has focused solely on operational emissions, future work should incorporate the embodied carbon associated with retrofit measures. This includes emissions from material production, installation, maintenance, and eventual replacement. For instance, the addition of AC units not only increases operational emissions but also contributes to embodied impacts through manufacturing, servicing, and disposal. When these factors are accounted for, certain retrofit strategies (especially those with marginal operational benefits) may no longer present a net carbon saving and could, in fact, lead to higher overall emissions. This life cycle perspective remains a key gap in current retrofit research and must be addressed to inform truly sustainable building strategies. A more holistic approach incorporating both operational and embodied emissions, alongside evolving building technologies and broader housing-stock characteristics, would be required before drawing more general policy conclusions. Such analysis could provide more robust evidence to support policymakers and designers considering approaches to future-proofing the existing housing stock. Additional building-related parameters warrant consideration, including the type and performance of insulation materials and the presence of roof insulation. The relatively high boiler energy demand observed in this model can be attributed to the absence of roof insulation, the inclusion of which would likely reduce heating requirements but potentially intensify overheating during warmer periods.

Finally, although this analysis employed a time-slice, emissions-weighted method, future work could more precisely capture annual dynamics by using year-by-year simulations or interpolated approaches. These methods would better represent the influence of climate change on annual carbon emissions, particularly under decarbonisation scenarios. Incorporating such dynamics is important

because they can shift interpretations of technology choices and the consequences of adoption or non-adoption.

5. Conclusions

This study evaluated the long-term operational carbon and thermal performance of five progressive retrofit strategies applied to a typical mid-terrace Victorian dwelling under current and future climate conditions. Using dynamic thermal simulation, shaded and unshaded configurations were assessed over a 55-year period to determine how increasing retrofit depth, future overheating risk, mechanical cooling, and external shading influence operational carbon emissions. The analysis addressed three main questions concerning the effect of retrofit depth on operational carbon, the influence of overheating and mechanical cooling on those benefits, and the role of external shading.

In relation to the first research question, progressively deeper fabric retrofit strategies substantially reduced heating demand and associated operational carbon emissions. The most comprehensive retrofit strategy, C5, combining insulation, triple glazing and improved airtightness, consistently achieved the lowest overall operational carbon emissions across the scenarios considered. Heating-related emissions were reduced by approximately 80.7% relative to the base case, while heating demand fell to 1.152 MWh by 2080 compared with 7.428 MWh for the base case. By comparison, triple glazing alone produced a considerably smaller lifetime carbon reduction of approximately 8.8%, demonstrating that the greatest operational carbon benefits were achieved through combined fabric improvements rather than isolated interventions.

The second research question examined whether increasing overheating and subsequent mechanical cooling could offset these operational carbon benefits. The results showed that deeper fabric retrofits, particularly those incorporating insulation and airtightness, generally increased overheating and cooling demand, especially in the absence of solar control. By 2080, cooling demand in the C5 scenario was approximately 1.195 MWh compared with a heating demand of 1.152 MWh, indicating that cooling could become comparable to, or exceed, heating energy demand in highly retrofitted dwellings under future climate conditions. Nevertheless, the increase in cooling-related emissions did not negate the operational carbon savings achieved through reductions in heating demand, and C5 remained the lowest-emission strategy across the cooling setpoints examined. Cooling setpoint selection was also shown to have a substantial influence on future emissions. In the unshaded base case, cooling-related emissions in 2080 increased from 35.2 $kgCO_2e$ at a 26°C setpoint to 71.3 $kgCO_2e$ at 24°C and 165.7 $kgCO_2e$ at 22°C. Similar trends were observed across all retrofit configurations, demonstrating that occupant cooling preferences and control assumptions can materially influence the operational carbon consequences of future AC adoption.

With respect to the third research question, fixed external shading consistently reduced overheating and cooling demand across the retrofit scenarios. In the 2080 base case, shading reduced cooling energy demand from 1.017 MWh to 0.875 MWh, while cooling-related emissions were reduced by approximately 13-25% across the different retrofit configurations. However, the influence of shading on total operational carbon was comparatively modest because heating-related emissions remained dominant over much of the analysis period. At the highest retrofit level and a 26°C cooling setpoint, shading reduced overall operational carbon by approximately 4.2%. The results therefore indicate that shading provides its principal benefit through improved summer thermal performance and reduced cooling demand rather than through large reductions in total operational carbon.

Overall, the findings demonstrate that fabric retrofit remains beneficial from an operational carbon perspective under future climate conditions, but its performance cannot be assessed solely through reductions in winter heating demand. Increasing retrofit depth can simultaneously reduce heating emissions and intensify summertime overheating, making passive solar control and assumptions surrounding future cooling increasingly important. The analysis therefore supports a climate-responsive approach in which fabric improvements are considered alongside overheating mitigation, cooling efficiency and occupant temperature preferences. These conclusions are limited

to operational carbon and to the dwelling archetype, modelling assumptions and scenarios examined here. Future work incorporating embodied emissions, component replacement, alternative heating technologies and year-by-year climate projections would allow these operational benefits to be assessed within a more complete whole-life carbon framework.

6. Abbreviations

Abbreviation	Meaning
AC	Air conditioning
EPS	Expanded polystyrene
VIP	Vacuum Insulated Panel
IESVE	Integrated Environmental Solutions: Virtual Environment
BC	Base-case
PV	Photovoltaic Panels

Declarations

Author contributions. Benjamin Abraham Cherian: Conceptualisation: Developed the overarching themes and objectives of the review. Methodology: Designed the review framework and criteria for literature selection. Writing – Original Draft: Wrote the initial manuscript draft, including key sections. Dr. Serik Tokbolat: Writing – Review & Editing: Contributed to the revision of the manuscript, focusing on clarity and coherence. Supervision – Supervised the study. Dr. Lucelia Rodrigues: Writing – Review & Editing: Assisted in editing and refining the final manuscript, ensuring accuracy and completeness. Supervision – Supervised the study. All authors have read and approved the final version of the manuscript.

Conflicts of interest. There are no competing interests.

Data availability. The simulation models, input schedules, construction assumptions and processed output data supporting the findings are available from the corresponding author upon reasonable request.

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