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INVESTIGATING OVERHEATING RISKS IN SUPERHOMES USING THE EMERGENT RETROFIT APPROACHES IN SOUTH ENGLAND

SUSTAINABLE ARCHITECTURE: EVALUATION AND DESIGN, DISSERTATION

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Abstract

The increasing frequency of heatwaves in the UK, driven by climate change, has raised concerns about overheating in residential buildings, especially those retrofitted for energy efficiency. This dissertation examines overheating risks in five SuperHomes [1]in South England using emergent [2] retrofit approaches. The study aims to develop evidence-based guidelines to mitigate overheating while maintaining energy efficiency and improving thermal comfort.

A mixed-method approach was used, combining environmental monitoring of living rooms and main bedrooms during the warm period from August 3rd to 18th, along with household and thermal comfort surveys. Overheating risk was assessed using CIBSE TM52 and TM59 criteria. Building simulations with Design Builder software evaluated the effectiveness of passive design strategies, such as insulation, ventilation, and shading, in mitigating overheating and enhancing indoor thermal comfort.

Results show that while retrofits improve energy efficiency and reduce carbon emissions, they can increase overheating risks if not managed properly. Most case study homes experienced elevated indoor temperatures during the summer, with 60% failing to meet CIBSE TM59 criteria B.

Key factors contributing to overheating include excessive insulation, inadequate ventilation, and solar gain through unshaded windows. To address these issues, the study recommends strategic planning and sequencing of retrofit measures, prioritizing improvements to the building envelope before integrating renewable energy systems, and tailoring strategies to occupant behavior. Effective ventilation solutions, such as night-time ventilation or mechanical systems, and passive design measures like internal blinds and adjustable external shading are suggested. The use of reversible low-carbon heat pumps is also recommended for heating and cooling. The findings offer valuable insights for homeowners, policymakers, and retrofit professionals, guiding them to optimize retrofit strategies that balance energy efficiency with occupant comfort, ensuring sustainable living conditions in a warming climate.

[1] SuperHomes: SuperHomes are existing homes that have been retrofitted to reduce carbon emissions by at least 60%.

[2] Emergent Retrofit Approach: The emergent approach involves implementing retrofits gradually over time

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Abbreviation

CIBSE - Chartered Institution of Building Services Engineers

DB - Design Builder

EPW - EnergyPlus Weather File

EPC - Energy Performance Certificate

GHG - Greenhouse Gas

iPHA - International Passive House Association

MVHR - Mechanical Ventilation with Heat Recovery

ONS - Office for National Statistics

PHT - Passivhaus Trust

PMV - Predicted Mean Vote

PPD - Predicted Percentage of Dissatisfied

RfF - Retrofit for Future

TFA - Treated Floor Area

TM - Technical Memorandum

UHI - Urban Heat Island

Contents

Table of Figures

1.0 Introduction

1.1. Background

Concerns about climate change and sustainable development have spurred efforts to reduce carbon emissions in the UK housing sector, where domestic energy consumption represents a significant portion of total energy use and greenhouse gas emissions. According to the Office for National Statistics (ONS, 2023), domestic energy accounts for approximately 30% of the UK's total energy use, with residential buildings contributing around 20% of national greenhouse gas emissions. Enhancing housing energy efficiency is thus crucial for lowering national energy consumption and meeting emission reduction targets.

The severity and impact of climate change have been rigorously evaluated in the scientific literature. Evidence projects that global warming will exceed 2°C above pre-industrial levels (1850–1900) during the 21st century under high and very high greenhouse gas (GHG) emission scenarios (SSP3-7.0 and SSP5-8.5), with global surface air temperatures likely to rise by 2.7°C to 5.7°C compared to 1995–2014 by century's end (“Summary for Policymakers,” 2023). In the UK's 'Net Zero Government Emissions Roadmap' (HM Government, 2023), the nation has committed to achieving net-zero GHG emissions by 2050, with interim targets of a 68% reduction by 2030 and 78% by 2035 compared to 1990 levels. Achieving these targets necessitates significant emission reductions across all sectors, particularly in the residential sector.

The gravity of this issue is further emphasized by projections from the Committee on Climate Change, which anticipate an increase in the annual mortality rate due to overheating from 2,000 in 2015 to 7,000 by the 2050s, highlighting the urgent need for effective assessment and mitigation strategies (CIBSE TM59) (Bonfigli et al., 2017). Approximately 2,000 people in UK, accounting for 16 percent of all deaths in Europe, were affected during the August 2003 heatwave (Department of Health, 2011). In the summer of 2022, the UK recorded its highest-ever temperature of 40.3°C, leading to approximately 2,803 excess deaths among those aged 65 and over during five distinct heat periods (UK Health Security Agency, 2024).

The increasing frequency and severity of heatwaves in the UK have exacerbated concerns about overheating in homes. In (Kendon, 2022) was reported that July 2022 was the driest July in England since 1935 and saw the highest recorded temperature of 40.3°C. According to the Office for National Statistics (Office for National Statistics, 2022), there were an estimated 2,803 excess deaths among those

aged 65 and over during the heat periods in June to August 2022. These events underscore the immediate need to address overheating risks in residential buildings, particularly as climate change projections indicate that such extreme weather events are likely to become more common. Although London's present climate poses only a modest risk of overheating, the combined effects of global climate change and urban heat island intensification are likely to create more significant challenges in the future (Yannas & Rodríguez-Álvarez, 2020).

The UK government has set ambitious emission reduction and net-zero targets, with retrofitting existing homes identified as crucial. With an estimated 26 million homes needing retrofits by 2050 (IET, 2020), standards and initiatives like Passivhaus, Energiesprong, and SuperHomes support these efforts. Achieving net-zero emissions requires urgent action to improve dwelling energy efficiency, decarbonize energy systems, and implement large-scale retrofits (RICS, n.d.). Retrofitting the housing stock is among the most effective strategies to reduce energy use and carbon emissions (RICS, n.d.). National initiatives, such as Home Energy Performance Retrofit Funding for local authorities and housing associations (*Home Energy Performance Retrofit*, 2021) and the National Retrofit Hub (*National Retrofit Hub,* n.d.), aim to coordinate the upgrade of the UK's 28 million homes. Additionally, the UK Green Building Council (UKGBC) advocates for domestic retrofit policies to achieve climate targets (*Domestic retrofit policy,* 2024). SuperHomes, part of a network aiming to reduce household carbon footprints by at least 60%, often involve phased retrofits meaning the retrofit process can span over two years (Fawcett, 2014a). Although SuperHomes effectively reduce energy consumption and carbon emissions, research on their potential overheating risks is limited. Enhanced insulation and airtightness may lead to higher indoor temperatures during heatwaves without proper ventilation and shading (Bonfigli et al., 2017) This gap highlights the need to examine overheating risks in SuperHomes, especially those using emergent retrofit approaches with incremental measures.

This study seeks to develop evidence-based guidelines for Superhomes to mitigate the overheating risks while maintaining energy efficiency and improving thermal comfort. The primary aim of this research is to investigate the relationship between emergent retrofit approaches and overheating risks in SuperHomes.

1.2. Research Objectives

To achieve this aim, the study is structured around the following specific objectives:

- Establish baseline features of each SuperHomes case study, understand retrofit approaches and sequences, and assess their impact on overheating risks.
- Deploy devices to measure indoor temperatures and humidity and conduct thermal comfort and household surveys to evaluate home performance.
- Analyse collected data using CIBSE TM52 and TM59 guidelines to assess overheating risks and identify influencing factors.
- Use Design Builder (DB) to simulate buildings and identify strategies that mitigate overheating risks, align with thermal comfort preferences, and reduce energy use and costs, resulting in evidence-based retrofit recommendations.

1.3. Significance of the Study

The significance of this study lies in its potential to address critical issues related to overheating risks in retrofitted homes, particularly within the context of SuperHomes in South England. As climate change leads to rising temperatures, the risk of overheating in residential buildings is becoming a growing concern, with projections indicating that more than half of the properties in the UK will experience overheating by 2050. This is particularly pressing for vulnerable populations such as older adults, infants, and those with chronic conditions. Retrofitting existing homes offers numerous benefits, including reduced energy consumption, lower energy bills, and improved indoor comfort and health. However, without proper planning and execution, retrofitting can inadvertently increase the risk of overheating, due to factors such as excessive insulation, inadequate ventilation, and poor solar heat gain management. This study aims to fill the research gap by investigating the emergent retrofit approaches in SuperHomes and their impact on overheating risks. The findings will provide evidence-based guidelines that help homeowners mitigate overheating risks while maintaining energy efficiency and improving thermal comfort. The research will benefit not only homeowners and residents of SuperHomes but also policymakers, architects, and retrofit professionals by offering practical solutions and strategies to enhance the effectiveness of retrofit interventions and ensure sustainable living conditions in the face of climate change.

1.4. Scope and Limitations of the Research

The research will analyse a selection of SuperHomes case studies, which are part of a network committed to reducing household carbon footprints. These case studies will provide a detailed examination of the retrofit measures implemented, the sequence of these measures, and their potential impact on overheating risks. Field

monitoring devices will be deployed to measure indoor temperatures and relative humidity within the selected SuperHomes, complemented by thermal comfort surveys and household surveys documenting the retrofit measures to assess the performance of these homes. Comprehensive data analysis will be performed using the CIBSE TM52 and TM59 guidelines to assess the risk of overheating in the studied homes and identify factors influencing these risks. Building simulation, analysis with Design Builder will be conducted to identify strategies that mitigate overheating risks, designed to align with residents' thermal comfort preferences while further reducing energy use and costs. The findings will be used to formulate evidence-based recommendations tailored to the emergent retrofit approaches.

While this research aims to provide comprehensive insights into the relationship between emergent retrofit approaches and overheating risks in SuperHomes, several limitations must be acknowledged. First, the selection of case studies is limited to homes within the SuperHomes network, which may not fully represent the diversity of housing types and retrofit approaches across the UK, potentially affecting the generalizability of the findings. Additionally, the field monitoring and surveys were conducted during a warm summer period, possibly skewing results due to weather conditions. Practical constraints, such as the availability and willingness of homeowners to participate, may have limited the variety of case studies included. Moreover, the research was conducted over a short period of three months, with field monitoring specifically limited to just three weeks. Ideally, a longer monitoring period would provide a more comprehensive understanding of overheating risks and thermal comfort across different seasons, but time constraints may have prevented capturing long-term trends and variations. The analysis relies on current CIBSE TM52 and CIBSE TM59 guidelines, which, while robust, may not account for all variables influencing overheating risks.

1.5. Structure of the Dissertation

This dissertation is organized into several key sections to comprehensively address the research objectives. Following this introduction, the Literature Review provides a detailed examination of the current knowledge surrounding domestic energy consumption, CO2 emissions, retrofitting practices, and the associated risks of overheating. The Methodology section outlines the research design, including the recruitment process, case study overview, and the environmental monitoring techniques employed. The Result section presents the findings from the surveys, temperature monitoring, and overheating assessments. It also includes a simulation

analysis to identify strategies for reducing overheating risk. This is followed by Discussion section, which integrates the quantitative and qualitative data, focusing on the key factors contributing to overheating, and highlighting the novelty of the research. The Strategy Development section offers recommendations for mitigating overheating risks. Finally, the Conclusion summarizes the research findings, discusses the contributions to knowledge, and suggests directions for future research.

2.0 Literature Review

This chapter critically examines the role of retrofitting in addressing the UK's energy consumption and carbon emission challenges, particularly within the residential sector. It explores sustainable building standards and retrofit networks, such as Passivhaus, Enerphit and SuperHomes, which play a pivotal role in guiding effective retrofits. The concept of whole house retrofit approaches is also discussed, emphasizing comprehensive strategies that address all aspects of a building's performance rather than isolated measures (Moody, 2020). The review delves into various retrofit approaches, assessing the benefits, challenges, and barriers associated with each, while emphasizing the importance of proper sequencing to maximize energy efficiency and avoid issues like overheating. In particular, the EnerPHit standard, which adapts Passivhaus principles for existing buildings, is evaluated for its applicability and effectiveness in refurbishing homes to high-performance standards (Taylor, 2011). Additionally, it evaluates the impact of retrofitting on thermal comfort and occupant experience, with a specific focus on the emerging risks of overheating in retrofitted homes. By analysing the existing body of research, including key guidance such as the RfF report by the UK Government (Technology Strategy Board, 2014), this review aims to provide a comprehensive understanding of how retrofit practices can be optimized to achieve both energy efficiency and occupant comfort. It also identifies gaps in the current knowledge, particularly concerning emergent retrofit approaches in urban environments.

2.1 Domestic energy consumption and CO2 emissions in the UK

The exhaustion of natural resources, climate change, economic instability, and health concerns have driven the rise of sustainable development initiatives globally (Oh et al., 2010). The UK government targets a 50% reduction in direct emissions from public sector buildings by 2032 and a 75% reduction by 2037, based on 2017 levels. The goal is for all UK emissions to achieve net zero by 2050 (Department for Energy Security & Net Zero, 2023).

Domestic energy consumption makes up approximately 30% of the UK's total energy budget (Scaling up Retrofit 2050, 2020) and contributes about 22% of the nation's greenhouse gas emissions (Waite, 2023). The UK's housing sector contributes significantly to CO2 emissions, with space heating alone responsible for 75% of residential emissions (DECC, 2012). Addressing this significant environmental impact requires prioritizing thermal retrofitting in the UK. Retrofitting existing homes can help meet emission reduction targets (Tuominen et al., 2012).

Decarbonization and decentralization of the UK's energy system are critical strategies to meet net-zero emission targets. Decarbonisation involves reducing carbon intensity in energy generation by shifting from fossil fuels to renewable energy sources, such as solar panels and heat pumps (Rosenow & Eyre, 2016). Decentralisation refers to distributing energy generation closer to the point of use, enhancing energy security and reducing transmission losses (Brown et al., 2019). Improving airtightness is essential to avoid heat loss during winter, enhancing thermal efficiency and reducing the demand for heating (Pan, 2010). Similarly, incorporating shading devices and enhancing natural ventilation helps to prevent excess heat gain in summer, mitigating overheating risks and reducing the need for mechanical cooling (CIBSE, 2015).

With an estimated 26 million retrofits needed in the UK by 2050 (Scaling up Retrofit 2050, 2020), addressing the need for retrofitting is crucial. Upgrading an existing building is among the most eco-friendly, sustainable, and effective methods to enhance its energy efficiency (Dixon, 2014).

2.2.0 Residential retrofit

Retrofit refers to the process of modifying and adapting components of a building or a group of buildings to enhance their energy, functional, or structural performance (Farghaly & Hassan, 2019). In the context of domestic buildings, retrofitting involves incorporating new technologies and features to optimize the use of natural resources, such as energy, water, and various materials (Dadzie et al., 2017). Over time, retrofit strategies have become increasingly popular globally for their ability to improve energy efficiency and reduce greenhouse gas emissions (Kim & Yu, 2018).

Residential retrofits are particularly significant, as homes account for a substantial portion of energy consumption and emissions. Examples of successful residential retrofit projects include homes retrofitted to the EnerPHit standard and SuperHomes. The EnerPHit standard adapts Passivhaus principles for existing

buildings, achieving high energy efficiency in retrofitted homes (Taylor & Trust, 2011). A notable example is the renovation of a Victorian terrace house in London, which achieved EnerPHit certification by incorporating external wall insulation, triple-glazed windows, and mechanical ventilation with heat recovery (MVHR) (Antonelli, 2015). Similarly, SuperHomes are existing homes that have been retrofitted to reduce carbon emissions by at least 60% (Fawcett, 2014b). An example is a 1930s semi-detached house in Oxfordshire, where a combination of insulation upgrades, solar photovoltaic panels, and efficient heating systems resulted in significant energy savings and improved thermal comfort (*SuperHomes*, n.d.).

2.2.1 Retrofit Approaches

In a retrofit, five approaches are identified: whole-house, fabric-first, room-by-room, step-by-step, and measure-by-measure (Topouzi et al., 2019). The whole-house method can be planned (completed all at once) or emergent (staged), depending on financial and personal factors (The Retrofit Playbook, 2020). This comprehensive approach maximizes energy efficiency and comfort by integrating all improvements, unlike isolated measures (Moody, 2020). However, only 2% of homeowners plan complete renovations, with most opting for gradual, room-by-room upgrades that collectively achieve high energy efficiency (Trigger Points: A Convenient Truth, n.d.). Table 1 compares the emergent and planned retrofit approaches.

Table 1: Comparison of Planned (One-Off) vs. Emergent (Over Time) Retrofit Approaches (Fawcett, 2014a)

Characteristic	**Planned (One-Off)**	**Emergent (Over time)**
Time	One-time comprehensive retrofit executed intensively over a period of months.	Gradual retrofit conducted over years or decades
Disruption	Typically necessitates temporary relocation of occupants	Multiple disruptive periods
Cost	Single upfront investment.	Phased financial commitment
Expertise	Often requires expert coordinator to manage diverse trades	Typically lacks central coordination; may involve upskilling existing trades in eco-renovation techniques.
Carbon Saving	up to 80%, with some cases reaching 90%	up to 60%

The emergent approach has its advantages and disadvantages, including flexibility and financial feasibility on the one hand, and potential inefficiencies and disruptions on the other. Despite limited research comparing the net energy, CO2

emissions, and cost savings between piecemeal retrofits and comprehensive single-phase installations, it is generally understood that front-loading multiple retrofits maximizes savings from a national policy perspective (S. A. Simpson et al., 2012). Implementing multiple-measure retrofits in a single phase minimizes disruption and leverages cost savings in materials and labor. However, the high upfront cost makes this approach less common, potentially leading to lower household net savings (Parker, J et al., 2021).

2.2.2 The Importance of Sequencing in Retrofit Measures

Sterman (2002) underscores the risk of unintended consequences, where today's solutions may become tomorrow's problems. The operational performance of individual emission-reducing technologies is often contingent upon existing measures, indicating that the sequence of retrofit interventions can significantly impact a dwelling's overall performance as demonstrated by the E.ON Retrofit Test House case study (S. Simpson et al., 2016).

Proper sequencing of retrofit measures is crucial for effective and efficient renovations. Adding insulation without adequate ventilation can lead to overheating, especially with future climate changes (Great Britain Department for Communities and Local Government, 2012). Carefully planning the order of measures helps maintain indoor conditions, ensure quality work, optimize technology efficiency, and avoid extra costs from outdated technologies (S. A. Simpson et al., 2012). Conversely, the Retrofit project on the Isle of Sheppey added insulation without addressing ventilation, resulting in dampness, mould, poor air quality, and health issues (Lowe & Oreszczyn, 2008).

In whole-house retrofits, poor management can cause measures to be implemented out of order, such as installing photovoltaic panels before roof insulation, leading to structural damage or additional removal costs. Unplanned interventions like drilling insulated walls for rewiring reduce airtightness and thermal efficiency (Topouzi et al., 2019). For example, a Cambridge project incurred higher costs and reduced performance by conducting electrical rewiring after wall insulation, necessitating insulation removal and replacement (Pallonetto et al., 2022).

Effective insulation requires reassessing ventilation strategies to ensure indoor air quality or investing in mechanical systems (S. A. Simpson et al., 2012). The timing of boiler renewal relative to other retrofit measures affects system capacity; an oversized system can lead to 2% more annual CO_2 emissions than a properly sized

one (S. A. Simpson et al., 2012). Maximizing energy efficiency involves continuous insulation of walls and floors and simultaneous installation of internal wall and floor insulation, especially in ground-floor areas, to eliminate cold bridges (Trigger Points: A Convenient Truth, n.d.). The Grove Cottage in London exemplifies this approach, achieving an 80% reduction in energy use and significantly improving occupant comfort by focusing on insulation, airtightness, and ventilation before installing renewable technologies (Richards Partington Architects, 2012; Grove Cottage, 2012).The Fabric First approach to retrofitting homes prioritizes minimizing heat and power demand through insulation and adequate ventilation before adding services and renewables, aiming to retain thermal capacity within the insulated envelope to ensure warmth during cold periods while preventing summer overheating (The Retrofit Toolkit, n.d.).

2.2.3 Retrofit Benefits, Challenges, and Barriers

Retrofitting existing homes offers numerous benefits, including lower energy bills, improved health and comfort, and job creation (Energy Efficiency of Existing Homes, 2021). It boosts the RMI sector economically by creating jobs and supporting SMEs, enhances indoor comfort and health, and reduces carbon emissions, aligning with UK climate goals and positioning the nation as a leader in global climate action (Greening Our Existing Homes National Retrofit Strategy, 2021). Retrofitting also reduces dependency on new construction (Khairi et al., 2017). Studies have identified psychological motivators for homeowners, such as moral obligation, attitudes, self-efficacy, innovativeness, perceived consumer effectiveness, social norms, problem awareness, and value orientations (Klöckner & Nayum, 2017).

However, structural barriers like timing, economic uncertainty, limited resources, and doubts about savings deter retrofits (Blomsterberg & Pedersen, 2015; Klöckner & Nayum, 2017). Non-economic factors, including comfort, indoor environment, and architectural considerations, can encourage higher retrofit budgets (Mortensen et al., 2014). Homeowners often balance thermal efficiency with heritage and aesthetics, while tenants prioritize visible improvements over long-term benefits (Blomsterberg & Pedersen, 2015; Sunikka-Blank & Galvin, 2016). Enhancing energy efficiency faces challenges due to diverse and fragmented policies and stakeholders (Karvonen, 2013). Retrofit decision tools require better information and features to increase homeowner motivation (Seddiki et al., 2021).

SuperHomes support homeowners in retrofitting by providing practical guidance and fostering a supportive network. Established in 2007 by the Sustainable

Energy Academy (SEA) and merged with the National Energy Foundation (NEF) in 2014, SuperHomes is dedicated to reducing household carbon footprints by at least 60%. As a free-access community, it aims to inspire and guide homeowners to lower energy bills and carbon emissions while enhancing home comfort (SuperHomes, n.d.). A survey of 57 SuperHomes owners and 14 interviews found that only 32.1% completed retrofits in one phase, with most undertaking renovations over two to five years (Fawcett & Killip, 2014). SuperHomes' goal is to ensure every UK resident is within a 40-minute journey of a SuperHomes, aiming to attract 5-10% of the UK population over 20 years, which would require approximately 200 Superhomes (Fawcett & Killip, 2014; personal communication).

2.3. Sustainable Building Standards and Retrofit Networks

Several existing and emerging standards for retrofitting buildings include Passivhaus and EnerPHit, the AECB Retrofit Standard, and the LETI Retrofit Guidance, (Palmer & Lewis, 2021). Passivhaus is a prominent international design standard known for providing exceptional comfort and health while drastically reducing energy consumption in newly built buildings. Thousands of structures worldwide have achieved certification under this standard (*Passivhaus Trust*, n.d.). EnerPHit is the Passivhaus standard specifically for retrofits. It follows the same criteria as the Passivhaus Classic for new builds but with slight relaxations for certain requirements(Palmer & Lewis, 2021). A typical five-story residential building in Guilin, China, was retrofitted to meet the EnerPHit standard, achieving a 66.77% reduction in energy demand and a 35% enhancement in thermal comfort (Wu et al., 2023).

Several programs and approaches have been introduced and adopted in the UK to construct Net-zero energy homes or retrofit existing buildings with low-carbon strategies to reduce energy use and carbon emissions. The adoption of Passivhaus in the UK is promoted by the Passivhaus Trust (PHT) an independent industry-leading organization, which is part of the global Passivhaus movement and serves as the official UK affiliate of the International Passive House Association (iPHA)(*Passivhaus Trust*, n.d.). A UK government-funded RfF program was introduced in 2009 and sought to achieve an 80% reduction in CO2 emissions between 2009 and 2013, in line with the goals of the Climate Change Act. The program required thorough evaluation, which included physical testing of materials, monitoring energy usage, assessing resident feedback, reviewing construction processes, and conducting an overall project evaluation (RFF, 2014). House 109 in West London, a semi-detached house retrofitted through the RfF program, achieved a 95% reduction in specific space heating demand

by focusing on airtightness and thermal envelope improvements, which led to marked health improvements for the residents due to better air quality (RfF, 2014)

The Energiesprong UK standard is also a comprehensive Whole-House Retrofit system designed to create Net-zero energy homes that are warm, cost-effective to heat, and comfortable. This approach incorporates low-carbon technologies such as heat pumps, a highly insulated wrap system with new windows, doors, and roof, as well as solar PV and energy storage solutions(Palmer et al., 2022). The Energiesprong retrofits in Nottingham improved thermal performance and increased resident comfort, though the reduction in heat loss was less than initially expected(Palmer et al., 2022) The National Retrofit Programme (2020-2050), developed with input from key stakeholders and led by Russell Smith, aims to use the Green Home Grant as a foundation for sustained investment in high-quality retrofitting (The Retrofit Toolkit, n.d.).

2.4 Thermal Comfort and Occupant Experience in Retrofitted Homes

Retrofitting measures that focus on improving insulation and airtightness can lead to increased risks of overheating, particularly if appropriate shading and ventilation strategies are not implemented. This risk is exacerbated by climate change, which is expected to result in more frequent and intense heatwaves, making adaptive strategies essential to maintaining thermal comfort (Hao et al., 2022). However, retrofitting can also significantly improve thermal comfort during colder months by reducing heat loss, eliminating drafts, and maintaining more consistent indoor temperatures (Baeli, 2019). Enhanced insulation and airtightness contribute to a warmer and more comfortable indoor environment in winter, improving occupants' satisfaction and reducing energy consumption for heating (Cheshire, 2019).

Thermal comfort is typically assessed using specific descriptors, with discomfort from heat generally indicated when participants rate their experience as +2 or +3 on the ASHRAE scale. The ASHRAE scale does not explicitly define comfort, but individuals who rate their experience between -1 and +1 are generally considered comfortable, while ratings of +2 or +3 suggest they feel uncomfortably hot (F. Nicol, 2013). The ASHRAE 7-point thermal sensation scale ranges from -3 (cold) to +3 (hot), with 0 representing 'neutral' (Beizaee et al., 2012).

Thermal comfort, as defined by the ASHRAE standard, is described as a psychological state reflecting an individual's sense of satisfaction with the thermal environment ("Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the Predicted Mean Vote (PMV) PMV and Predicted Percentage of Dissatisfied (PPD) PPD Indices and Local Thermal Comfort Criteria," 2005). Additionally, thermal comfort can be evaluated using the PMV and PPD indices, which consider environmental and personal factors such as air temperature, humidity, air velocity, metabolic rate, and clothing insulation (Fanger, 1970).

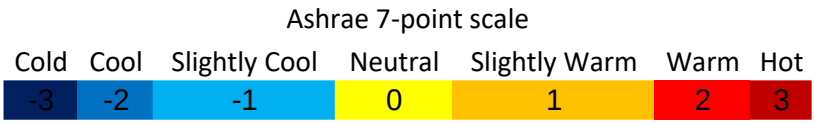


Figure 1: Ashrae 7 Point Scale

Another approach is the Nicol scale, used in adaptive thermal comfort studies, which acknowledges that occupants can adapt to a range of thermal environments through behavioral changes like adjusting clothing or modifying their environment (J. F. Nicol & Humphreys, 2002). This adaptive model is particularly relevant in naturally ventilated or retrofitted homes where occupant interaction with the building plays a significant role in thermal comfort.

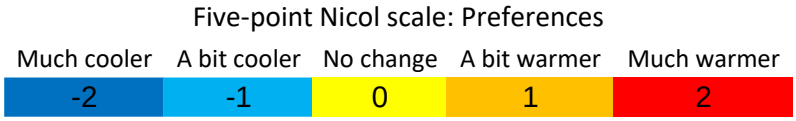


Figure 2: Five Point Nicol Scale: Preferences

In assessing thermal comfort in retrofitted homes, it is essential to combine objective measurements with subjective occupant feedback. Post-occupancy evaluations can provide insights into how retrofit measures impact occupants' thermal comfort and identify any issues related to overheating or underheating (Way & Bordass, 2005). By integrating appropriate shading devices, enhancing natural ventilation, and employing adaptive comfort strategies, retrofitted homes can optimize thermal comfort throughout the year (CIBSE, 2015).

2.5.0 Overheating Risks in Retrofitted Buildings

Despite the UK's relatively mild climate, there is growing concern about summertime overheating in dwellings and the potential increase in their frequency due to climate change with the forecasted global temperature rise of 2-4 °C (Hajat et al., 2014; *Why Do We Look at High Warming Levels When Assessing UK Climate Risk?*, 2022). TM52 highlights that overheating in buildings, often due to poor design,

inadequate management, or insufficient services, leads to discomfort, particularly in warm weather. It emphasizes that managing overheating is crucial for occupant comfort and should be an integral part of building design and operation (F. Nicol, 2013). As noted in CIBSE TM59, overheating can affect occupants' health and well-being, leading to stress, anxiety, sleep deprivation, and potentially premature deaths during heat waves, particularly affecting vulnerable individuals (Bonfigli et al., 2017). The UK Health Security Agency (2024) notes that 2022 had the highest heat-related deaths since 2004, with significant excess mortality during two main heat periods, particularly affecting those aged 65 and over. This highlights the growing need for better heatwave preparedness as climate change increases the frequency of extreme heat events. Indoor air temperatures can rise significantly during warmer seasons in retrofitted homes, especially under climate change scenarios where overheating is expected, posing a considerable risk to vulnerable occupants (Elsharkawy & Rutherford, 2015). Although retrofit strategies are designed to lower energy consumption during the heating season, they can lead to overheating issues if proper strategies are not implemented to avoid excessive heat gain during warm periods, or to remove heat from indoor spaces in summer. This problem may be further exacerbated by the warmer summers anticipated due to climate change (Lee & Steemers, 2017). Key factors contributing to overheating in retrofitted buildings include lack of adequate ventilation, excessive solar gain due to insufficient shading, and increased airtightness without proper ventilation strategies (Oikonomou et al., 2012; Psomas et al., 2016a).

Reducing building airtightness is crucial for preventing overheating (Psomas et al., 2016b). Zahiri & Gupta (2023) found that heat pumps, including Ground Source Heat Pumps (GSHPs), can contribute to overheating as homes with these systems are typically airtight to enhance energy efficiency, highlighting the need for careful system design and implementation. Colclough & Salaris (2024) confirmed that poorly installed heat pumps and inadequate control measures, such as limited external shading and window restrictors, hinder occupants' ability to regulate indoor temperatures, emphasizing the importance of proper installation and control provisions. Similarly, Baborska-Narożny et al. (2017) reported that design flaws in retrofitted UK tower blocks, like insufficient shading and inadequate ventilation controls, led to significant overheating due to poor heat dissipation and excessive solar gain from large unshaded windows.

Additionally, building-integrated solar thermal collectors can cause indoor temperature discomfort during summer. While beneficial for passive heating in winter,

these collectors can transfer excessive heat in summer, increasing cooling demands and making indoor spaces warmer than desired (Buonomano et al., 2019).

Studies indicate that insufficient shading, inadequate air exchange, and increased airtightness without proper ventilation significantly contribute to overheating in retrofitted homes (Oikonomou et al., 2012; Zahiri & Gupta, 2023). Homes with more exposed areas, particularly south-west and south-facing glazing, are at higher risk (Zahiri & Gupta, 2023). Grassie et al. (2022a) observed that southeast-oriented rooms experience four to six times more overheating hours compared to northern orientations.

Moreover, occupant behaviour significantly influences overheating, focusing on the importance of self-reported actions (Mavrogianni et al., 2017). Studies have shown that the occupancy profile, such as whether a family or elderly occupy a home, greatly influences exposure to overheating. For instance, elderly occupants, who are typically at home during the hottest part of the day, are more likely to experience extended periods of overheating compared to families, who are less likely to be at home during the daytime due to work or study commitments (Elsharkawy & Rutherford, 2018). Maintaining warmth is typically the primary thermal concern in regions with a brief cooling season, such as the UK.

Despite these findings, there is a lack of studies on overheating in retrofitted homes, particularly those that have used emergent retrofit approaches where measures are implemented incrementally over time. This gap underscores the need for further research to understand and mitigate overheating risks in such dwellings.

2.5.1 Strategies to Avoid Overheating Risks in Homes

Passive mitigation methods are effective low-carbon strategies to reduce overheating risks in retrofitted homes (Grassie et al. 2022). These strategies include passive cooling that helps to prevent and regulate heat gains, such as utilizing natural thermal reservoirs. Excessive heat is likely to be prevented during the night-time in summer by opening windows when the outside temperature is lower than the inside temperature (Porritt et al., 2012) (Traynor, 2019). Despite the benefit of night-time ventilation in removing excessive heat, it can be constrained by several factors, including the nocturnal temperature levels, the restricted duration available for ventilation, the practical air change rate, and the building's capacity to store and dissipate heat effectively (S. McLeod & J. Hopfe, 2015). Where passive cooling is restricted in warm seasons, techniques including high-quality, airtight building envelopes, solar control through shading, managing internal heat gains, optimizing

microclimate, and building orientation can be implemented in building design to prevent overheating (S. McLeod & J. Hopfe, 2015).

Windows plays a crucial role in managing both energy efficiency and overheating risks in retrofitted buildings. Memon's research (Memon, 2014, 2015; Memon & Eames, 2017) continuously supports triple vacuum glazing in retrofitting solid wall dwellings, demonstrating its potential to reduce space-heating energy requirements and improve building energy efficiency. However, Jariwala & Taki (2023) identified reduced window area and LoE triple glazing as excellent mitigation prototypes in a 2015 modern flat located in a high-risk overheating zone in London, illustrating the context-specific nature of effective interventions. Lowering the solar heat gain coefficient (g-value) of windows helps mitigate the risk of overheating in buildings (Psomas et al., 2016b) . For instance, In the Evangelical Church, in Germany, automated blinds were employed during the daytime to mitigate overheating risks, complemented by low G-value glass, enhancing daylight levels while effectively managing solar heat gain (Traynor, 2019).

Effective strategies to prevent overheating include external interventions such as wall insulation, reflective coatings, and external shading devices, which are more effective than internal wall insulation (Chvatal & Corvacho, 2009; Porritt et al., 2012). Managing solar gain through shutters and permanent shading structures is particularly effective for south, east, and west-facing windows (Porritt et al., 2012). Internal insulation can reduce natural heat regulation, leading to discomfort during elevated summer temperatures if ventilation or solar protection is inadequate (Chvatal & Corvacho, 2009; Cirami et al., 2017; Lee & Steemers, 2017; Tink et al., 2018). Floor insulation is crucial for minimizing overheating duration by acting as a natural heat absorber (Psomas et al., 2016b). According to Lewis (2017), summer comfort can be achieved by combining external shading devices with superior insulation and highly reflective surfaces on walls and roofs, while minimizing internal heat generation.

Design Builder, a leading building performance simulation tool, offers thermal modelling, energy analysis, and comfort assessment capabilities (Design Builder, n.d.). Studies have used Design Builder to enhance building performance and reduce overheating through passive design measures. For example, simulations for large panel buildings in Poland evaluated different window glazing and night cooling strategies, showing significant reductions in overheating and improved thermal comfort by implementing improved solar heat gain coefficients (SHGC) and natural ventilation techniques (Nowak-Dzieszko & Rojewska-Warchał, 2015).

2.5.2 Overheating Risk Assessment Methods

The assessment of overheating risk in buildings employs various methodologies, with CIBSE TM52 and TM59 being among the most widely recommended guidelines for UK homes. Developed by the Chartered Institution of Building Services Engineers, TM52 focuses on naturally ventilated environments, offering criteria based on factors like air temperature and humidity, with recommendations to maintain comfort while minimizing energy use (F. Nicol, 2013). TM59 complements this by providing a standardized approach specifically for residential buildings, using dynamic thermal analysis to ensure comfortable indoor environments in both naturally and mechanically ventilated homes. Together, these guidelines offer a comprehensive framework for evaluating and mitigating overheating risks across various building types (Bonfigli et al., 2017).

Fletcher et al. (2017) assessed overheating risk in an assisted living Passivhaus dwelling using the CIBSE TM52 criteria. They found that the dwelling failed two out of three TM52 criteria, with substantial overheating during summer and even some colder months. Elsharkawy & Zahiri (2020) applied CIBSE TM59 to assess overheating risk in a retrofitted 1960s tower block. Their findings showed that while improved insulation reduced heating energy use, it also increased the risk of overheating, especially under future climate scenarios. The study highlighted that overheating risks vary significantly with the retrofit approach and occupancy patterns, emphasizing the importance of considering realistic profiles when predicting post-retrofit indoor conditions. Similarly, Colclough & Salaris (2024) utilized CIBSE TM59 alongside other objective standards such as Passive House (PH) and World Health Organization (WHO) criteria, complemented by Occupant Satisfaction Surveys (OSS) and interviews, highlighting the importance of combining quantitative and qualitative assessment methods. Lee & Steemers (2017) employed a dual approach, initially using the CIBSE TM52 methodology, followed by an evaluation based on continuously overheated intervals (COIs), which measure periods of consistent exceedance of adaptive temperature limits. This multi-method approach underscores the complexity of overheating assessment and the need for comprehensive evaluation techniques. Lee & Steemers (2017) propose a new indicator for overheating risk that underscores the impact of climate uncertainties and the necessity for proper ventilation and solar radiation protection. Complementing this, (Botti et al., 2022) developed a meta-model for early-stage overheating risk assessment, highlighting the importance of window opening and natural ventilation capacity.

2.6 Research Gap

The 2014 survey on 57 Superhomes (Fawcett & Killip, 2014a) that were often retrofitted by residents using emergent approaches did not address the risk of overheating or summer indoor thermal comfort. Internal insulation, for example, could significantly diminish a building's natural heat regulation, potentially leading to discomfort from higher summer (Chvatal & Corvacho, 2009; Tink et al., 2018) particularly in spaces with inadequate ventilation or solar radiation protection (Lee & Steemers, 2017). Addressing this issue is particularly critical in South England and London due to the urban heat island effect (Oikonomou et al., 2012;).

This literature review has highlighted the crucial need for retrofitting to reduce energy consumption and CO2 emissions in the UK (A Housing Stock Fit for the Future: Making Home Energy Efficiency a National Infrastructure Priority, 2017; Climate Change Committee, 2019), while also underscoring the associated risks of overheating in retrofitted homes (Gupta & Gregg, 2013; Oikonomou et al., 2012). Effective retrofitting requires careful consideration of the sequence of interventions, insulation choices, and solar gain management to prevent overheating (Coley et al., 2012; Psomas et al., 2016a). Key retrofit standards like Passivhaus EnerPHit and programs such as SuperHomes demonstrate the potential for achieving energy efficiency without compromising comfort, if measures are context-specific and well-coordinated (Fawcett & Killip, 2014b; Schnieders & Hermelink, 2006). However, there is a significant gap in understanding the risks associated with emergent retrofit approaches, particularly in urban areas like London where the urban heat island effect exacerbates overheating (Oikonomou et al., 2012). Addressing this gap is essential for developing practical guidelines that ensure energy efficiency while maintaining thermal comfort. The next section, Methodology, will outline the research design and methods used to explore these issues in SuperHomes.

3.0 Methodology

This study uses a mixed-method approach to understand the risk of overheating across five SuperHomes dwellings in South England during a typical summer between 3rd and 18th of August 2024. The case study dwellings consist of four semi-detached houses and one end-terrace house, all of which were retrofitted using an emergent approach except one, which completed its retrofit in six months. The inclusion of this dwelling, which underwent a rapid retrofit, allows for a comparison between the

effectiveness and potential overheating risks associated with different retrofit timelines and approaches.

- Data such as treated floor area (TFA) and energy efficiency ratings were collected from Energy Performance Certificates (EPC).
- Indoor temperatures and relative humidity, were monitored using HOBO UX-100-003 data loggers in all case studies for three weeks in the main bedroom and living room.
- Outdoor temperature and relative humidity levels were monitored across three homes in their garden HOBO MX2301 data loggers.
- Five thermal comfort surveys were conducted during the first visits (29 July- 1 Aug), and five more were conducted during the final visit (20 and 22 Aug) to understand the residents' thermal behaviour, alongside 5 household surveys where data on retrofit measures were gathered.
- The risk of overheating was assessed using CIBSE TM52 and CIBSE TM59 criteria from 3rd to 18th of August.
- Building simulation analysis was carried out to develop strategies to mitigate overheating.

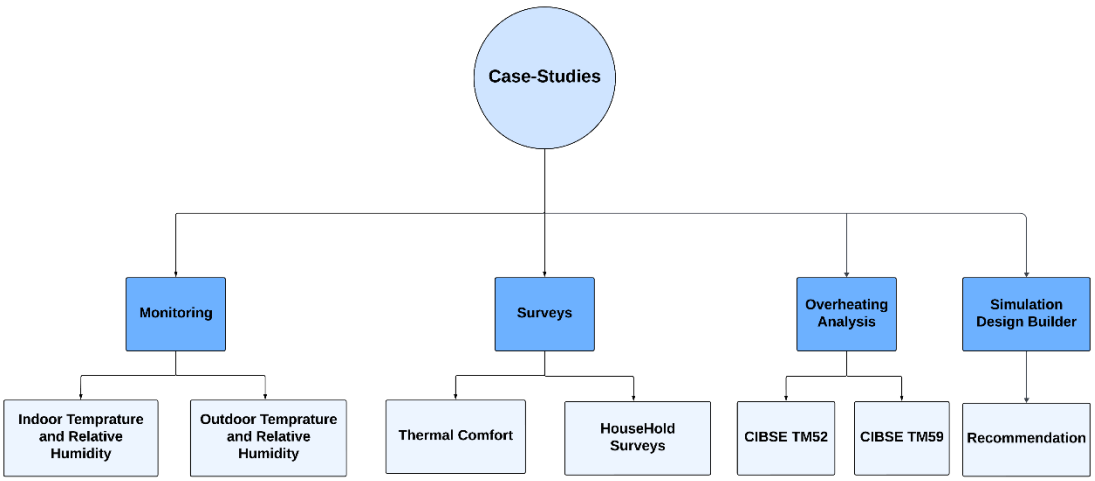


Figure 3: Methodology Flow Chart

3.1 Environmental Monitoring

Longitudinal physical monitoring of indoor temperatures was conducted at 30-minute intervals using HOBO UX100-003 data loggers. These devices were installed on the wall or placed in a closet away from doors, windows, and direct sunlight in the living room and bedroom in all 5 case studies. The monitoring period was from 3rd to 18th of August. Outdoor temperatures were also measured in the north and southwest of London, and Oxford during this time using HOBO MX2301.

Table 2: Specifications of monitoring devices

Device	Parameter	Range	Accurarcy	Interval	Number of Monitored Dwellings	Location	Concurrent Monitoring Days
HOBO UX100-003 (72 x 34 x 14 mm)	Indoor Temprature & Relative Humidity	-20° to 70°C	±0.21°C from 0° to 50°C	30 min	5	Bedroom and Living Room	16 Days (3-18 Aug)
HOBO MX2301 (85 x 100 x 26 mm)	Outdoor Temprature & Relative Humidity	-40° to 70°C	±0.25°C from -40 to 0°C		3	Garden/Front Yard/Back Yard	

Figure 4-6: HOBO Loggers in Living Room, Bedroom and Front Garden, O1

Figure 7-9: HOBO Loggers in Living Room, Bedroom and Front Yard, L1

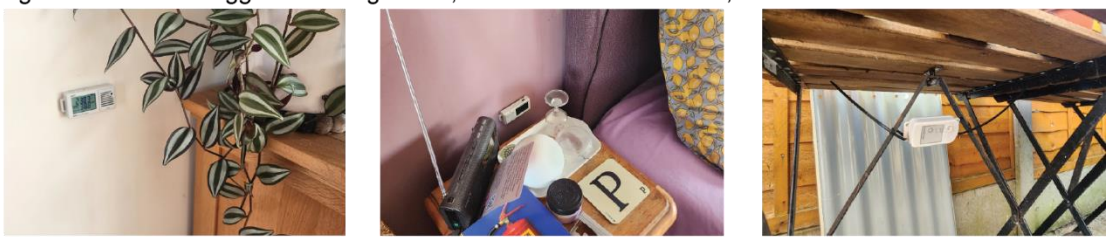


Figure 10-12: HOBO Loggers in Living Room, Bedroom and Back Yard, L2

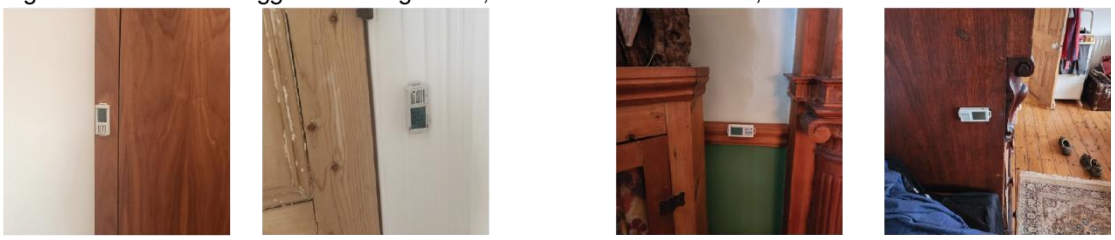


Figure 13-16: HOBO Loggers in Living Room, Bedroom, L3 and L4

3.2 Thermal comfort survey

A thermal comfort survey was conducted to evaluate residents' temperature perceptions and behaviours in five SuperHomes dwellings. The initial survey took place from July 29th to 2nd of August, followed by a final survey between August 20th and 22nd. Participants provided feedback on temperature perceptions, comfort levels, and preferences using the ASHRAE and Nicol scales. The survey also collected data on clothing, recent physical activity, use of environmental controls (e.g., window

openings, fans, air conditioning), barriers to using these controls, and strategies for maintaining indoor comfort. The thermal comfort survey is detailed in Appendix A.

3.3 Household survey

This survey conducted during the initial visit, collected background information about the households, including the number of occupants and their typical occupancy patterns. It gathered data on the physical characteristics of the homes, such as dwelling type, heating and cooling systems, insulation, and window glazing. The survey also explored the timing and nature of retrofit work, the motivations behind the retrofits, and specific measures taken to address overheating. Residents reported their satisfaction with the retrofits and any changes in energy use, energy bills, and thermal comfort post-retrofit, providing comprehensive insights into the effectiveness of the retrofit measures. Appendix A includes the Household survey templates used in this study.

3.4 Overheating assessment

To assess overheating in the case study dwellings, both dynamic (adaptive) and static metrics from CIBSE TM52 and CIBSE TM59 were utilized. These metrics consider outdoor temperature and the body's thermal adaptation. CIBSE TM52, employing adaptive methods, includes three criteria for evaluating overheating during both occupied and unoccupied hours. If at least two of these three criteria are not met, the indoor space is deemed overheated.

- Criterion 1: This criterion assesses the number of hours during which the difference (ΔT) between the actual operative temperature (T_{op}) and the maximum acceptable temperature (T_{max}) is at least one degree. For the period from May to September, this should not exceed 3% of the occupied hours. The value of ΔT can be calculated using Equations below:

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

T_{od-1} represents the daily mean outdoor temperature for the previous day, T_{od-2} is the daily mean outdoor temperature for two days ago, and so forth.

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

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

It's important to note that due to the study's constraints, the overheating assessment was conducted over two weeks in August, rather than the full May to September period recommended by CIBSE guidelines. While this is a limitation, the short-term assessment still offers a useful estimate of potential overheating over a longer period.

- Criterion 2 (Daily Weighted Exceedance (W_e)): This criterion stipulates that the daily weighted exceedance (W_e) should not exceed 6 on any given day. The value of We can be calculated using the Equations below:

$$Weighting\ Factor\ (WF) = 0\ if\ \Delta T \leq 0, otherwise\ WF = \Delta T, and\ h_{ey}\ is\ the\ time\ (h)\ when\ WF = Y$$

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

- Criterion 3 (Upper Limit Temperature (T_{upp})): To establish an absolute maximum value for the indoor operative temperature (T_{op}), known as the upper limit temperature (T_{upp}), the difference (ΔT) should not exceed 4 K.

CIBSE TM59: CIBSE TM59 employs both dynamic (adaptive) and static criteria. Criterion A of CIBSE TM59 is dynamic and aligns with CIBSE TM52's Criterion 1, which focuses on hours of exceedance from May to September in both bedrooms and living rooms. Criterion B of CIBSE TM59 is static and sets an upper comfort temperature of 26°C, which should not be exceeded for more than 1% of the annual hours in bedrooms during sleeping hours (22:00 to 07:00). For the May–September period, living rooms are considered occupied from 9:00 to 22:00 over 153 days, while bedrooms are considered occupied 24 hours a day for the evaluation of Criterion 1 in both CIBSE TM52 and CIBSE TM59.

3.5 Building Simulation Analysis

Design Builder software was utilized to create a detailed model of the house identified as L2, which was experiencing significant overheating issues. The simulation enabled an analysis of solar exposure on the building, highlighting areas most susceptible to excessive heat. Various mitigation strategies were tested within the model, including the addition of shading devices and enhancements to ventilation. These interventions were found to be effective in reducing overheating and improving indoor comfort by optimizing air circulation and limiting direct solar gain.

4.0 Case Study Characteristics

4.1 Recruitment Process

The recruitment process for this study began with identifying the names of SuperHomes owners and their approximate locations from the SuperHomes website. Using this information, further searches were conducted on LinkedIn and other internet sources to find either their professional accounts on LinkedIn or their professional websites. Through this method, contact information for the homeowners was obtained. Subsequently, 13 homeowners were contacted with an invitation to participate in the study. Interested homeowners who approved the invitation then reached out to the researcher to confirm their participation. To ensure ethical compliance, several documents were prepared and provided to the participants before they agreed to take part in the study. These documents included the Participant Information Sheet, the GDPR Privacy Notice Template for Researchers, and the Faculty of Technology, Design, and Environment - Ethics Review Form E1(Arch) (Can be found in Appendix B). Additionally, a consent form was provided to all participants, which they signed to confirm their informed consent. The researcher retained signed copies of the consent forms, while the participants were provided with copies of all the other forms for their records.

4.2 Overview of Case Study Dwellings

The five SuperHomes case studies are in Southeast of England including London and Oxford. three dwellings are in the north and east of London, one in the southwest of London in Kingston upon Thames, and one in Oxford. All these homes were retrofitted using an emergent approach except one dwelling (L2) in North London. While some homes followed a designed series of measures implemented over years and phases, others underwent random changes. One home (L2) completed its retrofit in just six months, two took between two to five years, and the remaining two finished in 15 years. The Energy Performance Certificates (EPC) for these case studies range from A to D. The physical characteristics of the dwellings were identified using EPCs, which are summarized in Table 3.

Table 3: Characteristics of case study dwellings

Dwellling Type	Dwelling ID	Location	Orientation Monitored Living Room	Orientation Monitored Bedroom	Efficiency Rating	Floor Area (m2)	Annual Heating (kWh/m2)	Retrofit Duration
End-terrace house	L1	Kingston upon Thames	E	W	A	80	57.63	15 Years
Semi-detached	L2	North London	W/E	W/E	B	65	78.41	6 month
	L3	East London	NE	SW	C	200	105.36	2 stage: 2010 and 2012
	L4	North London	S	S	C	173	73.64	15 years
	O1	Oxford	SE	NW/SE	D	141	128.76	2-5 years

As shown in Figure 17, the map illustrates the locations of the case study dwellings, which are spread across Southeast England, including areas in London and Oxford. Each case study will be introduced on the following pages, with pictures taken by the author during the first and final visits.

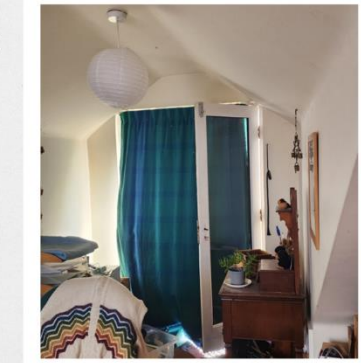
Figure 17: Map of case study dwellings

Case Study: O1

1930s Semi-detached house
Location: Oxford
TFA: 141 m2
EPC: D, 2015
Annual Heating Demand: 128.76 kWh/(m2a)
Occupants: 4
Bedrooms: +5
Ventilation: Naturally ventilated and single-room MVHR unit
Renewable: Solar photovoltaics, Biomass heating, and Solar water heating
Carbon Saving: 66%

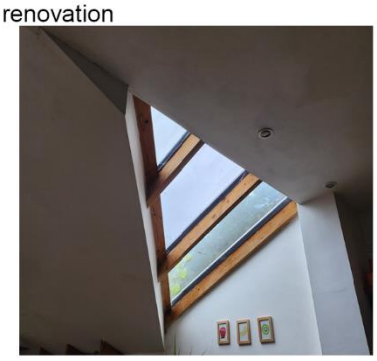
Northwest Facade

Floors Plans of dwelling O1 before renovation



Bedroom

Living Room



Living Room, Skylight

Bedroom, Skylight

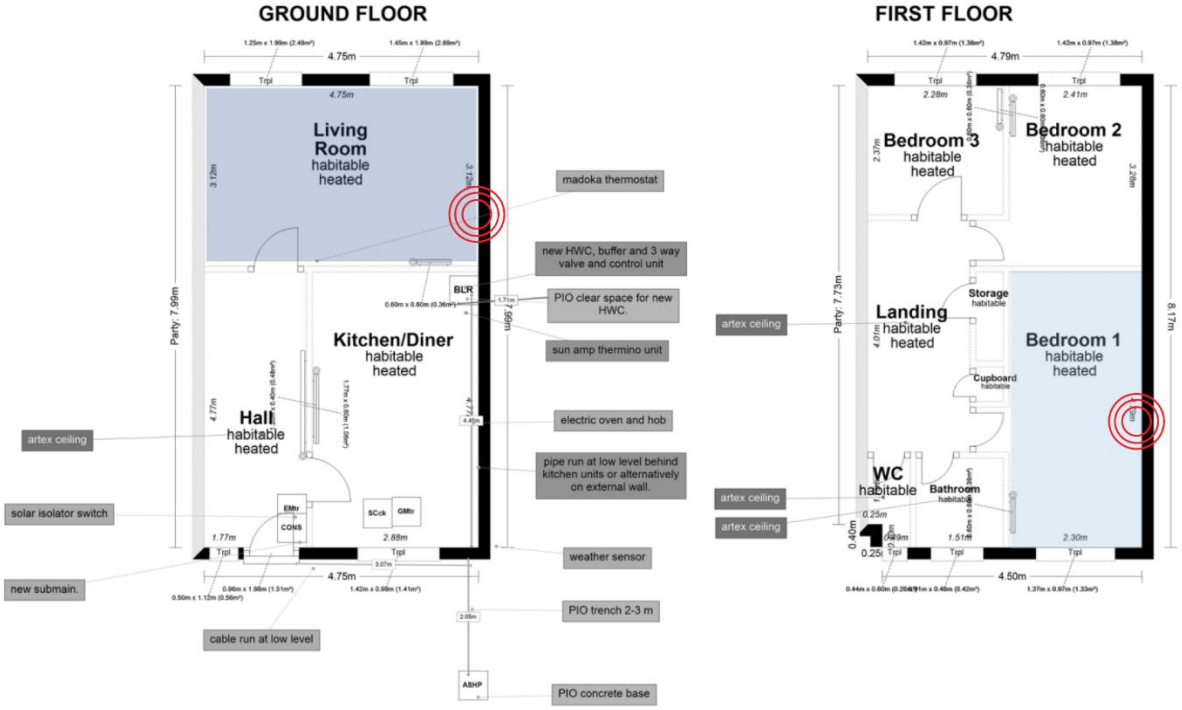
Solar Thermal and Solar PV

Southwest Facade

Case Study: L1

Late ’60s ex-council wood-framed end-terrace house
Location: Kings Upon Thames
End-terrace house
TFA: 80 m2
EPC: A, 2024
Annual Heating Demand: 57.63 kWh/(m2a)
Occupants: 4
Bedrooms: 3
Ventilation: Naturally ventilated and single-room MVHR unit (Envirovent PIV)
Renewables: Solar photovoltaics
Carbon Saving: 62%

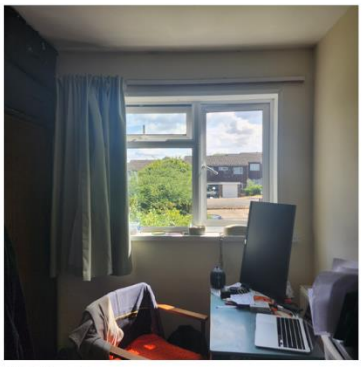
West facade



Ground Floor and First Floor Plan


East Facade

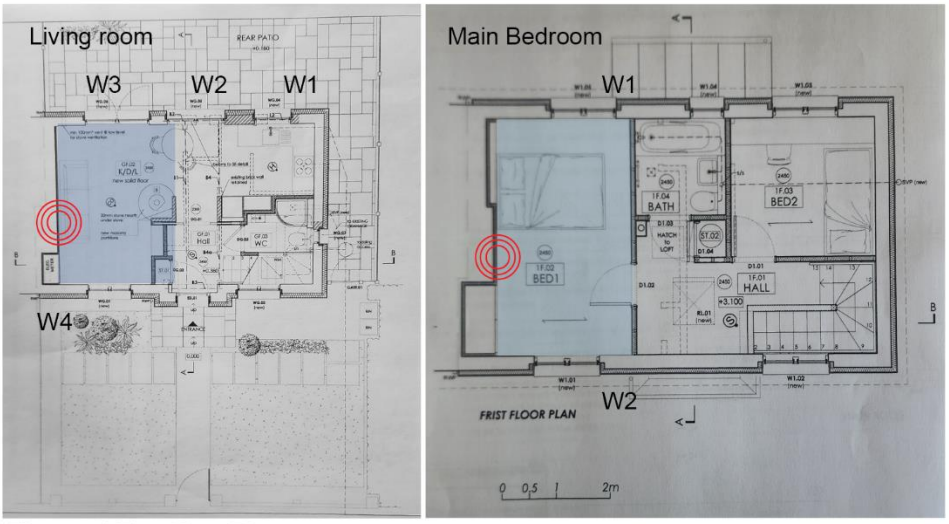

Living Room


Bedroom

Case Study: L2

1920s Semi-detached house
Location: North London
EPC: B, 2017
TFA: 65 m2
Annual Heating Demand: 78.41 kWh/(m2a)
Occupants: 1
Bedrooms: 2
Ventilation: Naturally ventilated, Envirovent PIV and MIV loft-mounted unit
Renewables: Solar photovoltaics, Biomass heating, and Solar water heating

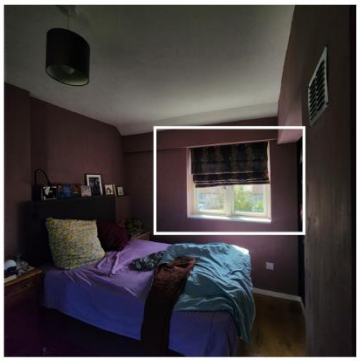
West Facade



Ground Floor and First Floor Plan

Living room (East Facing Window)

Living room (West Facing Window)



Bedroom (West Facing Window)

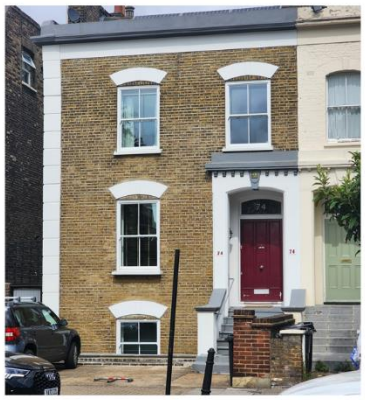
East Facade

Hall, Stairway

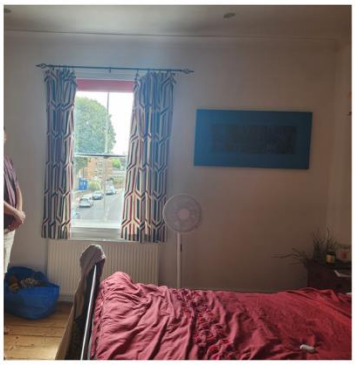
Bedroom (East Facing Window)

Case Study: L3

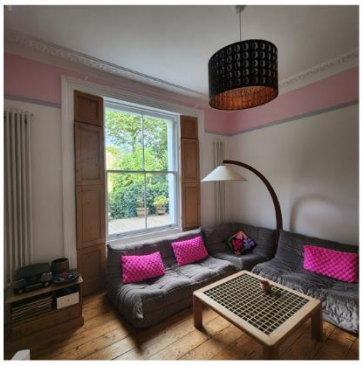
1870s Victorian Semi-detached house
Location: East London
EPC: C, 2022
TFA: 200 m2
Annual Heating Demand: 105.36 kWh/(m2a)
Occupants: 2
Bedrooms: 4
Ventilation: Naturally ventilated and single-room MVHR unit
Renewables: Air source heat pump and Solar photovoltaics
Carbon Saving: 63%



Southwest Facade



Bedroom 1



Reception 2

Northeast Facade

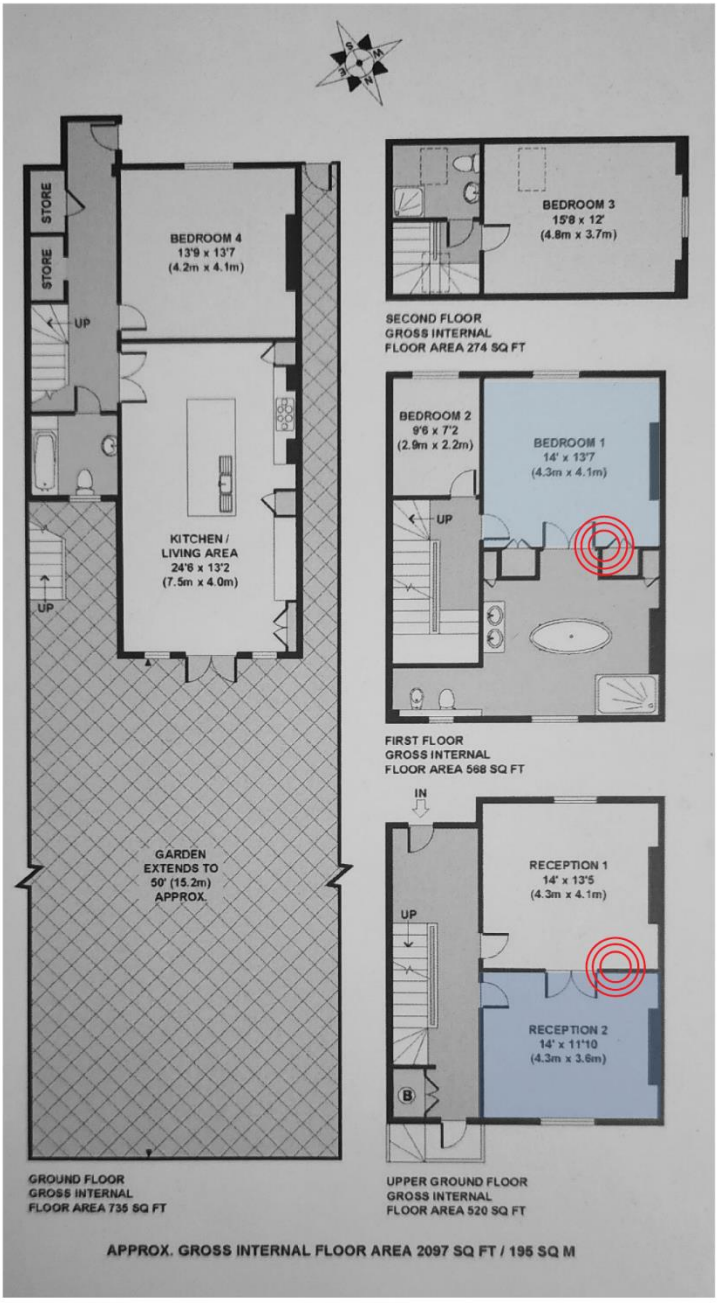
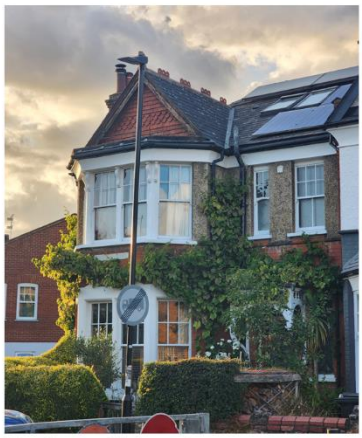


Figure X: Floors Plan, O1

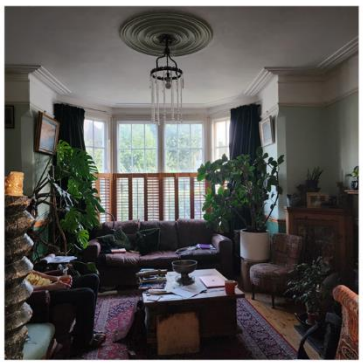
Case Study: L4

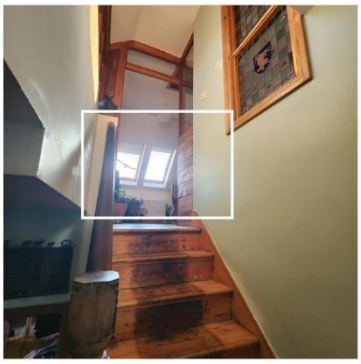
Edwardian 1900 Semi-detached house
Location: North London
EPC: C, 2014
TFA: 173 m2
Annual Heating Demand: 73.64 kWh/(m2a)
Occupants: 2
Bedrooms: 5+
Ventilation: Naturally ventilated
Renewables: Solar photovoltaics, Air Source Heat Pump, and Solar water heating


Southwest Facade

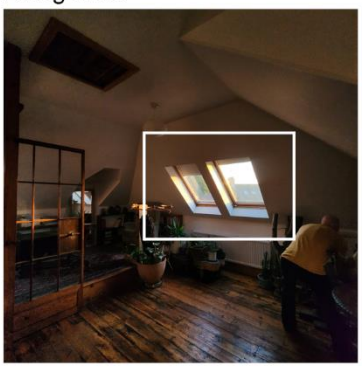

Bedroom


Kitchen


Living room


Skylights at the end of stairway in Loft


Office Loft


Skylight in Loft


Northeast


Reception


Secondary Glazing

5.0 Results

This section presents the findings of the study, which evaluated thermal comfort, temperature variations, and overheating risks in different case studies after either an emergent or one-off retrofit. The results are organised into subsections. First, survey responses summarise household demographics, the retrofit strategies employed, and residents' perceptions of thermal comfort.

Next, outdoor temperature trends in North London, the Southwest, and Oxford, along with indoor temperatures of two rooms per case study, are outlined. Data from site observations and documents provided by homeowners are then presented, offering insights into on-site conditions, occupant behaviour, and architectural details.

Indoor temperature monitoring data from living rooms and bedrooms are analysed, showing daily fluctuations and extreme temperature events. The section continues with results related to overheating criteria from CIBSE TM 52 and TM 59. Lastly, the simulation analysis explores different scenarios and potential improvements, demonstrating how alternative strategies could enhance thermal performance.

5.1.0 Overview of Case Studies

The case studies cover five dwellings located in Oxford, the Southwest, and North London. All were visited during the last week of July, one of the hottest weeks of summer, with outdoor mean temperatures ranging from 21.7°C to 23.7°C, and a maximum of 31.1°C on July 30th (Local weather forecast, news and Conditions, n.d).

During the first visit, thermal comfort data and household survey responses were collected. Sensors were installed in the main bedrooms and living rooms, and photographs were taken. The sites were revisited on August 20th and 22nd to retrieve the sensors, conduct another thermal comfort assessment, and take additional photographs.

Outdoor mean temperatures were 20.1°C and 18.0°C on those dates, respectively. Table 4 presents the EPC ratings and floor areas. L1 has the best EPC rating (A), while O1 has the worst (D). L1 and L2 are the smallest rooms at 65 m² and 80 m², while L3 is the largest at 200 m².

Table 4: Case Studies Energy Performance Certificate

Dwelling ID	Location	Orientation Monitored Living Room	Orientation Monitored Bedroom	Efficiency Rating	Floor Area (m2)	Annual Heating (kWh/m2)
O1	Oxford	SE	NW/SE	D	141	128.8
L1	Southwest London	E	W	A	80	57.6
L2	North London	W/E	W/E	B	65	78.4
L3	Northeast London	NE	SW	C	200	105.4
L4	North London	S	S	C	173	73.6

Below are the observations for each site:

5.1.1 Dwelling O1

Dwelling O1, a 1930s semi-detached house, located in Oxford, has an EPC rating of D issued in 2015 (Figure 23a). At O1's house, the homeowners retrofitted the property over two to five years with an extension that includes a south-facing dining room and

office, attached to a kitchen to the north. The dining room has a sloped roof with three skylights, one larger than the others. A grapevine, growing over the largest skylight, provides natural shading in summer. In winter, the vine sheds its leaves, allowing sunlight through the skylight into the living room (Figure 23b). The one-year-old grapevine is expected to cover the skylight by next year fully. A greenhouse is attached to the office, with solar thermal panels installed above. Initially, the panels were covered with cupboard material as they were overheating the water, but by late August, the material had been removed. The plan of the house can be found in Case Study O1 Figure 18.

The homeowner shared renovation documents, including U-value calculation reports, which can be seen in Table 5. The windows are a mix of double-glazed and triple-glazed units, with some fitted with internal blinds, though several lack blinds. Notably, the windows over the sink and patio (both southeast-facing) and the south-facing conservation window in the office do not have blinds. A detailed table regarding curtains can be found in Appendix C.

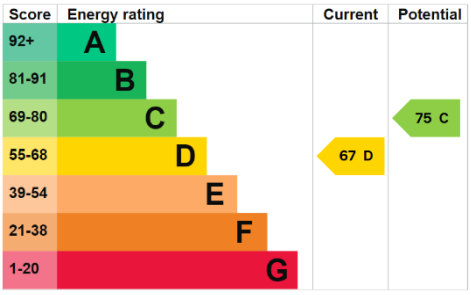


Figure 23a (Left): EPC of Dwelling O1, assessed in 2015 and Valid Until 2025

Figure 23b (Right): Patio door and Skylight of living room

Table 5: Envelope U-values

	Description	Construction	U Value (W/m2k)
External walls	External 1	Solid wall: dense plaster, 200 mm dense block, insulated externally	0.23
	External 2	Solid wall: dense plaster, 210 mm brick, insulated externally	0.31
	External 3	Cavity wall: dense plaster, AAC block, Filled cavity, any outside structure	0.3
	External 4	Solid wall : dense plaster, 200 mm dense block, insulated externally	0.15
	Office Wall 5	Other	0.22
	Gable end 6	Timber framed wall (one layer of plasterboard)	0.45
External Roofs	Attic Roof 1	External Slope Roof: Plasterboard, insulated slope	0.35
	Extension Roof 2	External Slope Roof: Other	0.14
	Office Roof 3	External Flat Roof: Plasterboard, insulated Flat roof	0.15
Heat Loss Ground Floors	Suspended Floor 1	Timber: Suspended Timber, insulation between joists	0.21
	Office Floor 2	Solid: Slab on ground, screed over insulation	0.15
	Extension and Kitchen Floor 3	Solid: Slab on ground, screed over insulation	0.17
	Utility room Floor 4	Solid: Slab on ground, screed over insulation	1.95
Windows and Roof Windows	Ecocontract	Double Low-E Soft 0.05 (G value: 0.63)	1.4
	Warmcore	Triple Low-E Soft 0.1 (G value: 0.57)	1
	Roof lights	Triple Low-E Soft 0.2 (G value: 0.57)	1.1
	Extension Velux	Double Low-E Hard 0.2 (G value: 0.72)	1.4
	Attic Velux	Double Glazed (G value: 0.76)	2.2
	Attic windows	Double Low-E Soft 0.1 (G value: 0.63)	1.7
	Door to Consevatory	Double Glazed (G value: 0.76)	2.2
	Office Behind Solar	Triple Low-E Soft 0.1 (G value: 0.57)	1.1

5.1.2 Dwelling L1

Late 60's ex council wood frame end terrace house located in southwest London, Dwelling L1 recently received an EPC rating of A in 2024 (Figure 24a). The retrofit process has been ongoing for 15 years and, as the occupant described in the survey, "it's still going." All the details of the retrofits and studies are available on the Earth Notes: Saving the Planet website, created by the homeowner who is a PhD researcher in sustainability and environmental engineering. One key focus was loft insulation, with several improvements made between 2007 and 2012. Detailed descriptions of these measures are outlined in Table 6. Upgrades included loft insulation and draught exclusion, bedroom dry-lining with Magnaline boards and aerogel, whole-house air-leak testing, and the installation of MVHR systems in both the bathroom and kitchen.

Before the bedroom insulation project, whole-house air-leak testing was conducted in March and April 2009, identifying problem areas using smoke-pencil tests. In L1's kitchen, the mechanical ventilation system, though slightly noisy, provided a refreshing airflow.

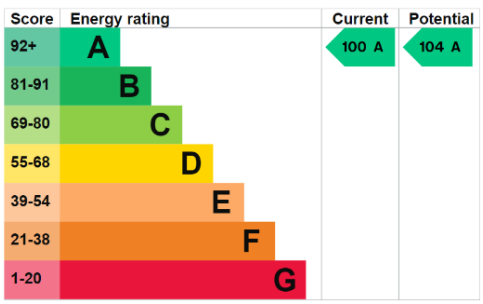


Figure 24a (Left): EPC of Dwelling L1, assessed in 2024 and Valid Until 2034

Figure 24b (Middle): MVHR Fan in the Kitchen of Dwelling L1

Figure 24c (Right): MVHR Fan in the Bathroom of Dwelling L1

Dwelling L1 expanded its solar photovoltaic (PV) system in 2010 to achieve a total annual electricity generation of approximately 4 MWh. The system comprises two south-facing solar PV panels installed at a 70-degree angle to the ground. This steep inclination optimizes solar energy capture during the winter months by maximizing exposure to low-angle sunlight.

Table 6: List of Measures and Dates Implemented in Dwelling L1

	Date	Measures
Insulation and Airtightness	2007/12	Extra loft insulation and some draught exclusion
	2008/06	Added an extra 20 cm of loft insulation.
	2010/07	Internally super insulated (dry-lined) the living-room external walls with aerogel.
	2011/04	Fixed flaws in existing loft insulation, replaced loft boards with insulated ones, and topped up insulation to exceed building regulations.
	2011/10	Experimental dry-lining in bedrooms used Magnaline 9mm magnesium board with 30mm aerogel, with greater focus on reducing thermal bridging. Some air infiltration through the west-facing wall was also reduced.
	2011/11	Improved insulation on the loft hatch with EPS strips and an aerogel-backed plasterboard offcut, wrapped in cardboard for protection. Loft insulation depth was measured/estimated to vary between 240mm and 300mm during an iButton reading.
	2013/05	In 2013, 40mm aerogel IWI was added to exterior walls during a kitchen refurb. Switched from a gas stove to an induction hob and electric oven for lower carbon impact. Insulated DHW pipework, cutting heat loss from ~60W/m to ~20W/m, potentially saving 400W when a bathroom tap runs.
Doors and Windows	2009/07	Replaced front door and side panel with double-glazed/insulated units.
	2009/11	Replaced outer seal/gasket on living-room double-glazed doors to reduce draughts.
	2011/05	Replaced broken patio door with double-glazed, low-emissivity glass.
	2012/09	Replaced old double glazing with Passivhaus-compliant triple glazing to improve airtightness and reduce heat loss.
Heating and Ventilation Systems	2008/04	Lagged central heating and domestic hot water pipes.
	2009/03 &	Performed whole-house air-leak testing with smoke-pencil tests to identify problem areas.
	2009/04	Air permeability at 50Pa was 7.1–7.2 m^3/h, over 20 times the Passivhaus standard.
	2009/09	Installed thermostatic valves on radiators and had a boiler tune-up.
	2012/11	Installed a Lo-carbon Tempra P MHRV fan in the kitchen to reduce humidity and improve ventilation with lower energy costs.
	2011/12	Installed a Vent-Axia HR25H MHRV in the bathroom to improve upstairs air quality and reduce condensation in bedrooms, aiming to minimize the need for window opening and heat loss.
	2014/03	Fitted an external bypass for the boiler.
	2022/03	Installed a Sunamp Thermino heat battery with a Myenergi Eddi PV diverter.
Renewable Energy Systems	2008/02	Installed a 1.29kWp grid-tie solar PV system
	2009/02	Installed an additional 2.58kWp of grid-tie solar PV
	2010/04	Expanded solar PV to generate ~4MWh/year, aiming for near-zero carbon.
	2018/08	Installed a 1kWh AC-coupled Enphase battery to improve self-consumption of PV generation.

5.1.3 Dwelling L2

Located in north London, Dwelling L2 which is a 1920 semi-detached house is home to an elderly occupant and was issued an EPC rating of B in 2017 (Figure 25a). The homeowner of dwelling L2, a retired individual passionate about sustainability, regularly hosts open houses to showcase the thermal comfort of her retrofitted home. Before the retrofit, the house was so cold in winter that she stayed with friends for two months. The retrofit took six months and was handled by an architecture firm. Detailed documentation, such as window dimensions and U-values, is available in Table 7 and Table 8 respectively. Initially, the architectural firm planned to extend the dining room and add a patio with three-sided windows, but budget constraints prevented this.

During the initial visit, the house felt overly warm due to solar heat gain from three large west-facing windows in the living and dining rooms. Two of these, 200 cm tall, opened to the garden, while the third in the living room was partially obstructed by a thin curtain, reducing its effectiveness in controlling heat. The homeowner was also unsure about the functionality of the mechanical ventilation system, which may have contributed to the discomfort.

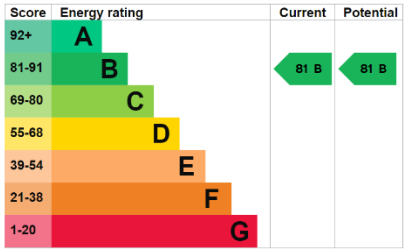


Figure 25a: EPC of Dwelling L2, assessed in 2017 and Valid Until 2027

Figure 25b: West façade of Dwelling L2

Figure 25c: MVHR Fan on stairs ceiling in dwelling L2

Table 7: Envelope construction detail and U Values in Dwelling L2

Description	Construction	U Value (W/m2k)
Wall	EWI: 215mm Masonry wall, 120mm STEICO PROTECT (dry system) Wood Fibre Insulation boards on levelling parge coat	0.3
Main Pitched Roof	100mm STEICO FLEX wood fibre insulation between and over ceiling joists, 42.5mm insulated pbd KOOLTHERM	0.2
Ground Floor	150mm Concrete Slab, 120mm Kingspan Kooltherm K3	0.14

Table 8: Windows Dimensions in Dwelling L2

	Orientation	Location	Width mm	Height mm
Ground Floor	East	Entrance Front Door	885	2090
		Living Room	1210	1520
		Hall	1230	1180
	South	WC/	420	750
	West	Kitchen	1000	1300
		Kitchen/Dining/ Living room	775 & 1000 & 775	2450
		Kitchen/Dining/ Living room	500 & 1000	2300
First Floor	East	Main Bedroom	1210	1100
		Hall	1210	1100
	West	Bedroom Single	1210	1100
		Bathroom	630	1100
		Main Bedroom	1210	1100
	(Skylight)	Hall	990	780

5.1.4 Dwelling L3

Dwelling L3 is a semi-detached Victorian house from the 1870s, the oldest among the case studies, located in northeast London. L3's house holds a certificate by the front door confirming its SuperHomes status, awarded for exceptional carbon reduction through eco-refurbishment. During the visit, the house was remarkably cool. The homeowner mentioned that visitors often asked whether they had air conditioning even though they did not.

The living room was rarely used as the occupants preferred the larger kitchen, which had direct access to the garden, connecting to the backyard and a sitting area. Additionally, the house has an extension that includes a sauna, accessible through the kitchen, and situated near the backyard. They were also planning to replace the front door with an airtight model, as the current door, an old design, allowed a noticeable breeze to enter the home. Fresh air was also entering through a duct in the storage room.

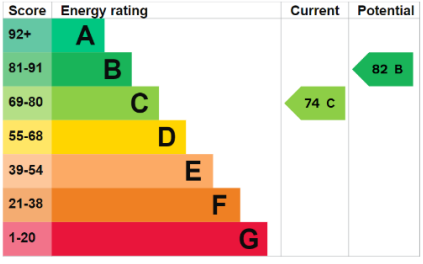


Figure 26a (Left): EPC of Dwelling L3, assessed in 2022 and Valid Until 2032

Figure 26b (Middle): MVHR Fan in the utility room, Figure 26c (Right): Kitchen of Dwelling L3

5.1.5 Dwelling L4

Dwelling L4 is an Edwardian semi-detached house constructed around 1900, located in North London. The occupants are two middle-aged individuals who have been retrofitting the house over the past 15 years. The homeowner of Dwelling L4, who owns an underfloor insulation company, completed most of the retrofit themselves, with help from three others. Their attention to detail and creativity were evident throughout.

Despite high temperatures, the house stayed cool due to effective insulation and minimal solar heat gain. During a tour, the homeowner explained how they built a secondary frame for the old windows and added removable secondary glazing for summer ventilation. They also installed weatherstripping on all windows and doors to reduce drafts and heat loss.

The top floor, where the office was located, had two skylights that lit the staircase, and the roof planted with sedum to create a green roof. In the bathroom, a dehumidifier was used to prevent mould without opening windows in winter, avoiding heat loss.

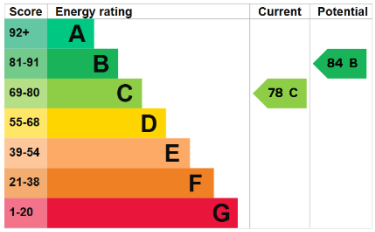


Figure 27a (Left): EPC of Dwelling L4, assessed in 2014 and Valid Until 2024 (Expired in January)

Figure 27b (Medium): weatherstripping of the entrance door in dwelling L4

Figure 27c (Left): Two Skylights on the top floor of dwelling L4

The homeowner also kept a detailed Excel sheet tracking carbon emission, including gas, electricity, water, transport, and appliance electricity use, along with monthly consumption and costs.

5.2.0 Surveys

This section presents the results from household and thermal comfort surveys conducted across five case studies. Homeowners completed the surveys, reporting the retrofitting measures implemented, their satisfaction with energy savings, carbon reductions, and indoor environmental quality.

The survey also explored occupants' perceptions of thermal comfort, their use of ventilation systems, and strategies for managing indoor temperatures; providing insights into how various retrofit approaches affect comfort and behaviour.

5.2.1 Household Survey

The survey showed that most adults in the case studies work from home or are retired, with the majority aged 45-64 (Table 9). This focused on middle-aged adults, who may be more sensitive to overheating due to spending more time at home, while also including younger and older occupants.

Table 9: Case Studies occupant age group

Case Studies/Age	0-4	5-15	16-24	25-44	45-64	64-84	+85
O1		1	1		2		
L1		1	1		2		
L2						1	
L3				1	1		
L4					2		

Survey responses showed four dwellings used an emergent retrofit approach that was completed between two to 15 years, while dwelling L2 took six months to be retrofitted. Among these four dwellings, two implemented planned changes over time through separate projects, while the other two evolved as the projects progressed. A detailed summary of the retrofit approaches can be found in Table 10.

Table 10: type of approach in case studies

Dwelling ID	Location	Type of Approach	Series of Planned Changes	Retrofit Duration
L1	Kingston upon Thames	Emergent	No	15 Years
L2	North London	One-Off	Yes	6 month
L3	East London	Emergent	Yes	2 stage: 2010 and 2012
L4	North London	Emergent	No	15 years
O1	Oxford	Emergent	Yes	2-5 years

Table 11 outlines the division of work between professionals and homeowners in planning the retrofit measures. Most homeowners undertook the retrofit themselves, except for L2, where tradespeople handled the work. In most cases, homeowners made the decisions about the next steps, except for L2, where an architect and energy consultant guided the process.

Table 11: Retrofit Work and Decision-making Involvement

Dwelling	Professionals/Trades Involved	Planning and Decision-making
O1	Much of the work	Homeowner
L1	Much of the work	Homeowner and Builder
L2	All the Work	Architect and Energy Consultant
L3	(builders to fit the products)	Homeowner
L4	Some of the work	Homeowner

In the retrofitting process across the case studies, it was identified that energy use reduction and energy cost savings were the key targets considered in most dwellings.

Measures such as insulation improvements, energy-efficient heating systems, and ventilation upgrades were prioritized in most cases. However, only a few homes, specifically L3 and L4, targeted overheating risk and minimizing solar heat gain during their retrofits. Overheating was not a widely considered goal in most of the retrofitted homes at the time.

Table 12: Targets of Retrofit in 5 Case Studies

Targets	L1	L2	L3	L4	O1
Reduce Energy Use	X	X	X	X	X
Reduced Energy Bills		X	X	X	X
Reduce overheating risk				X	
Reduce heat loss	X	X	X	X	X
Improved airtightness	X	X	X	X	X
Improved ventilation	X			X	X
Better indoor air quality				X	
Lower carbon emissions	X	X	X	X	X
Reduced (mains) water use			X	X	X
To become a 'Superhome'				X	
Other: Reduce Solar Heat Gain			X		
Don’t know					

Table 13 outlines the measures undertaken during the retrofitting of each case study, including the sequence in which these measures were implemented. A '0' in the table indicates the measures associated with the case study that completed its retrofit in a single six-month process. The numbers 1, 2, 3, etc., correspond to the sequence in which these retrofitting steps were completed over time. O1 initially focusing on installing systems such as a gas boiler, solar water heating, solar photovoltaic panels (PV), and a wood burner before improving the performance of windows and walls. The retrofit of dwelling L3 work began with enhancing the building envelope and adding insulation. Simultaneously, solar photovoltaic (PV) panels and an air-source heat pump were installed.

Table 13: Retrofit Measures sequence among Case Studies

	Measures	L1	L2	L3	L4	O1
Envelope	External wall insulation		0	1		5
	Internal wall insulation		0	1	1	
	Cavity wall insulation					
	Ground floor insulation			2	1	
	Loft/roof insulation	1	0	2	1	
	High-performance doors		0	4		
	Double/triple glazed windows	3	0	1		4
Expansion	Extension			2		
	Re-modeling inside		0	3		
	Loft conversion				X	
	Conservatory					
	New outbuilding					
Ventilation	Improved airtightness		0	1	X	
	Extract fans without heat recovery					
	Extract fans with heat recovery	4				7
	Whole-home ventilation system		0			
Systems	Efficient gas boiler			1		1
	Efficient oil boiler					
	Efficient LPG boiler					
	Solar water heating				2	2
	Solar photovoltaics (PV)	2	0	1 or 2	3	3
Other	Wood burner		0		X	2
	Air Source Heat Pump (ASHP)		0	3	4	
	Under Floor Heating			2		
	Shower Save					8

Table 14: Overview of Insulation, Window, Ventilation, and Shading Strategies for Case Study Dwellings

Case study ID	Internal Wall Insulation	External Wall Insulation	Ground Floor Insulation	Loft Insulation	Window	Ventilation	Shading
O1	-	Yes	Yes	-	Double/Triple	MVHR	Grape Plant
L1	Yes	-	-	Aerogel and EPS	Triple	Envirovent PIV	Reflective Blinds
L2	Pavatex	Pavatex Wood Fibre	Kingspan	Yes	Triple	Envirovent PIV and MIV loft-mounted unit	-
L3	Yes	Yes	Aerogel	Yes	Double	Envirovent PIV	-
L4	Yes	Yes	Yes	Yes	Secondry Glazing	Natural Ventilation	Internal Wooden Shadings

Regarding ventilation, 80% of the case studies had ventilation systems, with only L4 lacking one as table 14 presents. Table 15 shows the types of renewables in the case studies. All have solar photovoltaic systems, while only dwellings O1 and L4 include solar water heating.

Table 15: Types of Renewable Energy Systems in Case Studies

Case study ID	Carbon Saving %	Biomass heating	Solar water heating	Solar photovoltaics	Heat Pump
O1	66	Wood Buring Stove (Plan to remove it)	4.26 m2 Evacuated tube data 300 L	0.9 & 1.6 kWp	-
L1	62	-	-	1.29 kWp grid-tie	-
L2	?	Wood Buring Stove (4.3 kW)	-	8 Panasonic 330 Wp panels (Total Power: 3.2 kWp)	Air Source
L3	63	-	-	2.7 kWp	Air Source
L4	61	-	Yes	2.1 kWp	Air to Water (COP: 3.15-4.46)

Table 16 shows that most participants were "Quite Satisfied" or "Very Satisfied" with energy savings, carbon reductions, and thermal comfort. However, some were neutral about air quality and ventilation, with one marking air quality as "Not Applicable," suggesting these factors were less relevant or not evaluated by all.

Table 16: Participant Satisfaction Levels Across Various Categories

	O1	L1	L2	L3	L4
Overall	Quite Satisfied	Very Satisfied	Very Satisfied	Quite Satisfied	Very Satisfied
Energy Saving	Quite Satisfied	Very Satisfied	Very Satisfied	Quite Satisfied	Very Satisfied
Carbon Saving	Quite Satisfied	Very Satisfied	Very Satisfied	Quite Satisfied	Very Satisfied
Indoor Thermal Comfort	Quite Satisfied	Quite Satisfied	Quite Satisfied	Quite Satisfied	Very Satisfied
Indoor Air Quality	Quite Satisfied	Quite Satisfied	Neither Satisfied Nor Dissatisfied	Not Applicable	Very Satisfied
Ventilation System	Quite Satisfied	Quite Satisfied	Neither Satisfied Nor Dissatisfied	Quite Satisfied	Very Satisfied

5.2.2 Thermal Comfort Survey

A thermal comfort survey was conducted during both visits and revealed varying perceptions of indoor temperature across different case studies. The first survey took place during the hot summer week between 29th July and 2nd August with outdoor mean daily temperatures ranging between 21.68 °C and 23.68°C, the maximum temperature reached 31.1°C in the afternoon of 30th July (*Local weather forecast, news and Conditions,* n.d),

The final survey was conducted on 20th and 22nd August and the mean daily temperature was 20.12 °C and 18.02°C (*Local weather forecast, news and Conditions,* n.d), All of the case studies conducted the test in the living room, except for L1 and L3, which conducted theirs in the kitchen.

During the initial survey, indoor temperatures ranged from 25.7°C to 29.9°C. The thermal comfort survey revealed that most of the respondents felt warm or hot during the hottest week of summer 2024 based on 7-point ASHRAE scale, which included 60% of the responses. Although the outdoor temperature decreased by approximately 7.24% during the final survey compared to the initial survey (mean daily temperature reduced from 21.68°C to 20.11°C), the resident of dwelling L2 still felt warm.

In contrast, the residents of dwellings L3 and L4 consistently perceived the room temperature as neutral across both visits, despite the temperature difference. This was likely due to the higher mean indoor temperature of 29.27°C observed in dwelling L2 during the first visit, compared to 25.65°C in dwelling L3 and 29.87°C in dwelling L4 during the survey.

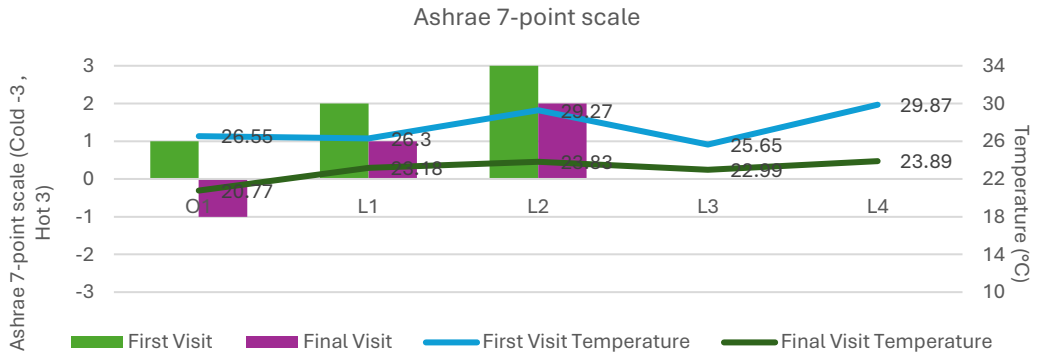


Figure 28: Ashrae 7-point scale among case studies in 2 visits with temperature

Interestingly, despite the highest mean indoor temperature being in dwelling L4, the occupant still felt neutral. On the other hand, it was found that the residents of dwelling O1 felt slightly cool during the final visit day with observed indoor temp of 20.77°C.

The Figure 29 revealed that 60% respondents preferred to be slightly cooler during the initial visit, while only 40% of respondents preferred to be cooler during the final visit. This was possibly due to the lower mean daily outdoor temperature of 20.11°C during the final visit, compared to the initial visit day that experienced a mean daily outdoor temperature of 21.68°C. dwelling L2 being consistent in both cases. Notably, L4 remained satisfied with the room temperature during both visits and did not desire any changes.

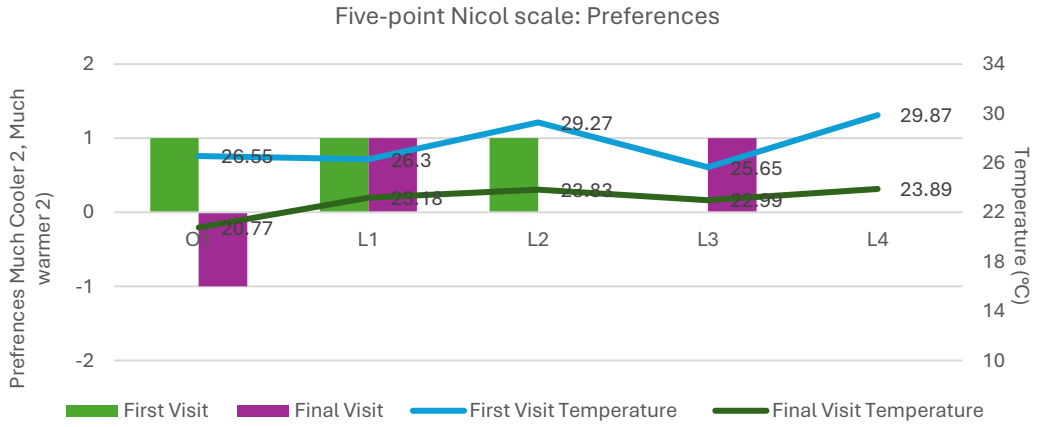
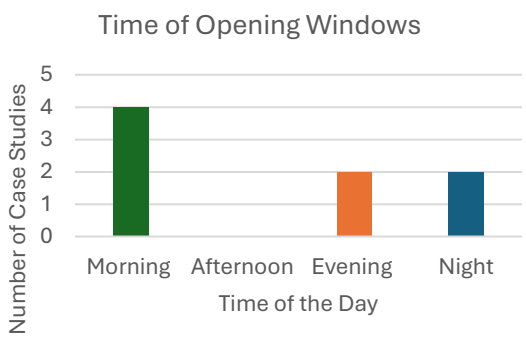


Figure 29: Five-Point Nicol Scale: Temperature Preferences among case studies in 2 visits with temperature

As shown in Figure 30a, 80% of occupants tend to open their windows in the morning, while only 40% do so in the evening or at night. However, Participant O1 rarely opened their window due to concerns about their cat escaping (Figure 30b). Similarly, residents of dwellings L2 and L3 kept their windows closed primarily due to concerns about security and noise.



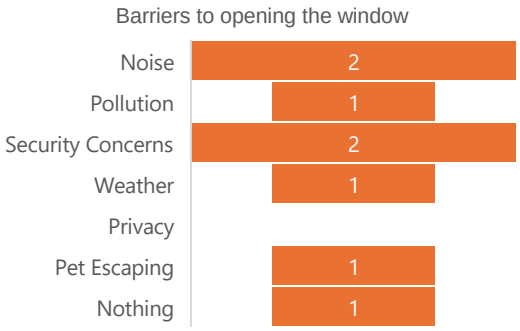


Figure 30a (Left): Time of Opening Windows

Figure 30b (Right): Barriers to Opening the Window

The survey responses in Figure 31 revealed that 80% of respondents adjusted their clothing, used blinds or curtains, and/or naturally ventilated their homes to keep themselves comfortable during the warm summer period. Interestingly, fan or air conditioning was not popular amongst the residents to improve the indoor thermal condition, possibly in the interest of keeping energy costs down.

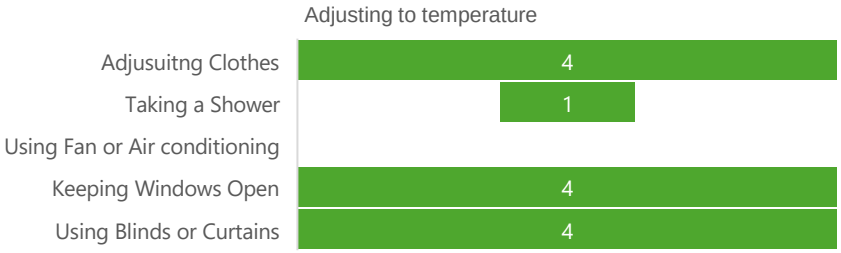


Figure 31: Methods Used by Participants to Adjust to Temperature

5.3.0 Monitoring

This section presents the results of monitoring outdoor and indoor temperature and relative humidity levels across five dwellings located in Oxford, South-West London, and North London between the 3rd and 18th of August 2024. Using HOBO data loggers, data was collected at 30-minute intervals to analyse temperature variations and assess indoor thermal comfort.

The monitoring focused on both outdoor conditions and indoor environments in key areas of the homes, specifically the living rooms and main bedrooms. Descriptive statistics, daily and hourly temperature profiles, and comparative analyses are provided to understand the thermal performance of the dwellings during the monitoring period.

5.3.1 Outdoor Monitoring Results: Temperature and Relative Humidity

Outdoor temperature and relative humidity were monitored at the outdoor spaces of dwellings O1, L1, and L2 between 3rd and 18th August 2024 at 30-minute intervals using a HOBO MX2301 data logger.

Figure 32 illustrates the actual outdoor daily temperature variations across three locations—Oxford, South-west London, and North London during this period.

Southwest and North London consistently recorded the highest temperatures throughout this period.

On the other hand, Oxford maintained the coolest temperatures, generally remaining below 22°C for most of the days, with some fluctuations observed on August 10th and 12th. Notably, all locations experienced a slight increase in temperature around August 12th, followed by a gradual decline towards the end of the monitoring period.

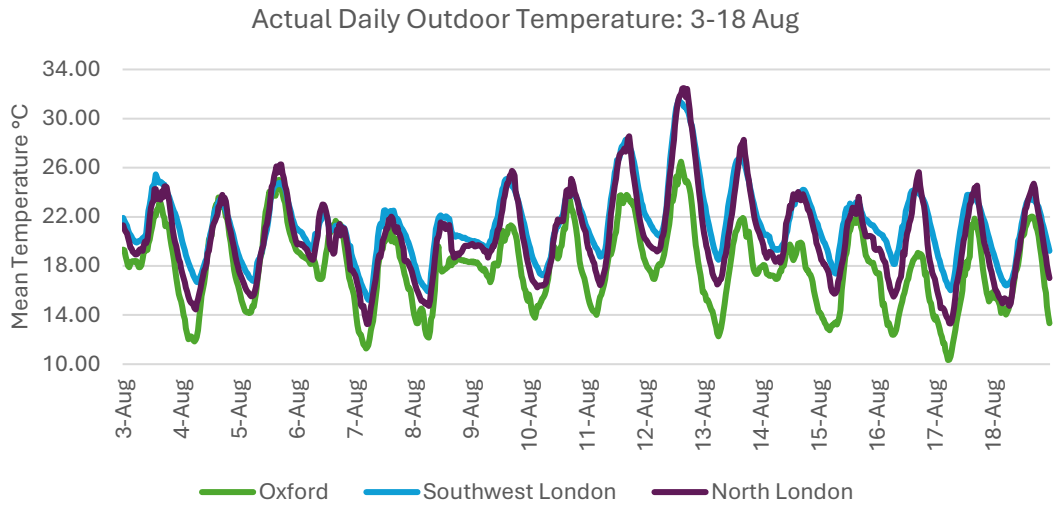


Figure 32: Actual Daily Outdoor Oxford, Southwest and North of London Temperature from 3 to 18 of August

Figure 33 shows the mean hourly temperature during the monitoring period. As expected, outdoor temperatures peak between 16:00 and 17:00 before steadily decreasing until around 6:00 in the morning.

This then rises again towards the next afternoon peak. In Oxford, humidity peaks in early morning with 80%, dips until 16:00, and rises again, while the other locations show less variation in humidity.

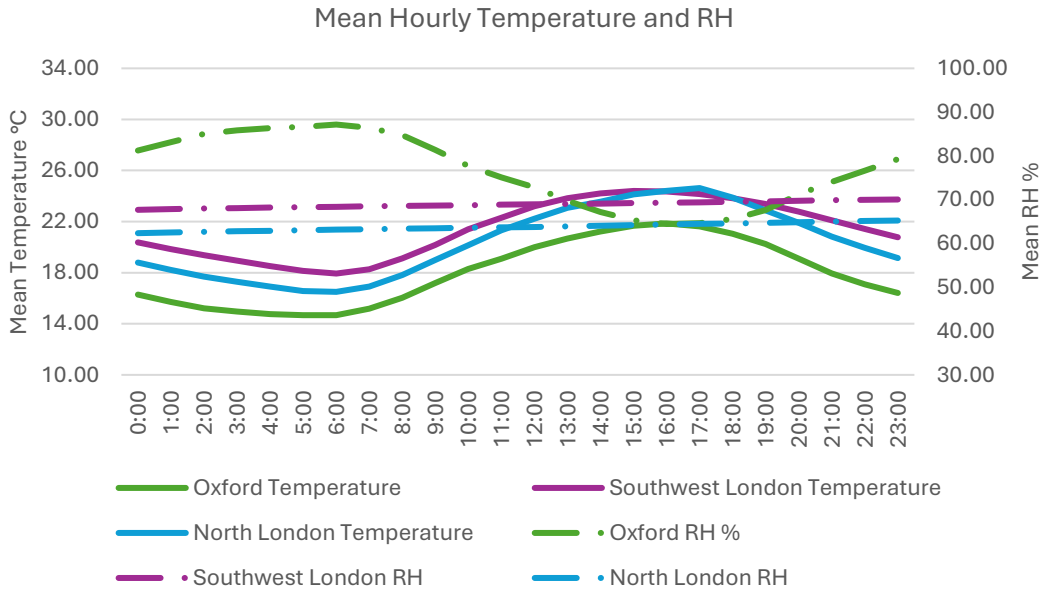


Figure 33: Mean Hourly Outdoor Oxford, southwest and north London Temperature from 3 to 18 of August

5.3.2 Indoor Monitoring Results: Temperature and Relative Humidity (RH)

The indoor temperature and RH were monitored continuously across the five case study dwellings in the living room and the main bedroom between 3rd and 18th August 2024 using HOBO UX-100-003 data loggers at 30-minute intervals. The indoor temperatures in each case study were monitored at two key locations: the living room and the main bedroom.

Indoor environment in Living Rooms

Table 17 presents descriptive statistics of indoor temperature and RH levels, along with mean daily profiles for the living rooms of five dwellings. In 80% of the homes, the average living room temperature was around 24°C. O1 recorded the highest maximum actual hourly indoor temperature (32.31°C), while L1 in Southwest London had the lowest minimum (19.89°C). O1 also had the highest humidity levels, with the highest mean RH both indoors (59.12%) and outdoors (76.64%).

Table 17: Descriptive Statistics of indoor living room temperature and RH levels (red text indicates maximum recorded temperature for the dwellings across the monitoring periods).

Dwelling ID	Orientation Monitored Living Room	Living room Temperature °C			Living room Relative Humidity %			Outdoor Temperature°C			Outdoor Relative Humidity %		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
L1	E	19.89	27.12	24.23	34.82	75.19	56.94	15.24	31.61	21.37	46.64	86.18	68.90
L2	W/E	21.75	28.10	24.93	31.61	62.57	50.36						
L3	NE	22.81	27.96	24.42	38.72	66.88	51.36	13.26	32.48	20.32	38.12	86.89	63.79
L4	S	22.47	27.34	24.71	38.23	66.85	54.65						
O1	SE	20.32	32.31	22.96	39.28	77.71	59.12	10.34	26.49	17.96	45.94	97.36	76.64

Figure 34 shows the daily living room temperatures, with O1 generally being the coolest, except for a brief spike from August 12th to 14th. In contrast, dwelling L2 consistently recorded the highest temperatures, staying near or above 26°C for most of the period..

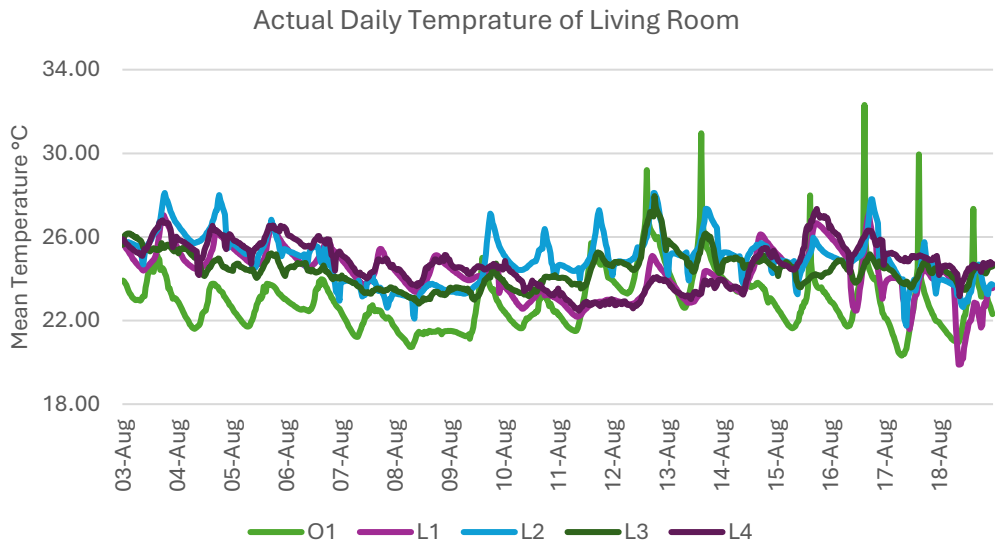


Figure 34: Actual Daily indoor Temperature Trends in the Living Room (August 3-18)

The following figures (35-38) show hourly mean temperature variations in the living rooms. Since outdoor temperatures differed across locations, each figure corresponds to the outdoor temperature for that specific site.

Figure 35 illustrates the hourly mean temperature and RH for dwelling O1 in Oxford, along with outdoor conditions. The indoor temperature in dwelling O1 (Oxford) stays fairly stable, ranging from 21°C to 24°C, with a brief afternoon peak near 26°C when outdoor temperatures reach around 22°C. Every day at 3 PM, a noticeable spike occurs, likely due to direct sunlight hitting the monitor through a skylight. O1's indoor RH remains steady between 60% and 70%, with small daytime increases and evening declines, in contrast to the larger fluctuations seen outdoors.

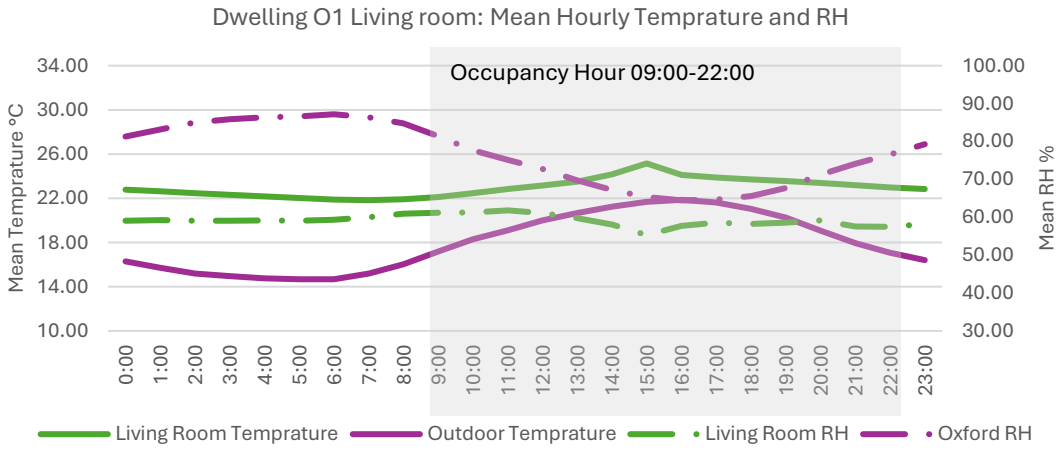


Figure 35: Mean Hourly Livingroom Temprature of O1 case study in Oxford from 3 to 18 August

Figure 36 shows the indoor and outdoor living room temperatures, as well as RH, for dwelling L1 in southwest London. The indoor temperatures in dwelling L1 remain stable, ranging between 22°C and 25°C throughout the day, while outdoor temperatures fluctuate more, peaking around noon and early afternoon. The RH in both indoor and outdoor conditions stays relatively constant, with no significant fluctuations. This stability in indoor temperature can be attributed to a good level of airtightness and insulation, which help maintain a consistent indoor environment despite external temperature variations.

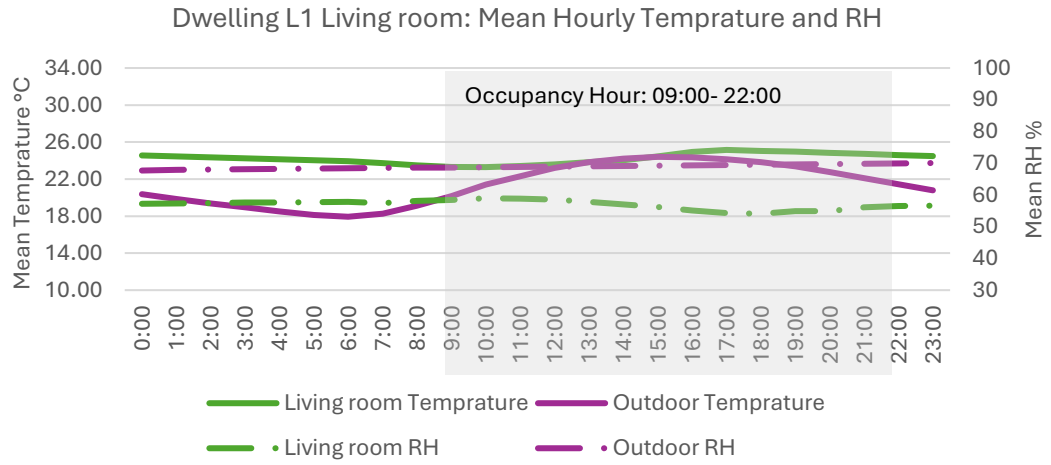


Figure 36: Mean Hourly Living room Temprature and RH of L1 case study in Southwest London from 3 to 18 August

Figure 37 presents mean indoor living room temperature in dwellings L2, L3 and L4 located in north London. While both L3 and L4 show relatively stable temperatures around 24°C throughout the day, dwelling L2 exhibits less stability, with temperatures fluctuating more significantly and particularly peaking in the afternoon around 18:00.

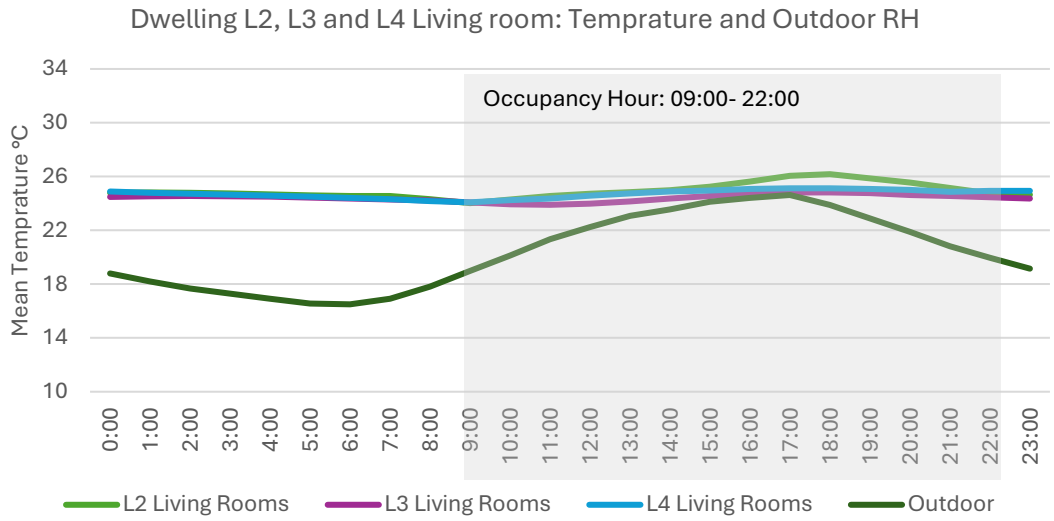


Figure 37: Mean Hourly indoor Living room Temprature of L2, L3 & L4 case studies and mean hourly outdoor temperature in North London from 3rd to 18th August

Figure 38 shows the indoor and outdoor RH, with most data remaining stable. L2 and L3 generally stay below 50%, while L4 consistently falls between 50% and 60%.

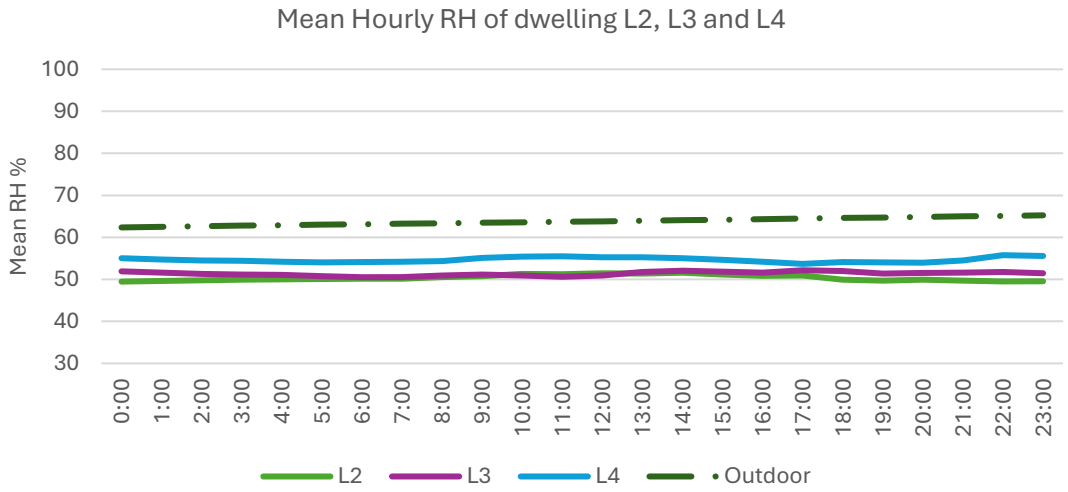


Figure 38: Mean Hourly indoor RH in the Living Rooms and Mean Hourly Outdoor RH of dwellings L2, L3, and L4 Case Studies in North London (3rd to 18th August)

Indoor environment in Bedrooms

Table 18 presents the descriptive statistics for indoor temperature, relative humidity, and mean daily profiles observed in the bedrooms of the five dwellings. The highest mean bedroom temperature was 25.52°C in L4, while the lowest was 23.17°C in L3. L3 also recorded the highest mean RH at 55.20%. The highest mean hourly temperatures were observed in L4 and O1, at 30.68°C and 30.17°C, respectively.

Table 18: Descriptive Statistics of indoor bedroom temperature and RH levels

Dwelling ID	Orientation Monitored Bedroom	Bedroom Temperature °C			Bedroom Relative Humidity %			Outdoor Temperature °C			Outdoor Relative Humidity %		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
L1	W	22.90	27.68	24.87	42.06	64.98	54.99	15.24	31.61	21.37	46.64	86.18	68.90
L2	W/E	22.71	27.46	24.92	32.74	61.87	48.57						
L3	SW	22.02	25.05	23.17	40.53	71.33	55.20	13.26	32.48	20.32	38.12	86.89	63.79
L4	S	23.12	30.68	25.52	37.96	58.96	50.41						
O1	NW/SE	20.63	30.17	24.28	39.28	68.23	52.01	10.34	26.49	17.96	45.94	97.36	76.64

Figure 39 shows the actual daily bedroom temperatures across all dwellings. As illustrated in Figure 13, L3 consistently had the coolest bedroom temperatures, while L1 was generally one of the warmest.

Both O1 and L1 experienced notable temperature spikes on August 13th. The lowest temperature, 21.99°C, was observed in the bedroom of dwelling O1 at 7 AM on August 4th. In contrast, the highest temperature, 30.17°C, was recorded in the same bedroom at 9:00 PM on August 12th, just before the onset of sleeping hours.

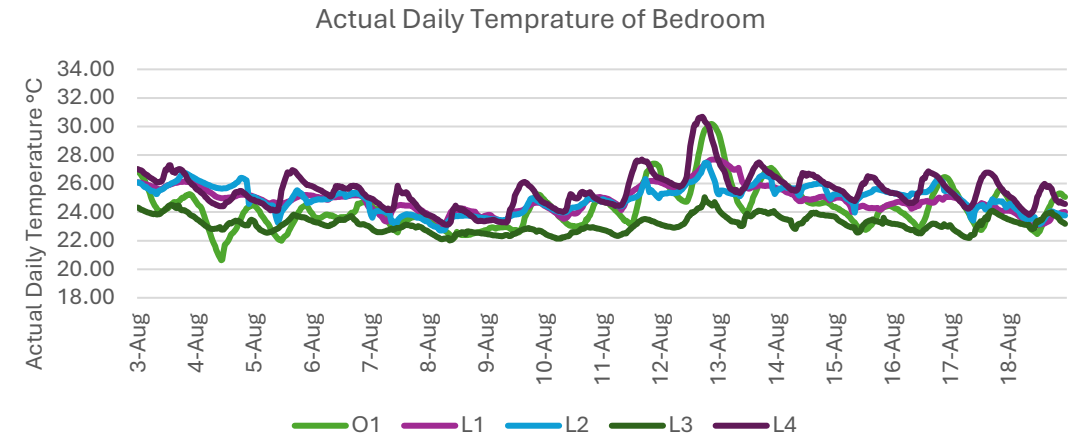


Figure 39: Daily Temprature among all case studies

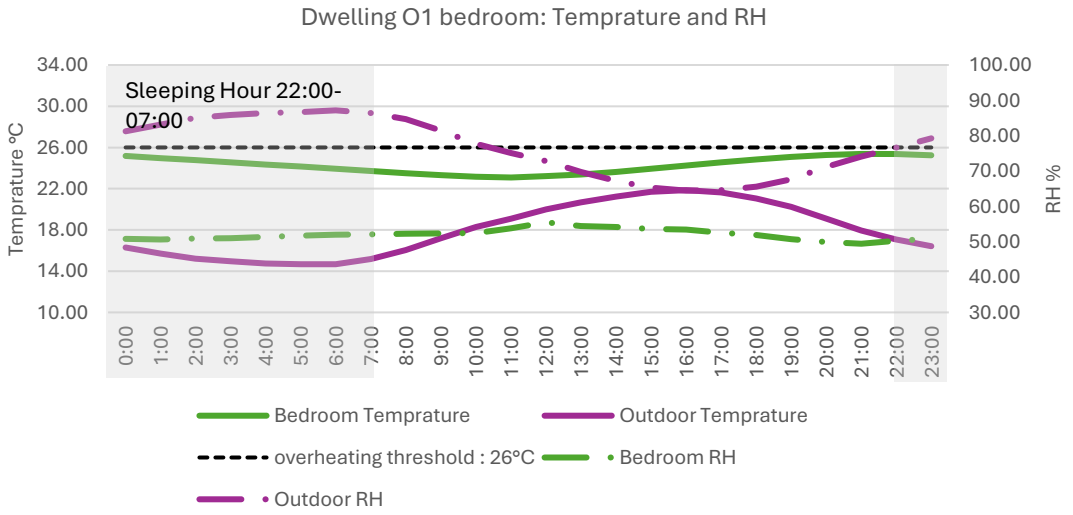


Figure 40: Mean Hourly Bedroom Temprature of O1 case study in Oxford from 3 to 18 August

Figures 40 to 42 present the mean hourly indoor temperatures recorded in the bedrooms of the five dwellings. Notably, the mean hourly temperatures remained below the recommended 26°C during the sleeping hours (22:00–07:00). Figure 40 presents the hourly indoor bedroom temperature and RH of dwelling O1, along with its outdoor temperature and RH. The bedroom in O1 (Oxford) maintains a stable temperature between 22°C and 24°C, despite outdoor temperatures rising significantly during the day, with a slight dip around 11 AM. The bedroom temperature consistently stays below the 26°C overheating threshold.

Figure 41 shows the L1 bedroom temperatures in southwest London. Indoor temperatures range from 22°C to 25°C, with a slight afternoon peak, consistently staying below the 26°C overheating threshold, ensuring thermal comfort.

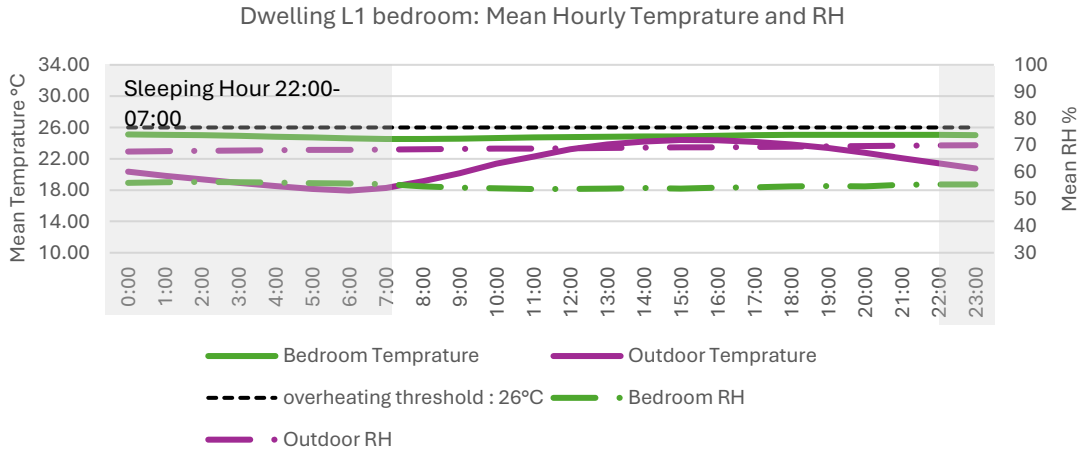


Figure 41: Mean Hourly Bedroom Temprature of L1 case study in southwest London from 3 to 18 August

Figure 42 shows the bedroom temperatures for dwellings L2, L3, and L4 in North London. All three bedrooms maintain temperatures between 22°C and 26°C, with L4 showing slightly more variation. L4 briefly exceeds 26°C between 13:00 and 18:00, during non-sleeping hours. Despite outdoor temperatures peaking around 17:00, L3's bedroom temperature remains stable and is even lower than the outdoor temperature between 14:00 and 18:00.

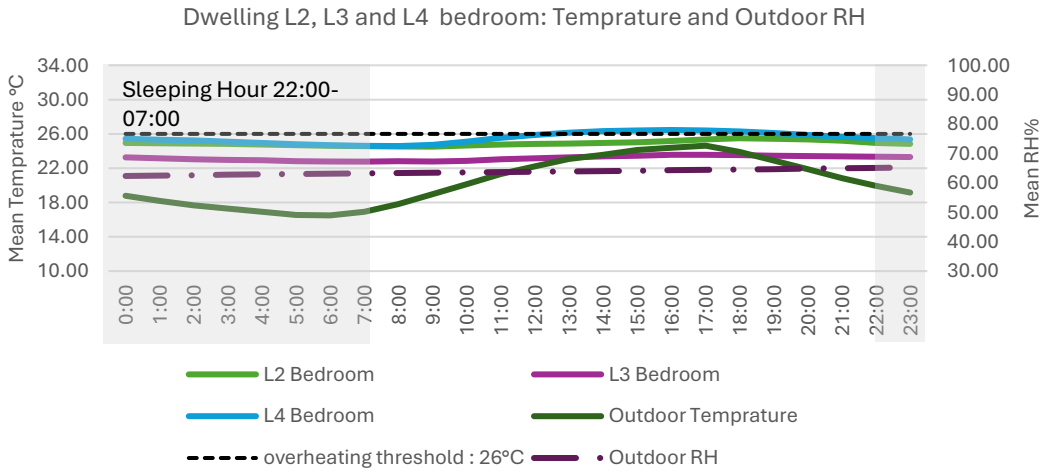


Figure 42: Mean Hourly Bedroom Temprature of dwellings L2, L3, and L4 case study in the north of London from 3 to 18 August

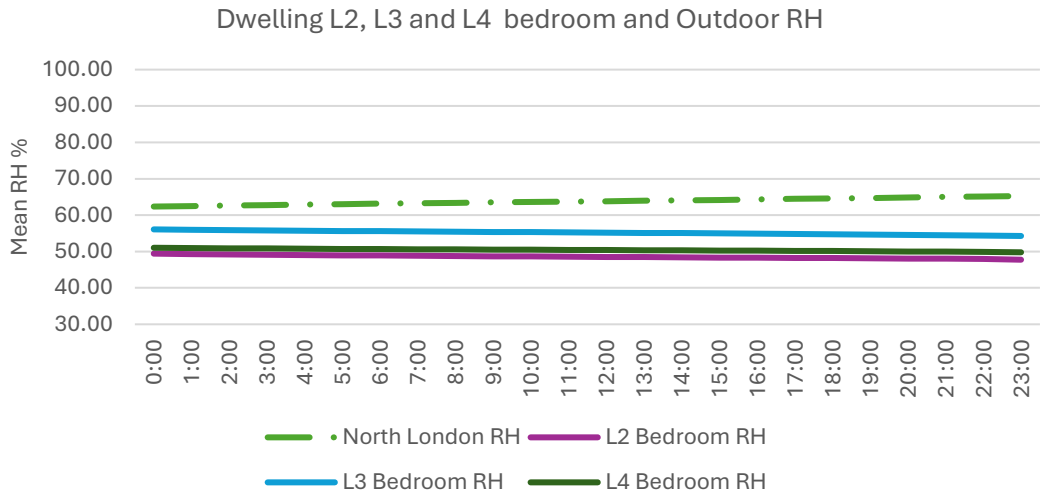


Figure 43: Mean Hourly Bedroom RH of dwellings L2, L3, and L4 case study in the north of London from 3 to 18 August

5.4.0 Overheating Risk Assessment

This section presents an overheating risk assessment conducted to understand the thermal performance of the case study homes during the warm summer period. The assessment was undertaken based on the criteria outlined in CIBSE TM52 and CIBSE TM59, covering the period between 3rd and 18th August 2024.

5.4.1 CIBSE TM52

All CIBSE TM52 criteria were applied across all case studies to evaluate the risk of overheating. The results for each criterion are detailed below:

Criterion 1 (Hours of Exceedance): All case studies met this first criterion of TM52; however, it is important to note that the study was limited to 16 days.

Criterion 2: While most case studies complied with this criterion, the bedroom in L4 failed on August 11th and 12th, indicating significant overheating on those days.

Criterion 3: Upper Limit Temperature (T_{upp}) All case studies successfully passed this criterion as well.

Table 19: TM52 Results for 5 Case Studies in 3 Criteria

	Criterion 1		Criterion 2		Criterion 3	
	Living Room	Bedroom	Living Room	Bedroom	Living Room	Bedroom
O1	Pass	Pass	Pass	Pass	Pass	Pass
L1	Pass	Pass	Pass	Pass	Pass	Pass
L2	Pass	Pass	Pass	Pass	Pass	Pass
L3	Pass	Pass	Pass	Pass	Pass	Pass
L4	Pass	Pass	Pass	Fail	Pass	Pass

Table 20 presents the highest temperatures recorded in living rooms during the occupancy hours (09:00 to 22:00) and in bedrooms during sleeping hours (22:00 to 07:00). Dwelling O1 had the highest recorded temperatures, reaching 32.17°C in the living room during occupancy hours, and 30.1°C during sleep time in the bedroom.

In contrast, the L3 case study maintained the lowest maximum temperature at 24.7°C, staying comfortably below the overheating threshold throughout the monitored period.

Table 20: Maximum Temperatures Monitored During Occupancy and Sleeping Hours in Living Rooms and Bedrooms Across Case Studies

Case Study	O1	L1	L2	L3	L4
Maximum temeprature monitored during occupancy hours in living room (°C)	32.31	27.12	28.10	27.96	27.34
Maximum temeprature monitored during sleeping hours in bedroom (°C)	30.10	27.68	26.53	24.71	28.80

All the TM 52 criteria were met, possibly due to the limited monitoring period; therefore, the CIBSE TM59 overheating risk assessment was also undertaken to gain a more comprehensive understanding of the overheating risk.

5.4.2 CIBSE TM59

TM59 sets specific criteria to ensure thermal comfort in bedrooms during sleeping hours. If the temperature exceeds 26°C for 33 hours or more, the building fails to meet this standard (Bonfigli et al., 2017).

It's important to note that TM59 is intended for annual overheating analysis, with the 33-hour threshold applying to the entire year. As shown in Table 21, the bedrooms of dwellings O1, L2, and L4 exceeded this 33-hour limit with 47,34 and 55 times respectively during the monitoring period.

Consequently, these 60% of case studies failed to meet the TM59 overheating criteria for maintaining comfortable sleeping conditions, as they surpassed the annual limit of 32 hours of overheating during sleeping hours within the monitoring period.

In contrast, L3 had no hours above 26°C during this time. Notably, dwelling L2 recorded 18 hours of overheating in this short span, suggesting that it could potentially face significant overheating if evaluated on an annual basis.

Table 21: TM59 Results for 5 Case Studies in Criteria B

Case Study	O1	L1	L2	L3	L4
Hours Above 26°C	47	34	18	0	55

5.5.0 Simulation

Simulations were conducted using Design Builder (DB) software, chosen for its advanced capabilities and compatibility with the Energy Plus engine, to identify strategies for improving indoor thermal comfort and energy efficiency. To ensure accuracy, base case models were validated against actual measured data. Simulations were conducted from July 16 to 22, during the hottest period according to Met Office data (*Met Office*, n.d), to assess performance under peak summer conditions when overheating risk is highest.

Passive design strategies, including internal shading, external shading devices such as overhangs, side fins, and louvres, and glazing options (double or triple glazing), were applied to enhance thermal comfort by mitigating overheating through controlling

solar gains and promoting natural ventilation (Lewis, 2017). Additional measures, such as the impact of Mechanical Ventilation with Heat Recovery (MVHR) and occupant behaviour based on thermal comfort surveys, were also explored. For example, night-only ventilation during sleeping hours (22:00-07:00) was tested to assess its effectiveness in reducing indoor temperatures, particularly during summer when outside temperatures are lower than indoor temperatures (Traynor, 2019). Research by Memon et al. demonstrates that triple vacuum glazing can be highly effective in retrofitting solid wall dwellings, significantly enhancing energy efficiency and reducing the demand for space heating (Memon, 2014, 2015). A detailed list of these measures and their configurations is provided in Table 22. Three dwellings L1, L2, and O1 were modelled. Specific rooms were selected based on overheating challenges and occupant thermal comfort survey: O1's living room had significant solar gains resulting in the highest recorded temperatures; L2's living room, with three large west-facing windows, was uncomfortably hot as reported by the occupant; L2's bedroom was also modelled due to overheating risk concerning an elderly occupant; and L1's bedroom was included because it experienced overheating according to the TM59 assessment.

Table 22: Measures and their configurations in Simulation Models

Internal Shading	Blinds Opening Behavior	Window Type	Adjustable External Shading	Window Opening Behavior	Mechanical Ventilation	Reduced glazing Size	Insulation
Blindshigh-reflectance, low-transmittance shades	Morning Afternoon Evening Most of the Day 09:00-18:00	Double Triple	Overhang Overhangs and Side Fins Louvres	Day 09:00 - 18:00 Night 22:00-07:00 All Day	On Off	Skylight Length Windows Height	Reducing U value Adding Insulation

5.5.1 Climate Data

EPW files, sourced from Energy Plus weather data, were utilized in DB to provide average outdoor climate information for the simulations. For the Oxford case study, the Wallingford EPW weather file was employed, as specific data for Oxford was unavailable. In contrast, the two dwellings L1 and L2 located in London, used Central London EPW data. These weather files were essential in delivering precise environmental inputs, ensuring the accuracy of the energy simulations.

5.5.2 Simulation Validation

All models were calibrated using the daily mean temperature data from the first week of the monitoring period (3rd to 10th August), with a difference percentage of less than 15% as shown in Table 23a and 23b. This calibration was applied to the base case model using the original building characteristics to ensure accurate representation and comparison throughout the analysis. The first week of monitoring was chosen for calibration due to its higher temperature trends compared to the second week. The complete calibration data and detailed dates are provided in Appendix D.

Difference percentage:

$$\frac{(Monitored\ Temperatrue - Opertive\ Temperature)}{Average\ of\ Monitored\ and\ \ Operative\ temprature} \times 100$$

Table 23a (Left): Calibration of DB Models for temperature of Dwellings O1 and L2 Living Rooms

Date	Difference Percentage of Mean Daily Temperature of Living room O1 %	Difference Percentage of Mean Daily Temperature of Living room L2 %
3-Aug	5.53	3.72
4-Aug	2.12	3.70
5-Aug	0.15	0.75
6-Aug	4.64	0.68
7-Aug	9.30	3.63
8-Aug	8.32	1.10
9-Aug	3.21	6.90
10-Aug	12.56	6.11

Table 23b (Right): Calibration of DB Models for temperature of dwellings L1 and L2 bedrooms

Date	Difference Percentage of Mean Daily Temperature of Bedroom L1 %	Difference Percentage of Mean Daily Temperature of Bedroom L2%
3-Aug	9.37	4.94
4-Aug	6.81	4.03
5-Aug	3.90	2.08
6-Aug	5.12	2.05
7-Aug	4.28	0.24
8-Aug	5.65	0.80
9-Aug	9.70	6.47
10-Aug	10.87	7.32

5.5.3 Shading Calculation

For each case study, various types of external shading such as overhangs, side fins, and louvres were meticulously calculated and applied as illustrated below. These passive design strategies were selected to effectively manage solar gain, particularly for south, east, and west-facing windows (Porritt et al., 2012; Shading for Housing Design Guide for a Changing Climate, n.d.). Movable shading devices can be adjusted to block excessive solar radiation and glare during the summer, while being removed or retracted in winter to maximize solar gain and enhance natural daylighting. Each shading option was tested in the simulation model to identify the most effective solutions for reducing overheating.

Overhangs: $H = \frac{D * \tan A}{\cos(Z-N)}$

Side Fins: $W = D\ x \tan\ (Z - N)$

Optimal Blade Angle (α) for Louvres: $\alpha = \frac{\theta_{Summer} + \theta_{Winter}}{2}$ (Ngungui & Kitio, 2018)

Table 24 presents the detailed data for each window, including the projection of shading devices, the depth of side fins, and the optimal blade angle for louvres.

Table 24: Shading Calculation Parameters for Windows and Shading Devices in O1 and L2 Living Rooms, and L1 and L2 Bedrooms

	Window	Latitude	Longitude	A Shadow Angle (θ Summe)	θ Winter	Z Solar Azimuth	N Window Azimuth	H Window Height m	D Shading Device Projection m	W Side Fins Depth m	α Louver Blade Angle
O1 Living Room	W 1	51.74407	-1.226295	58.39°	13.23°	147.86°	300°	2.09	1.14	0.6	35.8 °
	W 2							1.1	2.06	0.32	
L2 Living Room	W 1	51.606071	-0.081884	60.04°	14.9°	151.21°	270°	1.3	0.36	0.65	37.5°
	W 2							2.45	0.68	1.24	
	W 3							2.3	0.63	1.15	
	W 4						90°	1.52	0.42	0.77	
L1 Bedroom	W 1	51.407223	-0.288136			151.21	270°	1.37	0.27	0.49	
L2 Bedroom	W 1	51.606071	-0.081884			151.21°	270°	1.1	0.3	0.54	
	W 2						90°				

5.5.4 Living room simulation

Passive design strategies such as external shading and natural ventilation were applied to the simulation models of the living rooms in L2 and O1 to evaluate their

impact on reducing solar gain and improving thermal comfort during the period July 16th and 22nd. Table 25 summarizes the various scenarios tested for the living rooms of dwellings O1 and L2 to mitigate overheating and improve thermal comfort during summer. Each scenario, only the specific measure being tested was changed, while other conditions remained unchanged to isolate its impact.

Table 25: Scenarios Tested for Living Rooms in Dwellings L1 and L2 to Mitigate Overheating

Case Study	Scenarios	Internal Shading	Window Type	Adjustable External Shading	Window Opening Behavior	Mechanical Ventilation	Reduced glazing Size	Reducing U value
O1 Living room	Base Case	None	Double	None	Morning 07:00-11:00	MVHR	Same	Same
	A	high-reflectance, low-transmittance shades 09-18, internal blinds for skylight	Double	None	Morning 07:00-11:00	MVHR	Same	Same
	B	None	Triple	None	Morning 07:00-11:00	MVHR	Same	Same
	C	None	Double	None	Night 22:00- 07:00	MVHR	Same	Same
	D	None	Double	None	Morning 07:00-11:01	None	Same	Same
	E	None	Double	None	Day 07:00-18:00	MVHR	Same	Same
	F	None	Double	Overhang 1.14m & 0.6m	Morning 07:00-11:01	MVHR	Same	Same
	G	None	Double	Side fins 0.6m & 0.32m	Morning 07:00-11:01	MVHR	Same	Same
	H	None	Double	Louvre 0.18 m, 38°	Morning 07:00-11:01	MVHR	Same	Same
	I	None	Double	None	Morning 07:00-11:01	MVHR	Biggest skylight Length from 2m to 1m	Same
	J	None	Double	None	Morning 07:00-11:01	MVHR	Same Size	Wall: 0.15 W/m²K Roof:0.12 W/m²K
L2 Living room	Base Case	None	Triple	None	Morning, Evening & Night 17:00-10:00	MVHR	Same	Same
	A	high-reflectance, low-transmittance shades 09-18	Triple	None	Morning, Evening & Night 17:00-10:00	MVHR	Same	Same
	B	None	Double	None	Morning, Evening & Night 17:00-10:00	MVHR	Same	Same
	C	None	Triple	None	Night 22:00- 07:00	MVHR	Same	Same
	D	None	Triple	None	Morning, Evening & Night 17:00-10:00	None	Same	Same
	E	None	Triple	None	Day 07:00-18:00	MVHR	Same	Same
	F	None	Triple	Overhang W1: 0.36m, W2: 0.68m, W3: 0.63m & W4: 0.42	Morning, Evening & Night 17:00-10:00	MVHR	Same	Same
	G	None	Triple	Side fins 0.65m, 1.24m, 1.15m & 0.77m	Morning, Evening & Night 17:00-10:00	MVHR	Same	Same
	H	None	Triple	Louvre 0.18 m, 38°	Morning, Evening & Night 17:00-10:00	MVHR	Same	Same
	I	None	Triple	None	Morning, Evening & Night 17:00-10:00	MVHR	Window 3 height from 2.3m to 1.45m	Same

As illustrated in Figures 44a and 44b, a significant amount of natural light enters both the kitchen and living room areas in dwelling L2. Figure 45a and 45b highlights the extensive glazing in the O1 living room, which contributes to the high levels of natural light observed and may lead to excessive solar gain, ultimately resulting in overheating.

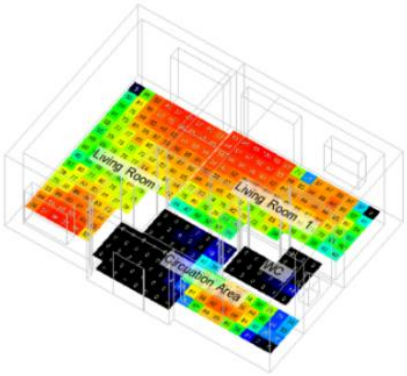


Figure 44a (Left): Annual Daylighting of dwelling L2 Ground Floor Base Case Model

Figure 44b (Right): Living room of dwelling L2

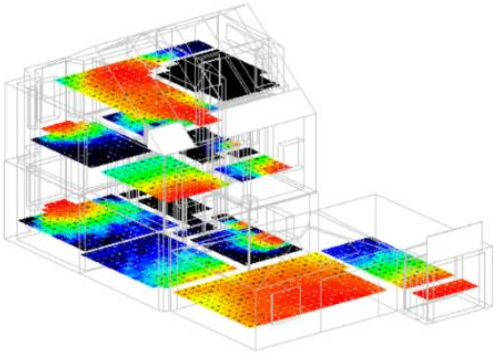


Figure 45a (Left): Annual Daylighting of dwelling O1 Base Case Model

Figure 45a (Right): Living room of dwelling O1

Table 25 presents the changes happened in indoor temperature in the living rooms of the dwellings O1 and L2. After the application of different scenarios to the base case model, it was revealed that after the application of the reflective blinds to the base case model, the dwelling O1 experienced a mean daily indoor temperature rise of 0.5°C in the living room, while the dwelling L2 experienced a reduction of 0.7°C in the living room after the application of reflective blind. Additionally, it was revealed that the application of natural ventilation from 7:00 to 18:00 to the base case model can reduce the mean daily indoor temperature by 1.12°C in the living room of dwelling O1. Additionally, the application of side fins to the southwest-facing side of the living room of the dwelling O1 could effectively reduce indoor temperature, while louvres provided the greatest temperature reduction in the living room of dwelling L2. Additionally, in both case studies, reducing the glazing dimensions contributed to a cooler indoor environment.

Table 25: Descriptive Statistics of Mean Indoor Living Room Temperature for Various Scenarios (16-22 July)

Case Study	Scenarios	Mean (°C)	Max (°C)	Min (°C)	Difference
O1 Living room	Base Case	26.17	32.87	22.00	-
	A	26.66	34.34	21.94	-0.49
	B	26.52	33.32	22.44	-0.35
	C	26.19	33.39	21.60	-0.02
	D	26.37	33.12	22.08	-0.20
	E	25.05	30.87	21.55	1.12
	F	24.27	26.92	22.08	1.90
	G	24.22	26.83	22.04	1.95
	H	25.14	29.96	21.47	1.03
	I	25.86	31.50	21.91	0.31
	J	25.29	32.41	22.46	0.88
L2 Living room	Base Case	24.03	30.47	21.39	-
	A	23.33	27.88	20.71	0.70
	B	24.10	31.81	21.34	-0.07
	C	24.66	31.79	21.67	-0.63
	D	24.09	30.57	21.43	-0.05
	E	24.59	31.50	21.42	-0.55
	F	23.52	28.63	21.15	0.51
	G	23.06	26.98	20.95	0.97
	H	23.03	27.11	20.86	1.01
	I	23.73	29.42	21.30	0.30

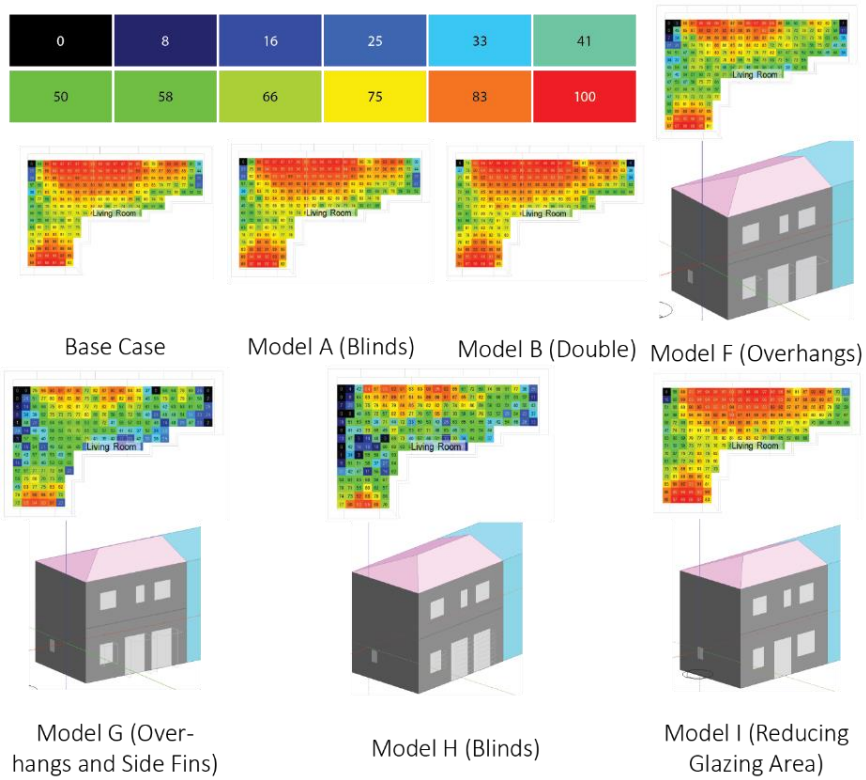


Figure 46: Impact of Different Scenarios on Annual Daylighting in the O1 Living Room

Figure 47 illustrates the effect of different scenarios on annual daylighting in the living room of dwelling O1, where solar gain remained consistent, likely due to the presence of skylights. In contrast, the L2 living room exhibited varying levels of solar gain under different scenarios. The base case recorded the highest solar gain, while Model H resulted the lowest.

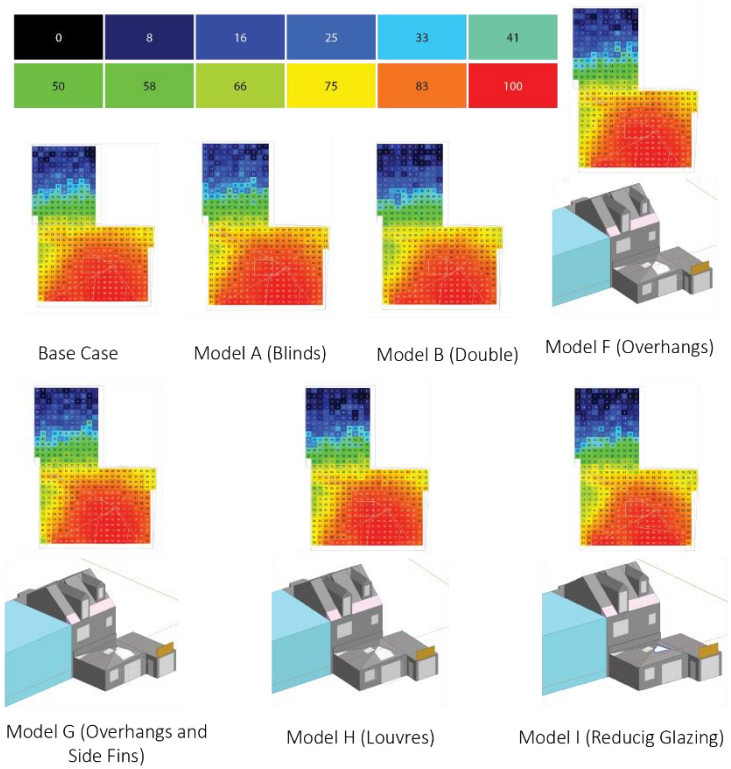


Figure 47: Impact of Different Scenarios on Annual Daylighting in the L2 Living Room

Optimal Models of Living rooms

In this section, the optimal models for the O1 and L2 living rooms were tested using scenarios that effectively reduced the mean temperature in each space. For the O1 living room, the optimal model incorporated natural ventilation during the day from 07:00 to 18:00 (Scenario E), the use of 0.6m and 0.32m side fins (Scenario G), a reduced glazing area by 1m2 (Scenario I), and lowering the U-value of the exterior walls from 0.2-0.3 W/m²·K to 0.15 W/m²·K (Scenario J). These strategies were chosen for their demonstrated positive impact on thermal comfort.

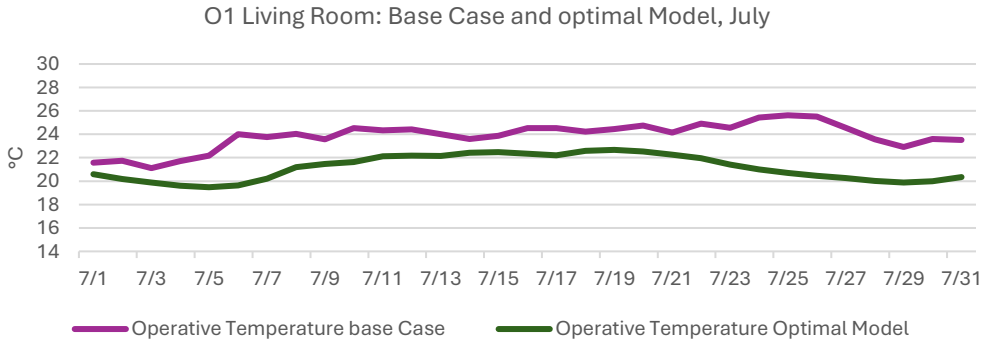


Figure 48: Daily Mean Operative Temperature for Base Case and Optimal Model in the O1 Living Room (July)

Figure 48 presents the changes happened on indoor temperature after the application of the optimal models to the base case. In the base case, the mean daily temperature reaches up to 26°C, while in the optimal model, it well remains below 23°C, highlighting the significant improvement in thermal performance. Table 27 shows the differences in temperatures, ranging from 1°C to 5°C.

Table 27: Difference Percentages of Base Case and Optimal Model of dwelling O1

Date	Operative Temperature Base Case °C	Operative Temperature Optimal Model °C	Differnece Temperature
7/1	21.57	20.59	0.98
7/2	21.73	20.18	1.55
7/3	21.11	19.87	1.24
7/4	21.70	19.61	2.08
7/5	22.18	19.48	2.70
7/6	24.00	19.64	4.36
7/7	23.75	20.21	3.54
7/8	24.04	21.18	2.85
7/9	23.58	21.45	2.12
7/10	24.52	21.62	2.91
7/11	24.32	22.12	2.20
7/12	24.41	22.17	2.24
7/13	24.02	22.15	1.86
7/14	23.59	22.43	1.16
7/15	23.86	22.48	1.38
7/16	24.54	22.34	2.20
7/17	24.53	22.20	2.33
7/18	24.22	22.58	1.64
7/19	24.46	22.67	1.79
7/20	24.76	22.52	2.24
7/21	24.16	22.25	1.90
7/22	24.90	21.97	2.93
7/23	24.56	21.41	3.15
7/24	25.41	20.99	4.42
7/25	25.62	20.69	4.93
7/26	25.50	20.46	5.04
7/27	24.56	20.25	4.31
7/28	23.58	20.00	3.58
7/29	22.93	19.87	3.06
7/30	23.59	20.00	3.59
7/31	23.52	20.34	3.18

In the L2 living room, significant temperature reductions were achieved using reflective blinds (Scenario A), louvres (Scenario H), and a reduced glazing area (Scenario I). These strategies were integrated into the optimal model, as illustrated in Figure 60, which shows the mean daily temperatures for the living rooms. In the base case, temperatures ranged from 22°C to 26°C, whereas in the optimal model, they were reduced to between 20°C and 24°C.

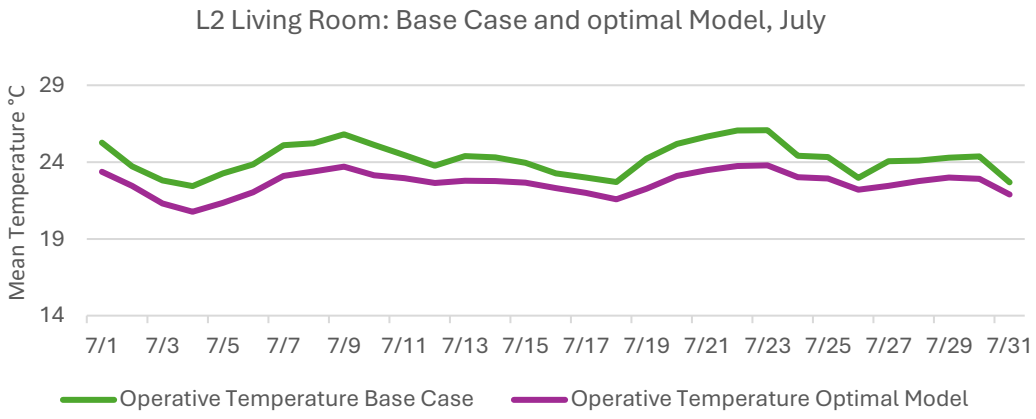


Figure 49: Operative Mean Daily Temperature for Base Case and Optimal Model in the L2 Living Room (July)

Table 28 shows the differences in temperatures in Base Case and Optimal Model of dwelling L2 Living room, ranging from 2°C to 9°C.

Table 28: Difference Percentages of Base Case and Optimal Model of dwelling L2

Date	Operative Temperature Base Case °C	Operative Temperature Optimal Model °C	Differnece Temprature
7/1	25.26	20.46	4.79
7/2	23.72	20.47	3.24
7/3	22.80	20.54	2.26
7/4	22.43	18.49	3.94
7/5	23.27	17.66	5.61
7/6	23.85	17.38	6.47
7/7	25.10	17.16	7.95
7/8	25.22	16.98	8.24
7/9	25.81	16.82	8.99
7/10	25.13	16.68	8.45
7/11	24.45	16.56	7.89
7/12	23.76	16.48	7.28
7/13	24.38	16.42	7.96
7/14	24.31	16.35	7.96
7/15	23.94	16.31	7.63
7/16	23.26	16.31	6.95
7/17	23.00	16.30	6.69
7/18	22.69	16.42	6.27
7/19	24.21	19.10	5.12
7/20	25.18	20.16	5.02
7/21	25.66	20.48	5.18
7/22	26.06	20.05	6.00
7/23	26.07	19.88	6.19
7/24	24.42	19.85	4.57
7/25	24.33	19.93	4.40
7/26	22.97	20.00	2.97
7/27	24.06	20.00	4.05
7/28	24.10	17.89	6.21
7/29	24.29	17.07	7.22
7/30	24.37	16.79	7.58
7/31	22.67	16.58	6.09

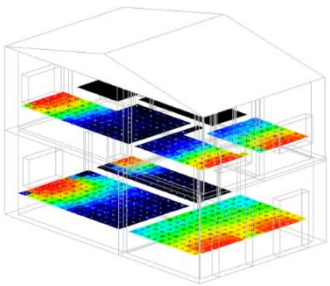
5.5.5 Bedrooms Simulation

In this section, the bedrooms in dwellings L1 and L2 were simulated under the same scenarios in Table 29 to evaluate their thermal performance from 16th to 22nd July. Different passive design strategies that are presented in Table 29 were applied to the base case models of the dwellings L1 and L2 to improve indoor thermal comfort and mitigate overheating risks. Different scenarios were applied to the base case model one at a time to evaluate their impact on indoor temperature, helping to identify the most effective option for improving the indoor environment during summer.

As shown in Figure 50a, the main bedroom in dwelling L1 receives minimal solar gain, indicating that this is unlikely to be the primary cause of the overheating issue. However, the room failed to meet the TM59 overheating criteria, suggesting that other factors, such as internal heat gains or inadequate ventilation, may be contributing to the problem. In contrast, the base case for dwelling L2, illustrated in Figure 50b, reveals that the main bedrooms have both west- and east-facing windows, which may significantly contribute to the risk of overheating without proper shading devices.

Table 29: Scenario Testing of Overheating Mitigation Measures for Bedrooms in Dwellings L1 and L2

Case Study	Scenarios	Internal Shading		Window Type	Adjustable External Shading	Window Opening Behavior	Mechanical Ventilation
L1 Bedroom	Base Case	Drapes semi open weave Medium		Triple	None	Morning & Night 21:00-10:00	None
	A	high-reflectance, low-transmittance shades 09:00-18:00		Triple	None	Morning & Night 21:00-10:00	None
	B	Drapes semi open weave Medium		Double	None	Morning & Night 21:00-10:00	None
	C	Drapes semi open weave Medium		Triple	None	Night 22:00- 07:00	None
	D	Drapes semi open weave Medium		Triple	None	None	MVHR
	E	Drapes semi open weave Medium		Triple	Overhang 0.27 m	Morning & Night 21:00-10:00	None
	F	Drapes semi open weave Medium		Triple	Side fins 0.49 m	Morning & Night 21:00-10:00	None
	G	Drapes semi open weave Medium		Triple	Louvre 0.18 m, 38°	Morning & Night 21:00-10:00	None
	H	Drapes semi open weave Medium		Triple	None	Day 07:00-18:00	None
L2 Bedroom	Base Case	Drapes semi open weave Medium	Drapes semi open weave Medium	Triple	None	Morning, Evening & Night 17:00-10:00	MVHR
	A	lectance, low-transmittance shades 09:(		Triple	None	Morning, Evening & Night 17:00-10:00	MVHR
	B	Drapes semi open weave Medium	Drapes semi open weave Medium	Double	None	Morning, Evening & Night 17:00-10:00	MVHR
	C	Drapes semi open weave Medium	Drapes semi open weave Medium	Triple	None	Night 22:00- 07:00	MVHR
	D	Drapes semi open weave Medium	Drapes semi open weave Medium	Triple	None	Morning, Evening & Night 17:00-10:00	None
	E	Drapes semi open weave Medium	Drapes semi open weave Medium	Triple	Overhangs W9 & W10: 0.3 m	Morning, Evening & Night 17:00-10:00	MVHR
	F	Drapes semi open weave Medium	Drapes semi open weave Medium	Triple	Side fins W9 & W10: 0.54 m	Morning, Evening & Night 17:00-10:00	MVHR
	G	Drapes semi open weave Medium	Drapes semi open weave Medium	Triple	Louvre W9 & W10: 0.18 m, 38°	Morning, Evening & Night 17:00-10:00	MVHR
	H	Drapes semi open weave Medium	Drapes semi open weave Medium	Triple	None	Day 07:00-18:00	MVHR



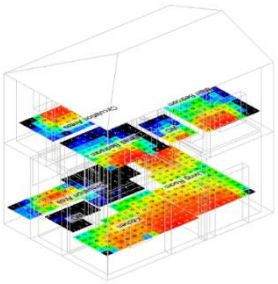


Figure 50a (Left): Annual Daylighting of dwelling L1 Base Case Model

Figure 50b (Right): Annual Daylighting of dwelling L2 Base Case Model

Table 30 presents the changes in the mean daily indoor temperature across the bedrooms of dwellings L1 and L2 after applying different passive design scenarios to the base case models. It is evident that scenarios B, C, and D were ineffective in both case studies, as they resulted in temperature increases of 0.15°C and 0.08°C in L1 and L2, respectively, under these conditions.

Table 30: Temperature Performance of Different Overheating Mitigation Scenarios for L1 and L2 Bedrooms

Case Study	Scenarios	Mean (°C)	Max (°C)	Min (°C)
L1 Bedroom	Base Case	21.89	25.17	20.17
	A	21.75	24.92	20.04
	B	21.92	25.29	20.16
	C	21.93	25.24	20.17
	D	22.04	25.40	20.17
	E	21.79	24.93	20.12
	F	21.72	24.82	20.07
	G	21.59	24.29	19.99
	H	22.00	25.25	20.17
L2 Bedroom	Base Case	23.40	27.94	21.18
	A	23.35	27.78	21.16
	B	23.81	28.68	21.29
	C	23.88	28.90	21.33
	D	23.48	27.99	21.33
	E	23.26	27.23	21.12
	F	23.12	27.21	21.07
	G	22.91	26.50	20.98
	H	23.79	28.59	21.22

Figure 51 illustrates the impact of different scenarios on annual daylighting in the L1 bedroom. As shown, Model G, which incorporates louvres, results in the lowest solar gain.

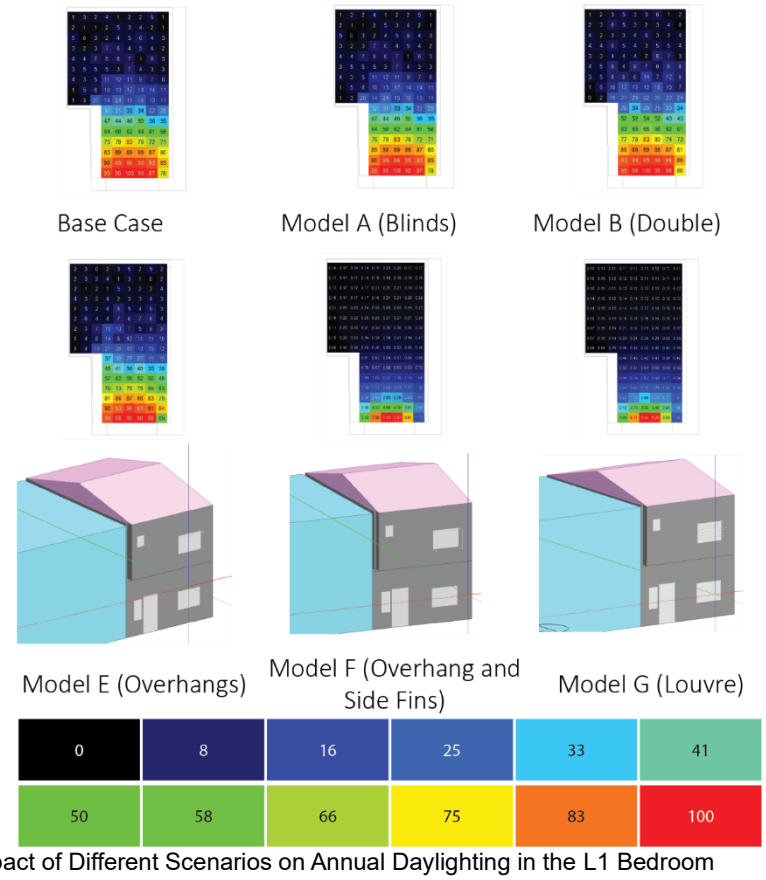


Figure 51: Impact of Different Scenarios on Annual Daylighting in the L1 Bedroom

Figure 52 shows the effect of different scenarios on annual daylighting in the L2 bedroom, like the L1 bedroom, with Model G (louvres) achieving the lowest solar gain.

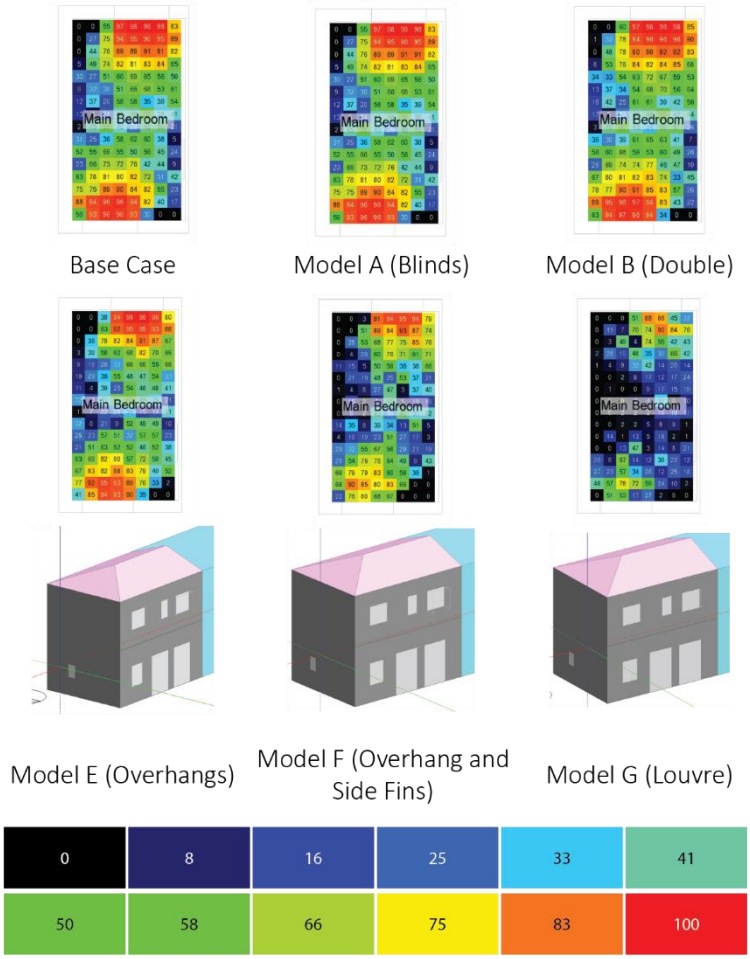


Figure 52: Impact of Different Scenarios on Annual Daylighting in the L2 Bedroom

Optimal Models of Bedrooms

For both bedrooms, Scenarios A (High reflective blinds) and G (18cm Louvres) were implemented as they effectively lowered temperatures during the period of July 16th to 22nd. Figures 53 and 54 show the changes in indoor temperature in the bedrooms of dwellings L1 and L2 respectively after the application of the optimal solutions to the base case models over the entire month of July.

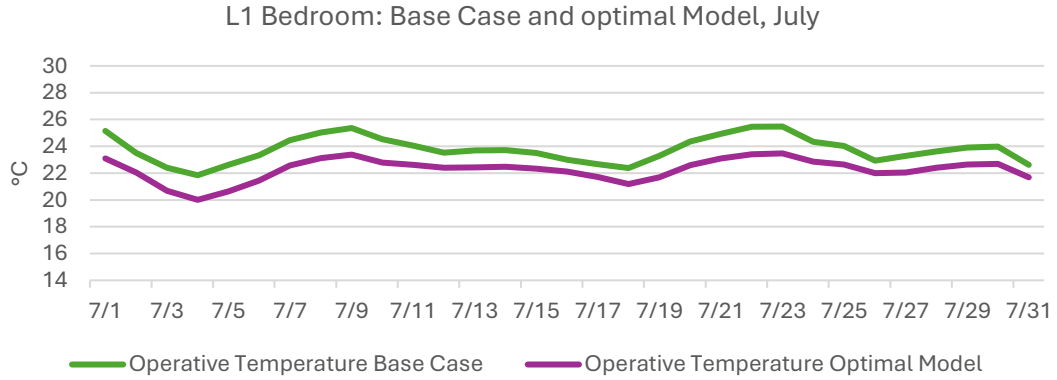


Figure 53: Daily Mean Operative Temperature for Base Case and Optimal Model in the L1 bedroom (July)

As shown in Figure 53, the base case model recorded temperatures ranging from 22°C to 26°C, while in the optimal model, temperatures ranged from 22°C to 24°C. Table 31 displays the differences in temperatures, varying from 0.5% to 4%.

Table 31: Difference Percentages of Base Case and Optimal Model of dwelling L1 Bedroom

Date	Operative Temperature Base Case °C	Operative Temperature Optimal Model °C	Differnece Temperature
7/1	23.48	22.91	0.57
7/2	22.36	21.93	0.43
7/3	21.24	20.74	0.50
7/4	20.64	20.12	0.52
7/5	21.14	20.46	0.69
7/6	21.71	21.11	0.60
7/7	22.79	22.13	0.66
7/8	23.36	22.77	0.59
7/9	23.72	22.99	0.73
7/10	22.97	22.65	0.32
7/11	22.64	22.38	0.26
7/12	22.36	22.18	0.18
7/13	22.40	22.21	0.19
7/14	22.40	22.26	0.15
7/15	22.30	22.10	0.21
7/16	22.03	21.88	0.15
7/17	21.67	21.47	0.21
7/18	21.37	20.95	0.42
7/19	21.93	21.33	0.59
7/20	22.73	22.12	0.61
7/21	23.25	22.66	0.58
7/22	23.67	22.98	0.69
7/23	23.69	23.09	0.60
7/24	23.01	22.67	0.33
7/25	22.87	22.46	0.41
7/26	22.06	21.87	0.19
7/27	22.14	21.90	0.24
7/28	22.39	22.12	0.28
7/29	22.70	22.30	0.40
7/30	22.72	22.43	0.28
7/31	21.75	21.55	0.20

As shown in Figure 54, the mean indoor temperatures ranged from 22°C to 26°C in the bedroom of the dwelling L2 base case model, while the mean indoor temperature, ranged from 20°C to 24°C after the application of the optimal models. Table 32 displays the percentage in temperatures, varying from 0.9°C to 2.1°C.

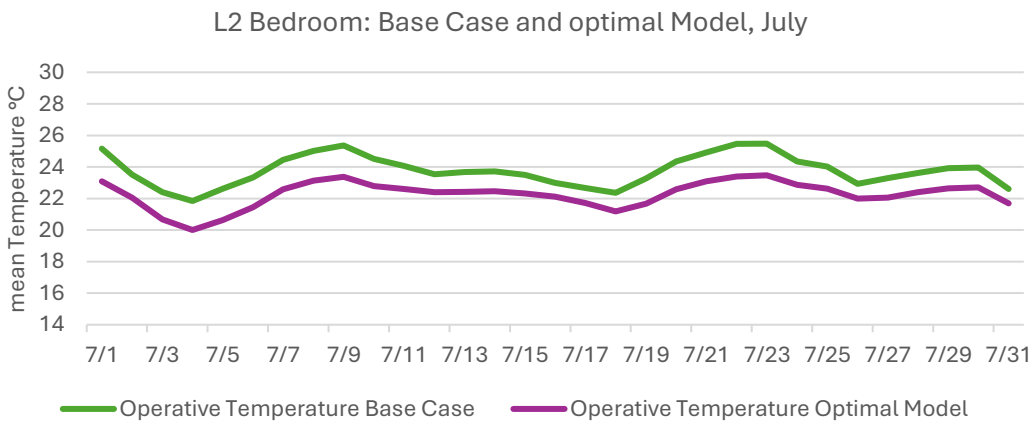


Figure 54: Daily Mean Operative Temperature for Base Case and Optimal Model in the L2 bedroom (July)

Table 32: Difference Percentages of Base Case and Optimal Model of dwelling L2

Date	Operative Temperature Base Case °C	Operative Temperature Optimal Model °C	Differnece Temperature
7/1	25.16	23.08	2.07
7/2	23.51	22.05	1.46
7/3	22.40	20.69	1.72
7/4	21.84	20.01	1.84
7/5	22.62	20.64	1.99
7/6	23.33	21.44	1.89
7/7	24.46	22.57	1.88
7/8	25.02	23.13	1.89
7/9	25.36	23.37	1.98
7/10	24.52	22.79	1.73
7/11	24.06	22.61	1.45
7/12	23.54	22.40	1.13
7/13	23.68	22.42	1.26
7/14	23.72	22.46	1.25
7/15	23.49	22.33	1.16
7/16	23.00	22.11	0.89
7/17	22.66	21.71	0.95
7/18	22.37	21.19	1.18
7/19	23.28	21.68	1.60
7/20	24.35	22.59	1.76
7/21	24.92	23.09	1.84
7/22	25.46	23.40	2.05
7/23	25.48	23.47	2.01
7/24	24.34	22.86	1.48
7/25	24.03	22.63	1.39
7/26	22.93	22.00	0.93
7/27	23.30	22.05	1.24
7/28	23.61	22.39	1.22
7/29	23.92	22.65	1.27
7/30	23.97	22.70	1.27
7/31	22.61	21.69	0.92

6.0 Discussion

The analysis of five retrofitted dwellings reveals a complex interplay between retrofit strategies, occupant behaviour, and overheating risks. Despite the implementation of energy efficiency measures and renewable energy systems, significant overheating persisted, especially in bedrooms. Passive design strategies such as external shading, enhanced insulation, and natural ventilation were effective in improving indoor thermal comfort during warm summers. These findings underscore the need for improved training and guidelines for emergent retrofits to balance energy efficiency with occupant comfort.

Overheating Despite Energy Efficiency Improvements

Overheating was prevalent even with enhanced energy performance, particularly in bedrooms where 60% of dwellings (O1, L1, and L4) failed to meet CIBSE TM59 standards, with some recording up to 55 hours of overheating. Causes included poor ventilation, excessive solar gains from west and southwest facades, and imbalanced retrofit processes. For instance, dwelling O1 experienced overheating in the bedroom and high temperature in living room, possibly because solar thermal and PV systems were installed before improving insulation and shading, adversely affecting indoor comfort. In contrast, the L2 living room passed the TM59 criteria with only 18 hours of overheating, likely due to the short monitoring period; however, an annual assessment

might result in failure. Applying passive design strategies significantly reduced indoor living room temperatures of dwelling L2, with simulations showing decreases of up to 9°C. This aligns with Porritt et al. (2012), who found that managing solar gain through shutters and permanent shading is particularly effective for west-facing windows. It is recommended that such louvres and shading devices be movable to avoid blocking solar gain in winter when additional warmth is needed.

Dwelling L1 exhibited stable temperature and relative humidity in the living room and bedroom, indicating efficient insulation and airtightness, yet it faced overheating with 34 hours recorded in bedrooms. This could be due to excessive loft insulation with aerogel. Extensive aerogel insulation improved energy performance but trapped heat due to poor ventilation, leading to overheating. This is consistent with findings by Oikonomou et al. (2012) and Psomas et al. (2016a), who noted that a lack of adequate ventilation, combined with increased airtightness, can lead to overheating. On the other hand, dwelling L3 did not experience overheating; the building's lower airtightness allowed for some natural ventilation.

This study uniquely demonstrates how the sequence and prioritization of retrofit interventions significantly affect overheating risks. Installing renewable energy systems without first addressing the building envelope and ventilation can compromise thermal comfort, underscoring the need for an integrated retrofit approach.

Role of Occupant Behaviour

Occupant behaviour critically affects the effectiveness of retrofitting. In dwelling O1, windows remained closed at night due to a pet, limiting natural ventilation and leading to an overheated main bedroom and high temperatures in the living room. Simulations indicated that adding insulation, reducing skylight glazing, and implementing external shading in dwelling O1 could mitigate this issue. In contrast, dwelling L3's northeast-facing living room avoided overheating, likely due to its orientation and effective natural ventilation. Grassie et al. (2022b) found that southeast-facing rooms have four to six times more overheating hours than northern ones, highlighting the impact of orientation. These cases show that occupant habits must be considered in retrofit strategies, as passive measures alone may not suffice. On the other hand, occupants in dwelling L2 felt restricted from opening windows due to security concerns and noise, and mostly opened them during the day, which prevented night-time ventilation. Where natural ventilation is limited, reversible low-carbon heat pumps can help maintain thermal comfort.

Pros and Cons of Emergent Incremental Retrofit Approaches

Homeowners often adopted emergent incremental retrofit approaches driven by personal preferences, budgets, and varying understanding of technologies. While this approach is flexible, it can lead to unintended consequences such as excessive insulation without adequate ventilation or installing renewable systems before improving thermal performance, contributing to overheating. The novelty of this research lies in revealing that emergent retrofits often lack a clear strategy to address thermal comfort alongside energy efficiency. This highlights the need for training and tailored guidelines to help stakeholders make informed decisions balancing energy savings with comfort. Providing structured guidance on the sequencing of retrofit

measures, such as prioritizing enhancements to the building envelope and ventilation before integrating renewable energy systems, could prevent such issues. Additionally, undertaking a well-planned emergent retrofit, as demonstrated by dwelling L3, can reduce the likelihood of problems arising later.

Practical Strategies for Future Retrofits

The findings suggest practical strategies for future emergent retrofits. Dwelling L3 exemplifies an effective balance between insulation, natural ventilation, and shading, preventing overheating. In contrast, dwelling L4 focused on energy efficiency measures like airtightness and secondary glazing without addressing cooling or ventilation, leading to overheating. Retrofit projects should prioritize integrated approaches that address both energy performance and occupant comfort, considering occupant behaviour and preferences. Holistic strategies combining insulation, shading, and ventilation can optimize energy efficiency and indoor environmental quality.

Importance of Tailored Training and Guidelines

The study found that homeowners often took primary responsibility for retrofit decisions and implementation, as seen in dwellings O1, L1, L3, and L4. For example, in dwelling L1, the homeowner, who is a PhD researcher in sustainability and environmental engineering, conducted the retrofit very efficiently, resulting in stable temperatures in both the bedroom and living room. This emphasizes the key role of tailored training and guidelines for homeowners pursuing emergent retrofits. Developing comprehensive training programs can provide guidance on effective sequencing of measures, such as improving the building envelope before integrating renewable technologies, and mitigating overheating through external shading and enhanced ventilation. Equipping stakeholders with knowledge and resources ensures that energy efficiency goals are achieved without sacrificing comfort.

Impact on Energy Use Reduction

Passive design strategies not only improved comfort but also reduced reliance on mechanical cooling, leading to energy savings. Simulations showed significant temperature decreases after implementing passive measures: dwelling O1's living room temperatures reduced by 5°C, and dwelling L2's living room by 9°C. These reductions lower the need for mechanical cooling, contributing to energy savings and reduced carbon emissions. Deploying reversible low-carbon heat pumps can further enhance efficiency by providing heating and cooling, reducing energy use and emissions year-round.

Limitations and Future Research

Limitations of this study include a small sample size, which limits generalizability; incorporating more case studies would enhance robustness. The monitoring period was short, lacking long-term data to assess full impacts across seasons. Future research should extend monitoring periods to capture seasonal variations. Simulation analyses focused on selected rooms due to resource constraints and data availability, which may limit comprehensiveness. Including more spaces in future studies would provide a fuller understanding of overheating risks and mitigation strategies.

Recommendation

Based on the case study findings, the following recommendations are suggested to enhance retrofitting practices and prevent issues such as overheating and inadequate ventilation:

- **Integrated Retrofit Planning:** Prioritize improvements to the building envelope, such as insulation, glazing, and airtightness, before integrating renewable energy systems. This holistic approach, including passive design elements like shading and natural ventilation, can prevent overheating and improve indoor comfort.
- **Consider Occupant Behaviour:** Tailor retrofit strategies to align with occupant habits, such as window operation and use of shading devices. Educate residents on effective ventilation and cooling practices to ensure the long-term success of energy efficiency measures.
- **Guidelines for Emergent Retrofit Approaches:** Develop guidelines and training for homeowners, designers, and architects on a phased retrofit approach, emphasizing the sequence of measures and addressing overheating and ventilation at each stage.
- **Ensure Effective Ventilation:** Combine enhanced airtightness and insulation with effective ventilation solutions like night-time ventilation or mechanical systems, especially in homes with high solar gains, to maintain indoor air quality and prevent overheating.
- **Use Reversible Low-Carbon Heat Pumps:** Encourage the use of reversible heat pumps in homes with solar PV systems for efficient heating and cooling, reducing energy costs and emissions year-round.
- **Adopt Passive Design Solutions:** Implement internal shading such as blinds, adjustable external shading devices like louvres, overhangs and side fins and natural shading to manage solar heat gain and reduce cooling demand, enhancing comfort and minimizing reliance on active cooling systems.

7.0 Conclusion

This dissertation has thoroughly investigated the overheating risks associated with retrofitted SuperHomes in South England, emphasizing the critical need for a comprehensive approach to retrofitting that balances energy efficiency with thermal comfort. The study contributes to the growing body of literature recognizing the unintended consequences of energy-focused retrofits, particularly as climate change leads to more frequent and intense heatwaves.

The detailed analysis of five case studies reveals that while retrofitting measures like improved insulation and airtightness effectively reduce energy consumption and carbon emissions, they can inadvertently heighten the risk of overheating if not complemented by adequate ventilation and shading strategies. Specifically, homes that prioritized insulation without enhancing natural ventilation experienced significant discomfort during warmer periods, illustrating the unintended consequences of a narrow focus on energy efficiency. In contrast, the modelled scenarios presented an optimal approach that integrated adjustable shading devices, natural ventilation, and efficient glazing alongside insulation, resulting in more stable indoor conditions even during peak summer temperatures.

The thermal comfort surveys and environmental monitoring conducted in this research provided valuable empirical insights into how different retrofit strategies impact occupant comfort. Despite universal improvements in energy efficiency across all case studies, thermal comfort varied considerably, with 60% of homes exceeding the CIBSE TM59 overheating criteria B during peak summer periods. This variability suggests that retrofit strategies must be tailored to the specific architectural features of each dwelling and the behaviours of occupants. Engaging with homeowners to understand their usage patterns, such as window operation habits and shading preferences, is crucial for designing retrofits that are not only energy-efficient but also enhance quality of life.

These findings have significant implications for retrofitting practices and policy development. Effective retrofit strategies should be designed with a comprehensive understanding of both energy efficiency and thermal comfort, recognizing them as interconnected goals rather than isolated objectives. Sequential and integrated approaches, where ventilation and shading solutions are implemented before or simultaneously with insulation upgrades, can help prevent overheating while still achieving energy efficiency targets. Current policies often prioritize individual measures, leading to suboptimal outcomes and potential adverse effects on occupant well-being. A shift towards integrated retrofit guidelines that address both winter and summer comfort would support broader adoption and yield better results.

This research makes a novel contribution by highlighting the importance of considering the sequence and prioritization of retrofit interventions, a topic that has not received sufficient attention in the field of sustainable architecture. By focusing on SuperHomes in South England, the study offers practical insights for similar retrofit projects in urban and suburban settings, where the urban heat island effect can exacerbate overheating risks. The empirical evidence underscores that retrofit strategies need to be context-specific, accounting for the unique characteristics of each dwelling, local climatic conditions, and the projected impacts of climate change.

However, several limitations must be acknowledged. The small sample size and the limited monitoring period may restrict the generalizability of the findings. Future research should aim to include a larger, more diverse sample of retrofitted homes across various climatic zones to enhance the robustness of the conclusions. Extending the monitoring period to capture seasonal variations would provide a more comprehensive understanding of the long-term impacts of retrofit measures on thermal comfort. Additionally, while this study focused primarily on physical interventions and their direct impact on thermal comfort, future research could explore the behavioural aspects in more detail. Investigating how occupant behaviours influence the effectiveness of retrofit measures and how these behaviours can be modified through design interventions and user education would offer valuable insights for optimizing retrofit outcomes.

In conclusion, achieving a balance between energy efficiency and thermal comfort in retrofitted homes requires an integrated, occupant-centric approach that considers both building performance and user needs. While retrofitting is essential for reducing carbon emissions and combating climate change, it must be approached with a comprehensive strategy that anticipates and mitigates potential overheating risks. By adopting holistic retrofit practices including passive design solutions, effective ventilation strategies, and an understanding of occupant behaviour, sustainable, comfortable, and resilient homes can be created. Such homes will not only contribute to environmental objectives but also enhance the well-being of occupants, ensuring preparedness for the challenges of a changing climate.

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9. Appendix

Appendix A: Surveys

Household survey

Survey of Housing Tenants Date: Dwelling ID:

Background information

We invite you to participate in a household survey and your experiences with retrofitting measures in your home. This survey is part of an MSc research project in Sustainable Architecture at Oxford Brookes University, investigating the relationship between innovative retrofit approaches and the risk of overheating in SuperHomes. By sharing your insights, you will contribute to developing evidence-based guidelines for homeowners adopting an emergent retrofit approach, aiming to enhance home comfort and sustainability. Your participation is valuable, and your responses will remain confidential.

A. About your household

1. How many adults (18 or over) and children live in your home?

Age/ Occupant	Occupant 1	Occupant 2	Occupant 3	Occupant 4	Occupant 5	Occupant 6
0-4						
5-15						
16-24						
25-44						
45-64						
64-84						
85+						

2. Please indicate when your home is typically occupied and by whom. This will help to understand the impact of occupancy on energy use and thermal comfort.

Weekdays				
Adults	Morning 8 am-12 pm	Afternoon Midday-6 pm	Evening 6 pm- Midnight	Night Midnight- 8 am
Children	Morning	Afternoon	Evening	Night

	8 am-12 pm	Midday-6 pm	6 pm- Midnight	Midnight- 8 am
Weekends				
Adults	Morning 8 am-12 pm	Afternoon Midday-6 pm	Evening 6 pm- Midnight	Night Midnight- 8 am
Children	Morning 8 am-12 pm	Afternoon Midday-6 pm	Evening 6 pm- Midnight	Night Midnight- 8 am

B. About Your home

3. Which of these best describes your home?
    a. Detached house
    b. Semi-detached house
    c. Terraced house
    d. End-terrace house
    e. Bungalow
    f. Other (please specify):
4. What type of heating and cooling systems do you have?
5. Are your walls solid or cavity?
    a. Solid
    b. Cavity
    c. Don’t know
6. Do you have wall insulation?
    a. Yes
    b. No
    c. Some
    d. Don’t know
    e. Not applicable
7. Do you have loft insulation?
    a. Yes
    b. No
    c. Don’t know
    d. Not applicable
8. Are your windows double or triple-glazed?
9. When was your home built?
    a. before 1919
    b. 1919-44
    c. 1945-64
    d. 1965-80
    e. 1981-90
    f. after 1990
    g. Don't know

10. How many bedrooms does your home have (including bedrooms used for other purposes, e.g. home office)?

    a. 1
    b. 2
    c. 3
    d. 4
    e. 5+

11. What is the floor area of your home?

    a. less than 50m2
    b. 50 - 69m2
    c. 70 - 89m2
    d. 90 - 109m2
    e. 110 - 129m2
    f. 130m2 or more
    g. Don't know
    h. Other (e.g. exact figure, or figure/estimate in square feet)

12. Please specify how you ventilate your home? (please tick all that apply)

    a. Open windows
    b. Use trickle vents
    c. Use exhaust fans in bathroom and or kitchen
    d. Mechanical Ventilation with Heat Recovery (MVHR) (please specify its efficiency)
    e. Other (please specify)

13. How many years have you been living in this home?

    a. Less than 1 year
    b. 1-2 years
    c. 2 - 3 years
    d. 3 – 5 years
    e. 5 – 10 years
    f. 10 – 20 years
    g. More than 20 years

14. For how long in the future do you think you will live in this home?

    a. Less than 1 year
    b. 1 - 2 years
    c. 2 - 3 years
    d. 3 – 5 years
    e. 5 – 10 years
    f. 10 – 20 years
    g. More than 20 years
    h. No plans to ever move
    i. Don’t know

C. Timing of renovation work

15. How would you characterize the timing and planning of your low-energy renovation work?

a. A planned improvement that took place largely at a one-time
b. A series of changes were planned initially, but with the work taking place as separate projects over time
c. A developing series of changes (not planned at the outset) resulted in a low-energy home
d. Don't know
e. Other (please specify)

16. How long did you start your low-energy renovation works after you bought the property? If the work was carried out as an incremental series of improvements, please answer for the first improvement.

a. Within the first three months
b. 3 months - 1 year
c. 1 - 2 years
d. 2 - 5 years
e. 5 - 10 years
f. Longer than 10 years
g. Don't know

17. Over what period were the major elements of your low-energy renovation carried out (not including maintenance work or minor improvements)?

a. Up to 6 months
b. 6 months - 1 year
c. 1 - 2 years
d. 2 - 5 years
e. 5 - 10 years
f. More than ten years
g. Don't know

D. Planning for renovation

18. How did you find out about SuperHome? Did SuperHome assist you during the retrofit process? If so, please explain how.

19. What did you want your renovation work to achieve? Please tick all that apply and provide details if applicable:

a. Reduced energy use
b. Reduced energy bills
c. Reduce overheating risk
d. Reduce heat loss
e. Improved airtightness
f. Improved ventilation
g. Better indoor air quality
h. Lower carbon emissions
i. Reduced (mains) water use
j. To become a 'Superhome'
k. Don’t know

l. Other (Please specify)

Please specify if you achieved all of the above targets. If not, what was not achieved?

20. Which of the following technologies or materials is an important part of your renovation?

    Please specify the type of technologies/ material for each answer

    a. Renewable energy (please specify the type and their capacity- e.g. Solar panel, Solar hot water system, battery to store electricity, wind power, smart meter, other)
    b. Advanced energy-related technologies (please specify-e.g. double/ triple glazing, sophisticated control systems)
    c. Recycled or re-used materials (please specify)
    d. Environmentally friendly' materials (please specify)
    e. Materials with low embodied energy (please specify)
    f. Energy feedback device (please specify e.g. electricity use display)
    g. Other (please specify):

21. Which of the following improvements have you made to your home? Please tick all that apply and specify the type/location where needed

    a. External wall insulation
    b. Internal wall insulation
    c. Cavity wall insulation
    d. Ground floor insulation
    e. Loft/roof insulation
    f. High-performance doors
    g. Double/triple glazed windows (Please specify which type)
    h. Extension (please specify where e.g. kitchen)
    i. Re-modelling inside (e.g. moving walls, doorways)
    j. Loft conversion
    k. Conservatory
    l. New outbuilding (e.g. office/studio)
    m. Improved airtightness
    n. Extract fans without heat recovery
    o. Extract fans with heat recovery
    p. Whole-home ventilation system
    q. Efficient gas boiler
    r. Efficient oil boiler
    s. Efficient LPG boiler
    t. Solar water heating
    u. Solar photovoltaics (PV)
    v. Wood burner
    w. Other (please specify):

    - Please list the above improvements in the order that they were carried out here.

- What factors influenced the order in which you implemented retrofit measures? (e.g., cost, convenience, professional advice, etc.)

22. Did you undertake any specific measures to address overheating in your home and improve indoor thermal comfort in warm seasons? Please select all that apply, and specify what type of measure was implemented
    a. Installed shading devices. Please specify (e.g., blinds, curtains, external/internal shading.
    b. Improved ventilation. Please specify (e.g., installation of mechanical ventilation systems, opening windows, adding vents, trickle vents)
    c. Implemented insulation measures targeting overheating. Please specify (e.g., reflective insulation, cool roof coatings)
    d. Upgraded or added cooling systems. Please specify (e.g., air conditioning, fans)
    e. Implemented passive cooling techniques. Please specify (e.g., natural ventilation, night purging)
    f. Consulted with an energy/environmental/sustainability consultant for overheating mitigation strategies
    g. I did not undertake any specific measures to reduce the risk of overheating.
    h. Other (please specify):

E. Your role/professional role in the renovation

23. Does anyone in your household have any education or work experience that is relevant to carrying out low-energy renovation work?
    a. No
    b. Don't know
    c. Yes (please give brief details):

24. Did you employ any professions or trades to help design, project-manage, or undertake low-energy renovation work? Please list all professionals/trades including yourself or family members worked on your house for each answer (e.g. architect, plumber, installer, household member).
    a. Yes - all the work was done by paid professionals and tradespeople.
    b. Yes - much of the work was done by paid professionals and tradespeople.
    c. Yes - some of the work was done by paid professionals and tradespeople.
    d. Yes - a little of the work was done by paid professionals and tradespeople.
    e. No - I / other household members did it alone
    f. No - it was done with help from family and friends, at least one of whom had relevant knowledge or expertise
    g. No - it was done with help from family and friends, none of whom had any relevant knowledge or expertise
    h. Other (please specify):

25. Who created the detailed plan for how the renovation should be done or who decided on the next steps throughout the process? If this work was shared or carried out by different people during different phases of the work, please tick all that apply.

    a. Me
    b. Another member of my household
    c. Architect
    d. Builder
    e. Environmental / energy consultant
    f. Specialist project manager
    g. There was no detailed plan
    h. Don't know
    i. Other (please specify):

F. Your retrofit experience satisfaction

26. Were you satisfied with the retrofit performance? Please tick the one that apply below.

Answer Options	Very satisfied	Quite satisfied	Neither satisfied nor dissatisfied	Quite dissatisfied	Very dissatisfied	Not applicable
Overall						
Energy saving						
Carbon Saving						
Indoor thermal comfort						
Indoor air quality						
Heating system						
Ventilation system						

Something else (please specify)						

G. Changes in energy use, energy bills, and thermal comfort post-retrofit

27. Have you changed how you use energy in your home since retrofitting your home?

a. Yes, I use a little less energy
b. Yes, I use much less energy
c. Yes, I use a little more energy
d. Yes, I use much more energy
e. No, I use the same amount of energy as before the retrofit
f. Don't know

28. Have you noticed any changes in your energy bills post-retrofit?

a. Yes, my energy bills increased a little
b. Yes, my energy bills increased a lot
c. Yes, my energy bills decreased a little
d. Yes, my energy bills decreased a lot
e. No, my energy bills are roughly the same as pre-retrofit period
f. Don't know

29. Are there any changes in your indoor thermal comfort post-retrofit?

In the non-heating season (May-September)

a. Yes, indoor environment in my home becomes a little more comfortable
b. Yes, indoor environment in my home becomes much more comfortable
c. Yes, indoor environment in my home becomes a little more uncomfortable
d. Yes, indoor environment in my home becomes much more uncomfortable
e. No, indoor environment is roughly the same as pre-retrofit period
f. Don't know

In heating season (October-April)

a. Yes, indoor environment in my home becomes a little more comfortable
b. Yes, indoor environment in my home becomes much more comfortable
c. Yes, indoor environment in my home becomes a little more uncomfortable
d. Yes, indoor environment in my home becomes much more uncomfortable
e. No, indoor environment is roughly the same as pre-retrofit period
f. Don't know

30. Do you open windows the same, more or less in different seasons after retrofitting? Please tick the one that applies and specify the reason.

In non-heating season (May-September)

a. I open windows in my home a little more than before
b. I open windows in my home much more than before
c. I open windows in my home a little less than before
d. I open windows in my home much less than before

e. I open windows same as before
f. Don't know

In heating season (October-April)

a. I open windows in my home a little more than before
b. I open windows in my home much more than before
c. I open windows in my home a little less than before
d. I open windows in my home much less than before
e. I open windows same as before
f. Don't know

Electricity use		**Strongly Disagree**				**agree**
31.	My electricity usage has been roughly the same as pre-retrofit period	□1	□2	□3	□4	□5
32.	I shop around every year to get the best deal from energy suppliers	□1	□2	□3	□4	□5
33.	I have been with my current energy supplier for more than 3 years	□1	□2	□3	□4	□5
Flexibility		**Strongly Disagree**				**agree**
34.	I would be happy to change the time at which I use energy if it meant I could save money	□1	□2	□3	□4	□5
35.	I would be happy to change the time at which I use energy if it meant I could help the environment	□1	□2	□3	□4	□5

Thermal Comfort Survey

This is the thermal comfort survey. Please read each question carefully and complete the survey to the best of your ability. Thank you for your participation in this research.

Survey details:

Dwelling ID:	Name:	Date:	Time:

Location:	Temperature:	RH (%):

1. How do you find the temperature in this room now?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2. How do you feel in this room now?

Very uncomfortable	Somewhat uncomfortable	Uncomfortable	Neutral	Comfortable	Somewhat comfortable	Very comfortable

3. What is your tolerance for the temperature in this room now?

Tolerable	Slightly difficult to tolerate	Fairly difficult to tolerate	Very difficult to tolerate	Intolerable

4. PREFERENCE: I would prefer to be…

Much warmer	A bit warmer	No change	A bit cooler	Much cooler

5. CLOTHING: I am currently wearing… (tick all that apply)

Short sleeve shirt/blouse	Long sleeve shirt/blouse	Trousers/ Long skirt	Shorts/ Short skirt	Other (specify):
Vest	Dress	Pullover	Jacket	
Short socks	Long socks	Tights	Cardigan	
Shoes	Sandals	Boots	Slippers	

6. ACTIVITY: In the last 15 minutes I have been…

Sitting (passive work)	Standing relaxed	Walking indoors
Sitting (active work)	Standing working	Walking outdoors
Laying down	Other (specify)	

7. CONTROLS: Where I am there is… (tick all that apply)

Internal door open	Blinds/curtains down	Air conditioning on	Fan on
Window open	Lights on	Heating on	Extra heater on
Window opening pattern: Morning afternoon evening night Most of the time 24/7			Other (specify)

8. When do you usually open the windows? (Select all that apply)

- **a.** Morning
- **b.** Afternoon
- **c.** Evening
- **d.** Night

9. How far can the windows be opened, and do you use a window restrictor? If you use a window restrictor, do you find it problematic? (Select one)

- **a.** They open fully without any restrictor.
- **b.** They open partially with a restrictor, and I find it convenient.
- **c.** They open partially with a restrictor, but I find it problematic.

d. Other (please specify)

10. When do you typically prop open the door? (Select all that apply)

a. Morning

b. Afternoon

c. Evening

d. Night

11. Is there anything that stops you from opening windows or internal doors? (Select all that apply)

a. Noise

b. Pollution

c. Security concerns

d. Weather

e. Privacy

f. Other (please specify)

g. Nothing stops me

12. Do you have a fan? When do you typically use them?

a. No, I don't have a fan.

b. Yes, Morning

c. Yes, Afternoon

d. Yes, Evening

e. Yes, Night

13. Do you use air conditioning? And when do you typically use an air conditioner?

a. No, I don't have air conditioning.

b. Yes, Morning

c. Yes, Afternoon

d. Yes, Evening

e. Yes, Night

14. What actions do you take to keep your house and yourself at a comfortable temperature during the summer? (Select all that apply)

a. Adjusting clothing

b. Taking a shower

c. Using fans or air conditioning

d. Keeping windows open

e. Using blinds or curtains

f. Other (please specify)

Appendix B: Ethic Forms

TDE Form E1(Arch

Faculty of Technology, Design and Environment - Ethics Review Form E1(Arch)

- This form should be completed jointly by the **Supervisor and Student** who is undertaking a research/major project which involves human participants. Note: if the supervisor is an Associate Lecturer, the Module Leader (permanent member of staff) must co-sign as an additional supervisor.

- It is the **Supervisor(s)'** responsibility for exercising appropriate professional judgement in this review.

- Before completing this form, please refer to the University **Code of Practice for the Ethical Standards for Research involving Human Participants**, available at http://www.brookes.ac.uk/Research/Research-ethics/ and to any guidelines provided by relevant academic or professional associations.

- Note that the ethics review process needs to be fully completed and signed **before fieldwork commences**.

(i) **Project Title:** Investigating the Risks of Overheating in UK SuperHomes using Emergent Retrofit Approaches

(i) **Name of Supervisor(s) and School in which located:** Dr Sahar Zahiri, School of Architecture

(ii) **Name of Student and Student Number:** Negin Kalantari, 19276697

(iii) **Brief description of project outlining where human participants and/or their data will be involved (approx. 250-500 words)** *(include details about: identified risks to participants and researchers and how they will be mitigated through the research design; participant recruitment and how personal data will be managed if relevant; how any participant consents will be recorded; whether and how data will be anonymised)*:

The study examines the relationship between overheating risks and emergent retrofit approaches adopted in 5 UK SuperHomes, aiming to develop evidence-based guidelines for improving indoor thermal comfort and enhancing energy efficiency. This research method involves monitoring indoor temperature and relative humidity using HOBO-UX100-003 data loggers. There is no risk and security concern in monitoring and downloading data since the

data loggers are non-intrusive, battery operated and silent in operation sensors that monitor indoor environmental data locally. Householder and thermal comfort surveys will be conducted to collect data on retrofit measures and thermal comfort. Overheating risks will be assessed using CIBSE TM52/TM59 methods and building simulation analysis to develop recommendations to effectively mitigate overheating risks. This approach aims to provide insights into the impact of emergent retrofit approaches on overheating risks in SuperHomes, informing the development of guidelines for effective retrofit strategies that enhance energy efficiency and maintain thermal comfort.

Participants will be recruited from the SuperHomes network, focusing on homes in South and Southeast England where overheating risks are higher. Recruitment will be voluntary and aim for diverse building typologies. Personal data will be managed according to GDPR guidelines, ensuring confidentiality and security. Consents will be recorded through signed consent forms, detailing the study's procedures, risks, benefits, and participants' rights. Digital copies of the survey and monitoring data, and consent forms will be securely stored in Oxford Brookes Google Drive.

There is no potential risk to participants and researchers during the visit. Participants willing to contribute would face no health or safety risk, since their involvement will be limited to providing information about their retrofit works carried out in their home and their thermal comfort. It is important to note that participation in surveys and building monitoring is entirely voluntary. No potential psychological and emotional risks associated with this study were also identified. It is important to note that participation in surveys and building monitoring is entirely voluntary. The researcher will explain how the light-touch environmental monitoring devices (HOBO UX-100-003) will record indoor environmental variables, and how data will be collected, which will be after removing the device from homes through a cable connected to the oxford brookes university PCs. Participants will complete an informed consent form, ensuring their comfort and privacy are maintained. Participants will be informed about the study's purpose, data usage, and their right to withdraw. The consent form and information sheet will be emailed to the participants before the visits. The researcher will keep the survey and monitoring data in Oxford Brookes Google Drive and will handle sensitive information appropriately with respect to participants privacy. Data will be anonymized by removing personal identifiers before analysis. Unique codes will be assigned to each participant, ensuring that individual responses cannot be traced back to them.

(v) Attached Documents Checklist

If you are using one of the following methods listed below in your research, you must include in your E1 paperwork the following additional documents to ensure informed consent of participants. All documents should have the Brookes logo on the top right-hand corner:

For interviews/focus groups:

Participant information sheet; list of interview questions; consent form or verbal consent script; recruitment letter or advertisement and gatekeeper approval letter as relevant (see the TDE templates).

For site observations (including sketching, photography, audio and visual recordings):

Participant information sheet: advertisement and gatekeeper approval letter as relevant (see TDE templates).

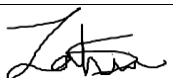
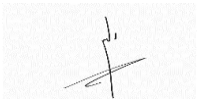
For surveys and administered surveys:

Survey that includes participant information, including data protection information, (or verbal consent script for administered surveys) and checkboxes for informed consent to use the data and 18+ age declaration (see TDE templates)

All other methods: If there are any other forms of 'research instruments' being used in the study (e.g. aide memoires; observational checklists; participant instructions for an interactive game, etc.) please include a copy with your E1 form.

		Yes	**No**
1.	Does the study involve participants who are unable to give informed consent (e.g. children, people with learning disabilities)?	☐	X☐
2.	If the study will involve participants who are unable to give informed consent (e.g. children under the age of 18, people with learning disabilities), will you be unable to obtain permission from their parents or guardians (as appropriate)?	☐	X☐
3.	Will the study require the cooperation of a gatekeeper for initial access to groups or individuals to be recruited (e.g. students, members of a self-help group, employees of a company)?	☐	X☐
4.	Are there any problems with the participants' right to remain anonymous, or to have the information they give not identifiable as theirs?	☐	X☐
5.	Will it be necessary for the participants to take part in the study without their knowledge/consent at the time? (e.g. covert observation of people in non-public places?)	☐	X☐

6.	Will the study involve discussion of or responses to questions the participants might find sensitive? (e.g. own traumatic experiences)	☐	X☐
7.	Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants?	☐	X☐
8.	Will blood or tissue samples be obtained from participants?	☐	X☐
9.	Is pain or more than mild discomfort likely to result from the study?	☐	X☐
10.	Could the study induce psychological stress or anxiety?	☐	X☐
11.	Will the study involve prolonged or repetitive testing of participants?	☐	X☐
12.	Will financial inducements (other than reasonable expenses and compensation for time) be offered to participants?	☐	X☐
13.	Will deception of participants be necessary during the study?	☐	X☐
14.	Will the study involve NHS patients, staff, carers or premises?	☐	X☐

Signed:		**Supervisor(s)** Sahar Zahiri
Signed:		**Student** Negin Kalantari
Date:	23/07/2024	

What to do now:

1. If you have answered **'no'** to all the above questions:

   (a) The student must **send** the completed and fully signed E1 form to the relevant **Module Leader** (permanent member of staff).
   (b) The student must keep a copy of the E1 form which must be included in the submission of the relevant coursework (e.g. dissertation, portfolio or assignment) as an appendix, including any attached documents. **Do not include any signed paperwork from participants in your submission.**
   (c) The supervisor must keep a copy of the E1 form as they are responsible for monitoring compliance during the fieldwork.

2. If you answer, **'yes' for question '3' (the 'Gatekeeper question') but 'no' to every other question:**

   This research may still be considered as 'low risk' and processed under the E1 form as above in point 1 at the discretion of the supervisory team. A Gatekeeper is someone who has to give permission for potential participants to be approached to take part in the research, and/or for the research to take part in their organisation or on their premises. Note that this may, or may not, be the same person approached to disseminate information on behalf of the researcher to potential participants.

   (a) After discussing your research with your supervisor and/or relevant Module Leader (permanent member of staff), and using the TDE template, approach your Gatekeeper and obtain a letter of approval for the work as described in your E1 form.
   (b) The student must **send** the completed and fully signed E1 form to the relevant **Module Leader** (permanent member of staff) with the Gatekeeper approval letter and any other relevant attachments included.
   (c) The student must keep a copy of the E1 form which must be included in the submission of the relevant coursework (e.g. dissertation, portfolio or assignment) as an appendix, including any attached documents. **Do not include any signed paperwork from participants in your submission.**
   (d) The supervisor must keep a copy of the E1 form as they are responsible for monitoring compliance during the fieldwork.

3. If you have answered **'yes'** to **any** of questions **1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14**:

   (a) The supervisor and student must complete the TDE E2 form available at http://www.brookes.ac.uk/Research/Research-ethics/Ethics-review-forms/
   (b) Note that the information in the E2 must be in **sufficient detail** for the ethical implications to be clearly identified.
   (c) The signed E2 and signed E1 Form must be emailed to Bridget Durning (bdurning@brookes.ac.uk) who is the Faculty Research Ethics Officer (FREO) for review. Please allow **at least two weeks** for this review process.
   (d) If/when approved the FREO will issue an E3 Ethics Approval Notice.
   (e) The student must send the E1, E2 and E3 Notice **to the relevant Module Leader** (permanent member of staff).

(f) The student must also keep copies which must be included in the submission of the relevant coursework (e.g. dissertation, portfolio or assignment) as an appendix, including any attached documents. **Do not include any signed paperwork from participants in your submission.**
(g) The supervisor must keep a copy of documentation to monitor compliance during fieldwork.

4. If you answered 'yes' to any of questions 1-13 and 'yes' to question 14, an application must be submitted to the appropriate NHS research ethics committee. This is an onerous and time consuming process so the supervisor should liaise early with the FREO if the student is considering this.

Privacy Notice Form

Guidelines for completion of the Privacy Notice for Research Participants

Please read these carefully before completing your Privacy Notice.

If the data being collected is completely anonymous or does not include information that can be combined with other data to identify an individual, a privacy notice is not required.

Data Controller:

Your Privacy Notice should specify the Data Controller. Usually this is **Oxford Brookes University (Oxford Brookes).** If it is not then this should be clearly stated. The exception to this is joint research projects where you should inform participants as to the other partner institution/s.

Purpose for Data Collection:

Your Privacy Notice should include the purpose for the data collection and your lawful basis for processing. The legal basis for processing personal data or information is as set out in Article 6 UK GDPR. Participant consent is required for the processing of their personal data for one or more specific purposes.

The basis for processing data includes:

- **Public task:** your Personal Data will be used in academic research. Oxford Brookes University is a public body and staff and students carry out research in line with the University's legal powers and constitution.

- **Legitimate interests:** for commercially oriented research the use of your Personal Data is considered to be in your legitimate interests, those of Oxford Brookes (to facilitate carrying out the research) or possibly in the legitimate interests of a third party.

You should insert as appropriate in the Privacy Notice.

Special Category Data:

This section can be removed if sensitive data is not being gathered.

Special Category Data (as defined in law) is a data relating to: racial or ethnic origin, political opinions, religious or philosophical beliefs, trade-union membership, data concerning health or sexual life, genetic/biometric data.

Special Category Data **can only be used** because one of the following processing exemptions applies; that is one of the exemptions set out in Art 9 UK GDPR:

- You consent to share this information
- This information is already made public (lawfully)
- Oxford Brookes needs to use this data for legal purposes
- Oxford Brookes needs to use this data for scientific or research purposes

Personal Data:

Your Privacy Notice should list the type/s of personal data that is being collected. This maybe only for contact purposes, such as online meetings, but this must still be included. Some examples include, but are not limited to:

Name; Date of Birth; Physical Address; Email Address; Health Information;

You should add/delete as appropriate.

Data Sharing:

Your Privacy Notice should include any institution/s that Oxford Brookes is collaborating with and who will have access to the research data. You should also include the name of any third party processors that host or have access to the data. For example: Google services for data hosting, office productivity software such as email, transcription services, etc.

Data Movement:
Your Privacy Notice should include notification to participants if their data will be shared, transferred or stored outside of the UK. Many software companies and organisations do not store their data in the UK. For example, Zoom, Panopto, Google, Nvivo, Qualtrics, RADAR

You can look at an organisation's Privacy Notice to see in which country the personal data is stored.

Data Source:
Your Privacy Notice should include the source of the data. For example: the participants themselves, public records, questionnaires, etc.

You should add/delete as appropriate.

Data Retention:

Your Privacy Notice should advise participants how long their data will be kept for. In line with Oxford Brookes policies data generated in the course of research must be kept securely in paper or electronic form for a period of time in accordance with the research funder or University policy. The standard period for keeping research data is 10 years. If it is a condition of your research funding that the research data must be shared and stored in a repository, you must explain how the data will be stored (for example with the UK Data Service or the UK Data Archive) and explain it will be anonymised.

You should add/delete as appropriate.

The template below should be completed and included with your ethics application.

Privacy Notice for Research Participants

This Privacy Notice provides information on how Oxford Brookes University (Oxford Brookes) collects and uses participant's personal information when you take part in one of our research projects. Please refer to the research Participant Information Sheet for further details about the study and what information will be collected about you and how it will be used.

Oxford Brookes is the Data Controller of any data that you supply for this research. This means that we are responsible for looking after your information and using it lawfully. We will make the decisions on how your data is used and for what reasons.

Name, position and contact address of researcher: Negin Kalantari, Msc Student, 19276697@brookes.ac.uk

Why do we need your data?

The purpose of this study is to examine the relationship between retrofit approaches and overheating risks in SuperHomes. This research aims to develop evidence-based guidelines and strategies to improve indoor thermal comfort, reduce overheating risks, and enhance energy efficiency.

Oxford Brookes' legal basis for collecting this data is:

The performance of a task carried out in the public interest, which is research that aims to advance knowledge in the field of sustainable architecture and climate change.

Your consent is an ethical requirement.

Oxford Brookes University's legal basis for processing your Personal Data (or information) is as set out in Art 6 UK GDPR.

What type of personal data will Oxford Brookes use?

1. Indoor temperature and relative humidity data collected through HOBO UX-100-003 data loggers.
2. Responses to thermal comfort and householder surveys, which include information on your retrofit work, thermal comfort and ventilation habits.

Who will Oxford Brookes share your data with?

The data collected will be shared with the research supervisors, Professor Rajat Gupta and Dr.. Sahar Zahiri. No third-party processors will have access to the data.

Will Oxford Brookes transfer my data outside of the UK?

No: it will be stored in Oxford Brookes Google drive and will be deleted later.

What rights do I have regarding my data that Oxford Brookes holds?

- You have the right to be informed about what data will be collected and how this will be used
- You have the right of access to your data
- You have the right to correct data if it is wrong

- You have the right to ask for your data to be deleted
- You have the right to restrict use of the data we hold about you
- You have the right to data portability
- You have the right to object to Oxford Brookes using your data
- You have rights in relation to using your data in automated decision making and profiling.

Your rights will depend on the legal ground used to process your data

Where did Oxford Brookes source my data from?

The data will be sourced directly from you through the use of HOBO data loggers and your responses to the thermal comfort and householder surveys.

Are there any consequences of not providing the requested data?

There are no consequences of not providing data for this research. It is purely voluntary. If you like to withdraw part way through the research, the Participant Information Sheet includes this information. It may be that some of the data that you have provided has already been used in the research. If you would like more information about this, you should feel free to contact the research team.

Will there be any automated decision making using my data?

There will be no use of automated decision making in scope of UK Data Protection and Privacy legislation.

How long will Oxford Brookes keep your data?

In line with Oxford Brookes policies data generated in the course of research must be kept securely in paper or electronic form for a period of ten years in accordance with the research funder or University policy.

Who can I contact if I have concerns?

In the event of any questions about the research study, please contact the research team in the first instance. Their contact details are listed on the Participant Information Sheet. If you have any concerns about the way in which the study has been conducted, please contact the Chair of the University Research Ethics Committee at ethics@brookes.ac.uk. For further details about information use contact the Information Security Management team on info.sec@brookes.ac.uk or the Data Protection Officer at brookesdpo@brookes.ac.uk. You can also contact the Information Commissioner's Office via their website ico.org.uk.

Participant Information Sheet

The Participant Information Sheet (PIS), covering letter or leaflet should be printed on Brookes headed paper, with full contact details for the principal investigator clearly indicated at the top.

The PIS should include a version number and date in the footer. Each time the document is updated, the version numbering and date in the footer should be amended to ensure accurate recording of the most up to date information sheet.

The PIS should contain the following information and for ease of reading use the suggested headings:

Study title:

Investigating the Risks of Overheating in UK SuperHomes using Emergent Retrofit Approaches

Invitation:

You are being invited to take part in a MSc dissertation research study in sustainable architecture at Oxford Brookes University. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

The purpose of this study is to examine the relationship between retrofit approaches and overheating risks in SuperHomes. The study aims to develop evidence-based guidelines and strategies to improve indoor thermal comfort, reduce overheating risks, and enhance energy efficiency. The study will run during July and August 2024, involving data collection through monitoring, surveys, and building simulation analysis.

Why have I been invited to participate?

You have been chosen to participate in this study because you have retrofitted your home to become a SuperHomes. This research focuses on five SuperHomes, and your experience with your retrofit project can provide invaluable insights.

Do I have to take part?

Participation in this research is entirely voluntary. If you decide to take part, you will be given a privacy notice that will explain how your data will be collected and used, and you will be asked to give your consent. You are free to withdraw at any time and without giving a reason. Any data collected from you can be withdrawn up to the point of analysis.

What will happen to me if I take part?

If you choose to participate, I will visit your home when suits you in July-August 2024 period to install two small light-touch HOBO UX-100-003 data loggers in your main bedroom and living room to monitor indoor temperature and relative humidity for 2 to 3 weeks. There is no risk and security concern in monitoring data since the data loggers are non-intrusive, battery operated and silent in operation sensors that monitor indoor environmental data locally. Additionally, thermal comfort and householder surveys will be conducted during my initial visit to install the devices when it suits you, which will take no more than 30 minutes. I will visit you again when it suits you to uninstall the devices after 2-3 weeks following my initial visit. The collected data will be used to carry out building simulation analysis and to develop tailored recommendations to improve indoor air quality, and further reduce energy use.

What are the possible disadvantages and risks of taking part?

There are no risks or security concerns associated with this research. The data loggers are battery-operated, silent sensors that monitor indoor environmental data locally. No potential psychological and emotional risks associated with this study were also identified.

What are the possible benefits of taking part?

By participating, you will receive insights about your home's performance, along with guidelines on how to improve the indoor environment, mitigate overheating risks, and further reduce energy use in your home.

Will what I say in this study be kept confidential?

All information collected about you will be kept strictly confidential, subject to legal limitations. Confidentiality, privacy, and anonymity will be ensured in the collection, storage, and publication of research material. Research data will always be kept securely, with data files encrypted and stored in Oxford Brookes University Google Drive under the University's contract. Data generated by the study will be retained for ten years after the completion of the research project.

What should I do if I want to take part?

If you are interested in participating, please reply to this message or contact me at 19276697@brookes.ac.uk

What will happen to the results of the research study?

The results of the research will be used in my dissertation for my MSc degree. They may also be published as an output or used in a conference paper/presentation.

Participants will be able to access the findings, which will be made available digitally or in an online repository.

Who is organizing and funding the research?

This research is being conducted as part of my MSc in Sustainable Architecture: Evaluation and Design at the School of Architecture, Oxford Brookes University. The study is supervised by Professor Rajat Gupta and Dr. Sahar Zahiri.

Who has reviewed the study?

The research has been reviewed by the researcher's supervisors at Oxford Brookes University.

Contact for Further Information:

If you have any concerns about the way in which the study has been conducted, you should contact the Chair of the University Research Ethics Committee on ethics@brookes.ac.uk.

Thank you

CONSENT FORM

This consent form is for the dissertation project in the MSc Sustainable Architecture program at Oxford Brookes University. Please read the information below carefully, complete the form, and return it to Negin Kalantari using the contact information provided above. Thank you for your time.

Full title of Project: Investigating Overheating Risk in Superhomes using the Emergent Retrofit Approach in south England

Name, position and contact address of researcher: Negin Kalantari, Msc Student, 19276697@brookes.ac.uk

	Please initial box	
1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions		
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason		
3. I understand that if I withdraw from the study my data can be withdrawn up to the point of analysis.		
	YES	**NO**
4. I agree with light touch environmental monitoring data loggers (temperature and relative humidity) to be installed in my home in July-August 2024.		
5. I agree to participate in the householder and thermal comfort survey.		
6. I give permission to the researcher to take photograph from my home for the research purpose		
7. I agree to the use of anonymised quotes and data in publications		
8. I agree that my anonymised data gathered in this study may be stored in a specialist data centre/repository and may be used for future research related to this study **Please note:** Data included in publications are increasingly made available in digital repositories, and will typically be freely available online. The researcher will take particular care to ensure all personal details are fully anonymised.		
9. I agree to take part in the above study		

Name of Participant:	Date:	Signature:
Name of Researcher: Negin Kalantari	Date:	Signature:

Appendix C: Table of openings and their type in Case study O1

13.0 Openings

Name	Opening Type	Location	Orientation	Curtain Type	Overhang Ratio	Wide Overhang	Width (m)	Height (m)	Count	Area (m^2)	Curtain Closed
Front door	Window	[1] External Wall 1	North West	None	0.00					2.60	
Front room window	Window	[1] External Wall 1	North West	None	0.00					4.40	
Bed 1	Window	[1] External Wall 1	North West	Dark-coloured venetian blind	0.00					3.40	20
Bathroom	Window	[1] External Wall 1	South East	None	0.00					1.10	
Bed 2	Window	[1] External Wall 1	South East	None	0.00					2.10	
Bed 3	Window	[1] External Wall 1	North West	None	0.00					1.40	
Patio door	Window	[4] Extension Wall 4	South East	None	0.00					5.04	
Extension window	Window	[4] Extension Wall 4	South East	Light-coloured curtain or roller blind	0.00					1.37	15
back door	Window	[2] External Wall 2	North East	None	0.00					1.70	
Extension velux	Roof Window	[2] Extension Roof 2	South West	Dark-coloured curtain or roller blind						1.31	10
window over sink	Roof Window	[2] Extension Roof 2	South East	None						1.50	
over patio door	Roof Window	[2] Extension Roof 2	South East	None						3.70	
office door	Window	[5] Office Wall 5	South West	Light-coloured curtain or roller blind	0.00					5.04	10
office to conservato	Window	[5] Office Wall 5	South	None	0.00					5.04	
office behind solar	Window	[5] Office Wall 5	South	White-coloured external shutter, window closed	0.00					1.16	80
attic velux 1	Roof Window	[1] Attic Roof 1	North West	Dark-coloured curtain or roller blind						1.10	10
Attic Velux 2	Roof Window	[1] Attic Roof 1	North West	Dark-coloured curtain or roller blind						0.90	10
attic bed window	Window	[6] Gable end 6	South East	Dark-coloured curtain or roller blind	0.00					3.36	15
Attic bath window	Window	[6] Gable end 6	South East	Light-coloured curtain or roller blind	0.00					1.20	30
attic stairs	Window	[6] Gable end 6	North East	Dark-coloured curtain or roller blind	0.00					0.60	15
stairs	Window	[1] External Wall 1	North East	Dark-coloured curtain or roller blind	0.00					0.60	15

Appendix D: Simulation Calibration

O1 Calibration Living room

Date	Operative Temperature °C	Monitored Temprature °C	Difference Percentage %
3-Aug	25.02	23.67	5.53
4-Aug	22.95	22.47	2.12
5-Aug	23.35	23.39	0.15
6-Aug	23.92	25.06	4.64
7-Aug	23.60	25.90	9.30
8-Aug	22.67	24.64	8.32
9-Aug	23.45	24.21	3.21
10-Aug	23.79	26.98	12.56
11-Aug	24.96	27.51	9.72
12-Aug	26.99	26.45	2.00
13-Aug	26.11	26.39	1.08
14-Aug	25.18	23.41	7.30
15-Aug	23.67	24.20	2.21
16-Aug	24.43	24.85	1.69
17-Aug	24.44	24.30	0.54
18-Aug	23.96	23.11	3.61

L2 Calibration Living Room

Date	Operative Temperature °C	Monitored Temprature °C	Difference Percentage %
3-Aug	25.26	26.22	3.72
4-Aug	25.39	26.34	3.70
5-Aug	25.31	25.50	0.75
6-Aug	24.85	25.02	0.68
7-Aug	24.44	23.57	3.63
8-Aug	23.59	23.33	1.10
9-Aug	22.68	24.30	6.90
10-Aug	23.45	24.93	6.11
11-Aug	23.03	25.06	8.45
12-Aug	22.83	25.69	11.78
13-Aug	22.76	25.60	11.74
14-Aug	23.49	25.10	6.61
15-Aug	23.66	24.91	5.12
16-Aug	24.51	25.48	3.89
17-Aug	24.99	24.24	3.07
18-Aug	25.88	23.67	8.91

L1 Calibration Bedroom

Date	Operative Temperature °C	Monitored Temperature °C	Difference Percentage %
3-Aug	23.61	25.94	9.37
4-Aug	23.64	25.31	6.81
5-Aug	23.91	24.86	3.90
6-Aug	23.81	25.06	5.12
7-Aug	23.12	24.14	4.28
8-Aug	22.50	23.81	5.65
9-Aug	21.75	23.96	9.70
10-Aug	21.75	24.25	10.87
11-Aug	21.63	25.29	15.60
12-Aug	21.63	26.43	19.98
13-Aug	21.56	26.06	18.90
14-Aug	21.59	25.14	15.19
15-Aug	21.79	24.50	11.70
16-Aug	22.21	24.67	10.49
17-Aug	22.82	24.55	7.30
18-Aug	23.72	23.56	0.67

L2 Calibration Bedroom

Date	Operative Temperature °C	Monitored Temprature °C	Difference Percentage %
3-Aug	24.75	26.00	4.94
4-Aug	24.84	25.86	4.03
5-Aug	25.17	24.65	2.08
6-Aug	24.58	25.09	2.05
7-Aug	23.79	23.73	0.24
8-Aug	23.23	23.42	0.80
9-Aug	22.48	23.99	6.47
10-Aug	22.72	24.44	7.32
11-Aug	22.66	25.04	9.98
12-Aug	22.39	26.03	15.04
13-Aug	22.31	25.77	14.37
14-Aug	22.77	25.66	11.94
15-Aug	22.91	25.21	9.55
16-Aug	23.72	25.50	7.24
17-Aug	24.27	24.57	1.23
18-Aug	25.26	23.80	5.92