# Adapting Homes to Heat in Greater Manchester

March 2025

UK Government

CS-NOW

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|---|---|
| Acknowledgements | Greater Manchester Combined Authority (GMCA) |
| | GMCA Ageing Hub |
| | Greater Manchester Low Carbon Asset Managers Group |
| | Your Home Better |

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| Publication date | [Date] |
| Recommended citation | Voke, E., Zepeda Rivas, D., Jones, C., Ap. Dafydd Tomos, B., Bowden, C., Bracci, F., Brown, C., Gresswell, E., Ireland, E., Monteleone, L., Parkes, B., Paul, A., Pérez-Vértiz, G., Simpson, C., Symonds, P., Mavrogianni, A., Wood, R., Smithers, R.J., 2025.<br><br>Adapting Homes to Heat in Greater Manchester. Climate Services for a Net Zero Resilient World. UK Government.<br><br>In collaboration with Greater Manchester Combined Authority. |

# About CS N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation, and climate action, and improves accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing, and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research partners **The Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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# Contents

# List of Tables

# List of Figures

## *List of Abbreviations*

| Abbreviation | Full term |
|---|---|
| A/C | Air Conditioning |
| CBA | Cost-Benefit Analysis |
| CCC | Climate Change Committee |
| CCRA | Climate Change Risk Assessment |
| CIBSE | Chartered Institution of Building Services Engineers |
| CS-N0W | Climate Services for a Net Zero Resilient World |
| DESNZ | UK Department for Energy Security and Net Zero |
| DSY | Design Summer Year |
| EPC | Energy Performance Certificate |
| EUI | Energy Use Intensity |
| GIS | Geographic Information System |
| GMCA | Greater Manchester Combined Authority |
| HVI | Heat Vulnerability Index |
| IPCC | Intergovernmental Panel on Climate Change |
| LEAD | Local Energy Advice Demonstrator |
| LSOA | Lower Layer Super Output Area |
| MSOA | Middle Layer Super Output Areas |
| NDVI | Normalised Difference Vegetation Index |
| OPEX | Operational Expenses |
| RCP | Representative Concentration Pathway |
| RdSAP | UK's Reduced Standard Assessment Procedure |
| RelHMax | Relative Height Maximum |
| TM59 | Technical Memorandum 59 |
| UCL | University College London |
| UHI | Urban Heat Island |
| UKCP | UK Climate Projections |
| UoM | University of Manchester |
| WPD4 | CS-N0W Work Package D4 – Assessing the Heating and Cooling Needs of the UK Housing Stock |

# Executive summary

Overheating in homes is a growing concern in the UK due to rising temperatures and more frequent and intense extreme heat events. Most existing UK homes are not designed to address overheating, so climate change poses increasing risks to health, comfort, productivity, and energy demand for cooling. Thus, there is a need for adaptation to address this growing challenge.

This report presents the outputs of the *"Adapting homes to heat in Greater Manchester"* work package, under the Climate Services for a Net Zero Resilient World (CS-N0W) Programme. This research was structured around three key questions:

1. What types of home are most sensitive to overheating in Greater Manchester?
2. What is the distribution of occupants considered vulnerable to overheating in Greater Manchester?
3. What low-cost, low-regret adaptation actions can reduce sensitivity to overheating in homes?

To answer these questions, two tasks were completed:

- Task 1: A heat sensitivity and vulnerability assessment of homes and occupants in Greater Manchester
- Task 2: A three-component analysis on potential low-cost, low-regret adaptation actions, including:
    a. Modelling to quantify the relative potential of the adaptation actions to reduce indoor overheating
    b. Analysis of the capital costs and benefits of each adaptation action
    c. A socio-technical analysis of the existing barriers that may hinder the implementation of the actions
    d. Development of simple infographics showcasing the adaptation actions for occupiers of the most sensitive types of homes

**Task 1** was addressed by two different approaches undertaken by University College London (UCL) and the University of Manchester (UoM). UCL applied a building-physics model focused on the heat sensitivity of homes to identify the most sensitive types of homes to overheating and their distribution, as well as understand where occupants vulnerable to overheating live in Greater Manchester. The model was designed to estimate the indoor thermal performance of domestic spaces and considers specific information about the characteristics of homes, such as the type and geometric form of the modelled buildings, building materials, and construction methods. However, the model does not consider variation in local urban climate. It also makes specific assumptions about potential occupant behaviour. UoM applied a composite Heat Vulnerability Index (HVI), which incorporates four domains, indoor sensitivity, outdoor sensitivity, occupant sensitivity, and restricted adaptive capacity. **Indoor sensitivity** identifies buildings that are more sensitive to overheating due to type, construction age, or insulation levels. **Outdoor sensitivity** identifies areas where ambient air temperatures are likely to be elevated compared to their rural equivalents due to the Urban Heat Island (UHI) effect. **Occupant sensitivity** identifies occupants who may be sensitive to overheating based on age or indicators of poor health or disability. **Restricted adaptive capacity** identifies households that are less able to adapt during extreme heat due to restrictions on finances, window opening, renting their homes, or limited access to green spaces.

**The key findings of Task 1 are:**

- **The type of home in Greater Manchester is a highly influential factor regarding sensitivity to indoor overheating** based on:
  - The **characteristics of homes** and assumptions about occupants' behaviour in this study and supporting studies, with mid-terrace houses and flats, and homes with limited ventilation and shading most sensitive to overheating.
  - Building **construction age,** with those built before 1900 and those built after 2007 most sensitive to overheating.

- **The homes most sensitive to overheating in Greater Manchester** are:
  - **Most prevalent in the boroughs of Manchester and Salford**, due to their building types and construction ages.
  - **Often found in areas of high Urban Heat Island (UHI) intensity**. These are usually located in the city centre where outdoor temperatures are higher compared to neighbouring rural locations. However, homes in suburban areas, although outside of the city centre, can still be sensitive to overheating due to the type and age of the buildings.

- Regarding **occupants' vulnerability to overheating in Greater Manchester**, spatial analysis shows that**:**
  - While **Manchester borough households have the lowest adaptive capacity overall**, there are areas and households within each borough that are vulnerable to overheating due to poor adaptive capacity.
  - **Manchester, Salford, Rochdale, and Tameside have the highest proportions of occupants of homes who are sensitive to overheating**, while Trafford has the lowest. Nevertheless, there are sensitive occupants in all areas who may need support.

- **The UCL building sensitivity model:**
  - **Can help local authorities and public health professionals to develop localised adaptation actions** that reduce the sensitivity of homes and vulnerability of occupants to

overheating or inform emergency public health action targeted at specific types of buildings and their occupants.

- Enabled identification of the areas of Greater Manchester where homes that are sensitive to overheating are most prevalent. This information **can be used by local authorities and urban planners to target urban planning strategies**, including green/blue infrastructure and relevant funding to where required.
- Enabled the identification of the types of homes that are sensitive to overheating in the short-term and long-term, as a result of the temporal resolution of the data applied to different future scenarios. It also estimated the amount of energy that might be needed to keep homes comfortably cool in the future.

- **The UoM heat vulnerability index can be used to identify the most appropriate adaptation options:**
  - High **indoor sensitivity** can be reduced by: maximising the co-benefits of building retrofit to address summer overheating; encouraging green space within gardens and on streets; and reducing overcrowding.
  - High **outdoor sensitivity** can be reduced by increasing green and blue spaces (e.g., through new parks, green walls and roofs, street-tree planting, re-exposing covered waterways etc.) that reduce the UHI effect. Additional adaptation options include spatial planning policies and development management to protect, maintain and enhance existing greenspace, and change the surface albedo of buildings and other surfaces to reduce their absorption of energy from the sun.
  - High **occupant sensitivity** can be addressed by working with healthcare providers and community groups to increase awareness of sensitive groups of people and increase support to them, e.g., by increasing frequency of contact, providing advice on keeping cool, and planning emergency response. Maps of occupant sensitivity can be used to target such support and to prioritise other adaptation options that improve the indoor environment, enhance adaptive capacity, and reduce the UHI effect.
  - High **restricted adaptive capacity** can be reduced through policy interventions such as provision of cool spaces and access to green spaces where people can experience respite from the heat, and funding for household-level retrofit and measures to improve the thermal performance of the rental sector. In addition, complementary policies which target air pollution, noise levels (which limits window opening), and financial deprivation and disability can enhance adaptive capacities, as a co-benefit.

**In conclusion, Task 1 identified that purpose-built high-rise and low-rise flats, mid-terrace, and semi-detached houses are particularly susceptible to indoor overheating**. These types of home were used in Task 2 to conduct the deep-dive analysis of adaptation actions that could reduce sensitivities to overheating.

**Task 2** explored the overheating of typical types of homes using the Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum (TM) 59 Criterion 1, which defines overheating as when the actual operative temperature is equal to or greater than one degree (K) above the limiting maximum acceptable temperature for more than 3% of the occupied hours between May to September. This percentage was quantified for the different types of home and multiple adaptation actions to reduce indoor overheating were tested using modelling under 2030 and 2050 climate scenarios. Task 2 then calculated the cost-benefit of each of the adaptation actions as a ratio of their total costs (capital and maintenance) and the total additional hours spent in thermal comfort to provide a cost per additional hour in thermal comfort. A literature review and stakeholder consultation, involving in-person interviews and an online survey of people in Greater Manchester, were also undertaken to identify the existing socio-technical barriers that may hinder implementation of the actions.

**The key findings of Task 2 are:**

The median percentage of the occupied hours between May to September when the actual operative temperature is equal to or greater than one degree (K) above the limiting maximum acceptable temperature was estimated across all types of homes for the current building stock to be between 6% and 9% under the 2030 scenarios, and between 6% and 11% under the 2050 scenarios. For the 2050 scenarios, this equates to **a median of 110 to 294 occupied hours from May to September where all types of homes are projected to overheat**, as defined by CIBSE TM59 Criterion 1.

**The four most effective actions in reducing indoor overheating in most types of home are:**

- **External window shading**
- **External wall shading**
- **Internal window shading, e.g., blinds or curtains**
- **Increasing the window area that could be opened.**

The levels of effectiveness of these actions vary based on the physical characteristics of the various types of homes. Overall, the most effective actions in the long term are those that reduce solar radiation from penetrating the building, such as window and wall shading measures, however, such measures can be costly and disruptive. The use of internal shading and switching off unnecessary appliances and lights could potentially reduce overheating to some degree in the short term. Opening windows when it is cooler outside could also marginally improve summer thermal comfort, but it may become less effective in the future as outdoor temperatures increase.

When adaptive, behavioural, non-structural actions were applied, the median percentage of the occupied overheating hours was estimated at between 3% and 6% (between 0 and 110 hours above the threshold) under the 2030 scenarios, and between 3% and 7% (between 0 and 257 hours above the threshold) under the 2050 scenarios. **More substantial, passive, structural actions, such as external wall and window shading, yielded greater reductions in overheating overall than behavioural actions.** However, **the structural actions performed slightly better when combined with the behavioural actions and together prevented any overheating, as defined by CIBSE TM59 Criterion 1.** With these combined actions, the median percentage of the occupied hours between May to September when the actual operative temperature is equal to or greater than 1°C above the limiting maximum acceptable temperature was estimated to be between 0% and 1% under the 2030 scenarios, and between 0% and 2% under the 2050 scenarios (i.e., in both cases no hours above the threshold defined by CIBSE TM59 Criterion 1).

**The most cost-efficient individual action was the installation of internal shading** using light (as opposed to black out) shading devices, which could cost between £261-£364 and deliver between 58-150 additional hours of thermal comfort annually, depending on the type of home. While external shutters were more effective, delivering between 172-316 additional hours of thermal comfort, costs were considerably higher, ranging from £2,363- £5,745 depending on the type of home. The structural action with the lowest cost-efficiency was replacing windows to increase the extent to which they could be opened. Overall, **the most cost-efficient approach for all homes was combining internal shading with behavioural actions** on the assumption that the behavioural actions incur no additional cost. This combination resulted in a 3% increase in total time in thermal comfort from May to September at a cost of £0.46 per additional hour in the first year and £0.28 per additional hour spread over the first five years. This assumes that the behavioural action would be followed by the household as modelled.

Over a third of survey respondents and interviewees (36%) responded that they considered themselves or someone with whom they resided were vulnerable. For this study, vulnerable people were defined as children under five years old, people over 65, pregnant women, and/or individuals with a health or other condition that could make it difficult for them to stay cool. **The biggest barriers to implementing the adaptation actions in Greater Manchester identified by the literature review and stakeholder consultation were:**

- **Low awareness of low-cost behavioural measures**, e.g., use of internal shading during the day
- **Many people not considering that addressing overheating in homes is a priority** (despite 70% confirming that they experience overheating)
- **Regulatory restraints and tenure implications** prevent residents implementing actions.

The report concludes that in the short-term, adaptive, behavioural, non-structural measures will go some way to reducing overheating in homes. Support would likely be required to encourage people to implement the structural actions considered here, particularly those with higher capital costs.

# 1. Introduction

The Department for Energy Security and Net Zero (DESNZ) has worked alongside Greater Manchester Combined Authority (GMCA) to understand the vulnerability of their homes and occupants to overheating and identify potential adaptation actions to reduce the sensitivity of homes to overheating.

Extreme heat events in the UK are increasing in frequency and intensity, with the potential to cause significant harm to people. The exposure of our homes to overheating, as a result of these events, is particularly concerning as homes are typically where people spend the majority of their lives and the conditions of home environments are important determinants of people's health and productivity (Mujan *et al*., 2019).

Greater Manchester is a diverse and densely populated[1] metropolitan area where impacts of extreme heat have, and will continue, to cause significant disruption to people's lives. The exceptional heat records of summer 2022, when temperatures in Greater Manchester exceeded 37°C [2], have highlighted the urgent need to further understand and adapt to the projected increases in the magnitude and/or frequency of extreme heat, and their duration, in order to address overheating and avoid harm to the occupants of homes.

Overheating in homes is generally defined as when the local indoor temperature exceeds the acceptable levels for human comfort or human health (Green Alliance, 2024). However, levels of comfort can vary from person to person, including the occupant's activity and clothing levels, and thermal comfort expectations. In addition, several factors can influence the potential for a home to overheat when exposed to warm outdoor temperatures. These include the location of the building, the level of urbanisation, the extent of blue and green infrastructure at neighbourhood level, the physical properties of the home itself, and occupant behaviour inside the home, for example the operation of shading and ventilation systems, and use of lights and appliances (Gill et al., 2007; Climate Change Committee, 2022).

To date, much of the existing UK domestic building stock has not been designed with overheating in mind. Instead, homes have been designed to minimise heat losses and reduce energy demand in winter. Successive Climate Change Risk Assessments (CCRA) conducted by the Climate Change Committee (CCC) have indicated overheating in homes is a risk for the UK[3]. However, the UK's Building Regulations Part O only requires developers to consider overheating for new homes (HM Government , 2021). With 54% of UK domestic building stock built before 1964 and 80% of homes in use today still likely to be

[1] Average population density across the 10 metropolitan boroughs from the 2021 Census was 2,328 residents per square kilometre. The average from all local authorities in England and Wales was 1,714 residents per square kilometre– source Office for National Statistics – Census 2021 Population and household estimates, England and Wales - Office for National Statistics (ons.gov.uk)
[2] 2022_03_july_heatwave_v1 (metoffice.gov.uk)
[3] CCRA3 (2021) presented the 'risk to human health, wellbeing, and productivity from increased exposure to heat in homes and other buildings' as one of the highest priorities for adaptation over the next 2 years.

inhabited by 2050[4], existing research indicates a significant number of properties are vulnerable to overheating (Arup, 2022).

Homes in urban areas are particularly vulnerable to overheating due to a phenomenon known as the Urban Heat Island (UHI) effect, whereby urban areas experience higher air temperatures than the surrounding countryside. Urban areas are characterised by roads and buildings, humanmade heat-absorbing surfaces that displace natural green and blue spaces, which otherwise provide cooling, e.g., through evapotranspiration. This material change, alongside the increased concentration of human behaviours, such as power generation and the use of cars, and the condensed and heightened geometries of cities, traps heat within these areas.[5]

Therefore, in a changing climate, it is a critical concern for public health and the functioning of society to understand in relation to overheating:

- The sensitivity and adaptive capacity of homes and their occupants, and thereby their vulnerability,
- The exposure of homes and their occupants and thereby potential impacts, and
- How homes and the behaviour of their occupants can be adapted to reduce their vulnerability and potential impacts.

This report presents the outputs for the *"Adapting homes to heat in Greater Manchester"* work package, under the Climate Services for a Net Zero Resilient World (CS-N0W) Programme. This research was structured around three key questions:

4. What types of home are most sensitive to overheating?
5. What is the distribution of occupants considered vulnerable to overheating in Greater Manchester?
6. What low-cost, low-regret adaptation actions can reduce sensitivity to overheating in homes?

To answer these questions, two tasks were completed:

- Task 1: A heat sensitivity and vulnerability assessment of homes and occupants in Greater Manchester
- Task 2: A three-component analysis on potential low-cost, low-regret adaptation actions, including:
    a. Modelling to quantify the relative potential of the adaptation actions to reduce indoor overheating
    b. Analysis of the capital costs and benefits of each adaptation action
    c. A socio-technical analysis of the existing barriers that may hinder the implementation of the actions

[4] New Build Standards | Policy | UKGBC
[5] Learn About Heat Islands | US EPA

d. Development of simple infographics showcasing the adaptation actions for occupiers of the most sensitive types of homes

### Task 1

In Task 1, two different assessments were conducted to identify the most sensitive types of homes to overheating and to map their distribution across Greater Manchester. In addition, one of the assessments also reviewed the distribution of occupants considered vulnerable to overheating[6]. UCL used a building-physics housing stock model to represent building characteristics, estimate indoor temperatures and quantify overheating in bedrooms following exposure to current and future climate change scenarios. The model's outputs present the **sensitivity** of different types of homes to overheating and, based on the concentration of each of these types of homes within a UK Census geographic unit, maps the locations where homes are most **sensitive** to overheating. The UoM used a combined heat vulnerability index (HVI) to assess heat vulnerability across the region. The index comprises four domains of vulnerability: outdoor sensitivity, indoor (home) sensitivity, occupant sensitivity, and adaptive capacity. The aggregated results across all four domains represent the composite **vulnerability** of households to overheating within a UK Census geographic unit.

The two research teams from UCL and UoM take distinct approaches to assess heat vulnerability. While UCL focuses purely on the sensitivity of homes to overheating, the UoM has a wider scope that also addresses the sensitivity and adaptive capacity of the occupants.

The factors included in the two assessments include the physical properties of homes and their influence on overheating, as well as some consideration of the level of urbanisation, socio-economic factors, and occupant behaviour and adaptive capacity. While other factors do have an important role to play, they are beyond the scope of this project.

### Task 2

The aim of the second task was a deep-dive analysis to prioritise low-cost, low-regret adaptation actions that can be adopted to reduce the sensitivity of homes and the vulnerability of their occupants to overheating.

[6] The project uses the IPCC Sixth Assessment Report Glossary of Terms to understand the chain of interactions for assessing climate vulnerabilities and risk.
*Sensitivity:* The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change.
*Adaptive capacity:* The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences.
*Vulnerability:* The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. (i.e., Vulnerability = Sensitivity x Adaptive capacity).

The deep-dive analysis consisted of three methodological components:

a. Modelling to quantify the relative potential of the adaptation actions to reduce indoor overheating

b. Analysis of the capital costs and benefits of each adaptation action

c. A socio-technical analysis of the existing barriers that may hinder the implementation of the actions

These three components together can be used to support decision making regarding the appropriate prioritisation and use of the adaptation actions for the different types of home.

The adaptation actions included in this task were identified in consultation with DESNZ and GMCA and build upon the findings of a previous CS-N0W work package, '*Projections of temperature change and impacts on UK housing'* – work package D4 (WPD4). The previous research quantified current and future indoor overheating levels, and heating and cooling requirements across the UK's housing stock, using UK Climate Projections 2018 (UKCP18) weather files. A range of energy retrofit scenarios were assessed, alongside the following cooling actions: external and internal shading; increasing the reflectivity of external building surfaces; and modifying window-opening/closing temperature thresholds. Task 2 builds on this research and considers additional adaptation actions, both behavioural and structural, and evaluates the relative effectiveness of a wide range of iterations in their application, for example through a detailed examination of the impact of different timings and durations of window and shading operation.

The following definitions have been applied in Task 2:

**Thermal comfort** reflects when residents are at home and experience indoor temperatures within recommended levels. Recommended levels in Task 2 are those set by CIBSE TM59 Criterion 1.

**Adaptive**, **behavioural**, **non-structural actions** are things occupants can do to keep cool without any structural changes to their building. For instance, the action of opening and closing windows.

**Passive**, **structural cooling actions** are things occupants can do to keep cool that may require interventions to a building (for example the installation of shutters) or the outdoor environment (for example, planting trees).

In order to support dissemination of the outputs, infographics were developed. These were produced for each of the most sensitive types of homes depicting the adaptation actions that were found to be effective in this research.

This report is structured to present the methodologies and results from Task 1 and then from Task 2, followed by an overall discussion and conclusions.

# 2. Task 1 Methodology

Section 2 details the two methodologies adopted by UCL and UoM, including information on their development, scientific rationales, and how the results have been analysed in this study.

## 2.1 Mapping of sensitivity of homes to overheating

### 2.1.1 Housing stock model development

The data presented in section 2.1 are the output of a building housing stock model of residential indoor environments developed by the UCL Institute for Environmental Design and Engineering as part of an earlier study. This prior study quantified current and future indoor overheating levels, and heating and cooling requirements across the UK's housing stock, using UK Climate Projections 2018 (UKCP18) weather files.

This housing stock model was based on the use of:

- A building physics dynamic whole-building energy performance simulation software programme, EnergyPlus. It is an Open Access, widely tested and validated program, used widely by engineers, architects, and researchers to model energy consumption (for heating, cooling, ventilation, lighting, appliances) and indoor environmental conditions (temperature, relative humidity, air quality etc.).
- Machine learning that reduces the computing time required to produce modelling estimates for a large number of buildings.

To map the sensitivity of homes to overheating for this study, results for the Greater Manchester Area were extracted from the existing housing stock model.

### 2.1.2 Housing stock modelling inputs

Estimates of overheating and energy demand were produced individually for each home address listed in the Energy Performance Certificate (EPC) database for the UK. To produce these estimates, a metamodel of EnergyPlus was trained using a large number of building performance simulations of multiple types of homes, representing the diverse characteristics of the UK building stock. The metamodel was subsequently run for all home addresses in the Greater Manchester Area for which an EPC was available. There were 862,309 EPCs across the Greater Manchester Area with an average coverage of 60.3%. The EPC data coverage at local authority and regional level, compared to the national average is presented in Appendix 1.

As part of this process, digital models of the UK homes were constructed. The geometries of homes included: mid-terrace, end-terrace, semi-detached, detached house; bungalow; low-rise purpose-built, high-rise purpose-built, and converted flat. The digital models were theoretical three-dimensional representations of typical home geometries reflecting interior layouts for each type of home. During modelling, the physical properties of the building materials were derived based on the construction age of the building, as specified in the EPCs. This included the levels of thermal insulation provided by different wall, roof, and window types (which may be higher in more recently built homes), the building fabric airtightness, the thermal mass of the building (how much heat is absorbed by the building to be re-released with a time delay), and the thermal reflectivity of external surfaces. The indoor thermal performance of the building stock was estimated under three UKC18 climate scenarios: 2030 RCP 2.6, 2050 RCP 2.6, 2085 RCP 8.5.

Please note that Manchester weather files were not available at the time of the CS-N0W WPD4 study and, therefore, London weather files were used instead. Given that only a single weather file was used, the modelling does not consider the UHI effect, as this is not typically captured in weather files, or any microclimatic variations near the modelled homes; the estimated relative overheating levels are only the function of building characteristics, assumed occupancy patterns and building operation. Monitored local urban temperature data were obtained in the context of this project and overlaid on the WPD4 outputs (Figure 3-4).

### 2.1.3 Housing stock modelling outputs

The Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum 59 (TM59) was launched in 2017 to standardise indoor overheating assessment methodologies and limit associated risks in new and refurbished residential buildings. It is cited in Approved Document O of the Building Regulations for England that came into force in 2022, and applies to all new homes including care homes, boarding schools, and student accommodation. Within TM59, two criteria are specified to assess overheating: Criterion 1 addresses overheating thresholds for living rooms, kitchens, and bedrooms, while Criterion 2 addresses bedrooms only. In CS-N0W WPD4, overheating of indoor spaces was specifically quantified using Criterion 2 of CIBSE TM59. For homes that are predominantly naturally ventilated, Criterion 2 requires the operative temperature in the bedroom from 10 pm to 7 am to not exceed 26 °C for more than 1% of annual hours. In addition to projected overheating, heating and cooling demand were also modelled in WPD4.

The modelling outputs for the Greater Manchester Area were selected from the WPD4 UK-wide database. This dataset included the boroughs of: Bolton, Bury, Manchester, Oldham, Rochdale, Salford, Stockport, Tameside, Trafford, and Wigan. These outputs were initially extracted on a building-by-building basis and subsequently aggregated at the Lower Layer Super Output Area (LSOA) and Middle Layer Super Output Area (MSOA) level.[7] For each LSOA/MSOA in Greater Manchester, modelling results were aggregated for

[7] LSOAs and MSOAs are UK Census geographic units. LSOAs typically contain between 400 and 1,200 households (between 1,000 and 3,000 residents). MSOAs are made of LSOAs, usually four or five, and contain between 2,000 and 6,000 households (between 5,000 and 15,000 residents). LSOA and MSOA boundaries fit within local authorities.

all domestic buildings within that area for which an EPC was available. Detailed assumptions are provided in the previous report on the WPD4 study.

## 2.2 HVI (Heat Vulnerability Index)

The UoM developed a HVI to assess the vulnerability of Greater Manchester residents in their homes to overheating. This index combines spatial information from a range of indicators to give an overall vulnerability score or rank for people living in each LSOA. A higher score indicates higher vulnerability to heat within the LSOA.

### 2.2.1 Domains

The index is split into four domains that contribute to vulnerability: “outdoor sensitivity”, “indoor (building) sensitivity”, “occupant sensitivity” and “adaptive capacity”:

- **“Outdoor sensitivity”** accounts for characteristics of the external environment around people’s homes that may exacerbate external temperatures. Outdoor sensitivity covers features which contribute to the UHI effect, which can vary within an urban area, exacerbating exposure to extreme heat in some areas (Stone *et al*., 2010; Habeeb *et al*., 2015). These features include land cover, the height of buildings, population density (as a proxy for anthropogenic heat emissions), and elevation (i.e., height above sea level).
- **"Indoor (building) sensitivity”** comprises indicators which mediate the indoor temperature of residential buildings, as compared to ambient air temperature. These indicators consider the relationship between the type of home and its thermal characteristics as well as overcrowding (which increases internal heat gains) and the presence of green (and blue) spaces in the immediate vicinity of homes (which can reduce internal temperatures through shading and changing the microclimate).
- **“Occupant sensitivity”** covers demographic characteristics (including age, health and disability) that have been identified by epidemiological studies of past heat events as important factors affecting the sensitivity of people to overheating.
- **“Restricted adaptive capacity”** covers indicators relating to occupants and their homes that prevent them from adjusting to the potential for becoming overheated. This includes income or factors that would affect individuals’ likelihood to open windows at night, such as air pollution, noise, or crime. In this index a high score means that adaptive capacity is restricted.

### 2.2.2 Indicator selection

For each domain, a set of indicators were selected based on the work of Brown (2022). These indicators were selected based on a literature review of existing heat vulnerability studies, a review of factors influencing heat vulnerability, and a regression test between Greater Manchester temperature data and the indicators related to the UHI. The Pearsons Correlation test was then used on all indicators to ensure there was not any multicollinearity within domains. Correlated indicators were either removed or combined and weighted together within a domain to avoid double counting. This step avoids bias arising from the over representation of correlated indicators within the index while still identifying areas of high vulnerability. For example, income and education deprivation are highly correlated, while both are found to influence adaptive capacity, only income is selected for the index, as it is more overtly connected to the ability of people to spend money on adaptation measures.

Appendix 1 provides additional detail on the indicators used within each of the HVI's four domains.

# 3. Task 1 Results

Section 3 presents the results of the two approaches undertaken by UCL and UoM for the assessment of sensitivity to overheating. A comparison of the findings is included in this section.

## 3.1 Mapping of the sensitivity of homes to overheating

This section presents the outputs of UCL's approach described in Section 2.1.The first series of maps (Figure 3-1) shows the geographical distribution of the average percentage of time that bedrooms are projected to experience nighttime temperatures above 26°C, which generally decreases with increasing distance from the city centre. A clear trend of increasing overheating levels is observed as the climate becomes warmer if no cooling measures are applied. Using the same assumptions for uptake of air conditioning used by CS-N0W WPD4[8], cooling demand increases towards the end of the century (Figure 3-2), within LSOAs with increased demand clustered in the centre of Manchester. Based on the existing assumptions, a considerable increase in air conditioning uptake is observed by the end of 2085, rising more than tenfold compared to the estimate for 2030. However, it is important to note that even though the initial increase from 2030 to 2050 appears small, the uptake more than doubles between these two periods. An inverse relationship is observed for heating demand (Figure 3-3), with the city centre appearing to have the warmest homes, characterised by lower heating needs. Across all projected future scenarios, there is a consistent trend of increasing temperatures. This rise is manifested as a decrease in heating demand, coupled with an increase in both cooling demand and the number of hours exceeding comfortable summer indoor temperature thresholds.

As all homes were modelled using weather files for the same location, i.e. without including local urban climate variation, these results isolate the effect of building characteristics on overheating and energy demand. UHI data provided by the UoM were subsequently overlaid on indoor overheating estimates (Figure 3-4). Outdoor local urban temperatures and indoor home temperatures are generally warmest in the centre; as we move away from the centre, both indoor and outdoor temperatures tend to decrease. However, it is not possible to establish a direct link between these two datasets due to their distinct nature. The building performance calculations are aggregated data from individual building estimates of overheating and energy demand, corresponding to specific areas, while the UHI dataset consists of ambient temperature readings at specific points in the city. There is a complex, intricate relationship between indoor temperatures, the UHI and urban microclimates, and disentangling this relationship can be challenging. However, overlaying these maps demonstrates that, across the Greater Manchester Area, it is likely that homes with high sensitivity to heat (high indoor overheating levels and associated cooling demand) are

[8] CS-N0W D4 Report– see Section 2.3.5. The assumptions were based on Crawley, J., Wang, X., Ogunrin, S., Vorushlyo, I., & Taneja, S. (2020). Domestic Air Conditioning in 2050. Increasing Visibility of Underrepresented Groups in Energy Research (IVUGER) Report.

likely to be found in areas of high UHI Intensity, primarily in central locations and should, therefore, be prioritised for further modelling.

Figure 3-1: Average percentage of time that bedroom temperatures exceed 26°C from 10 pm to 7 am under each scenario

a) 2030 RCP 2.6, b) 2050 RCP 2.6, and c) 2085 RCP 8.5

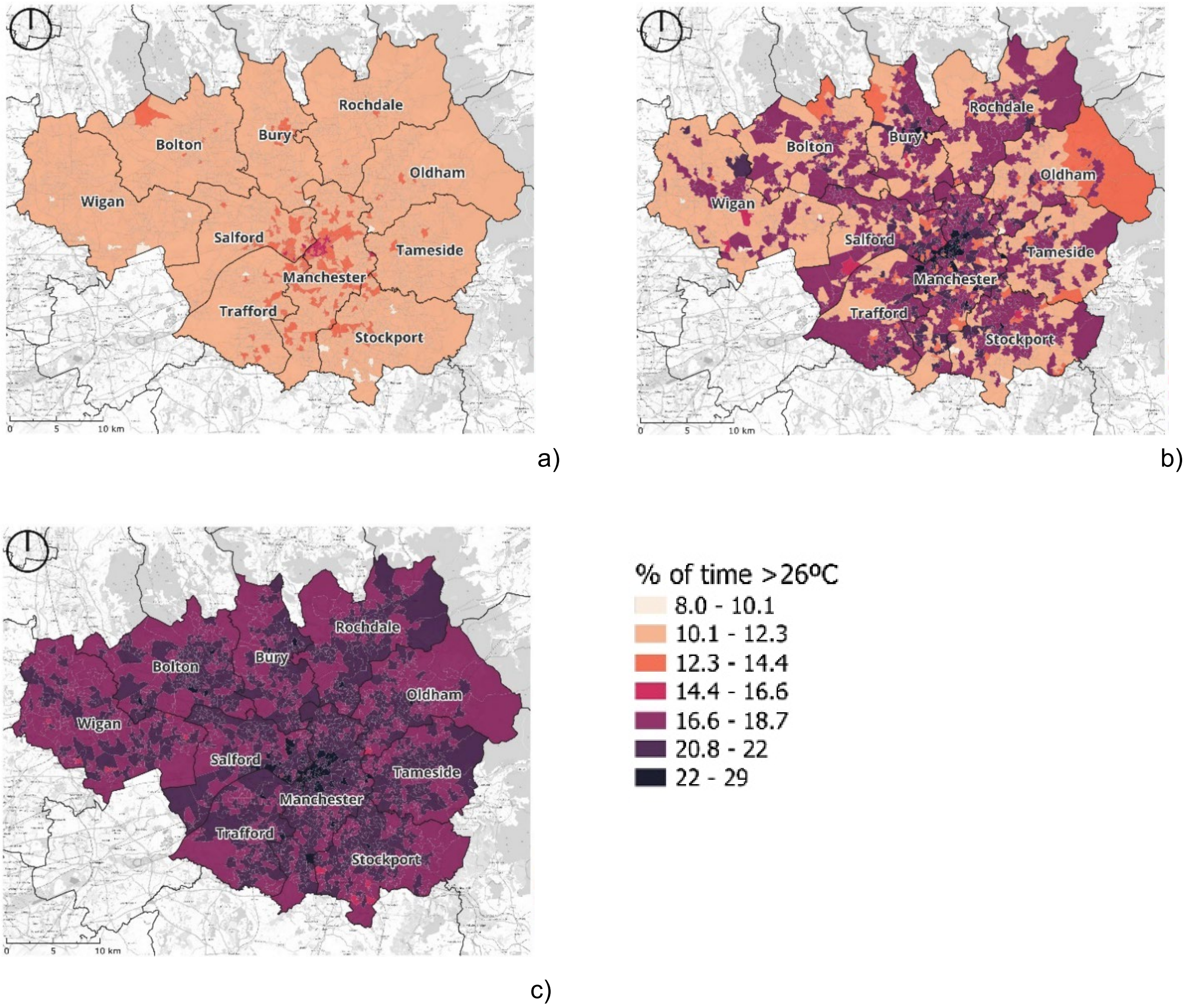
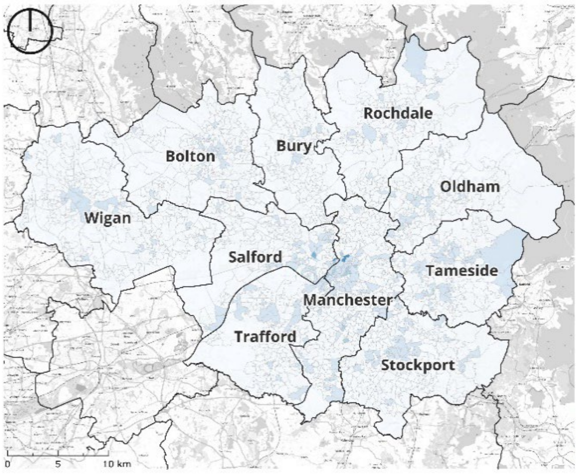


Figure 3-2: Average projected end energy use for cooling under each scenario

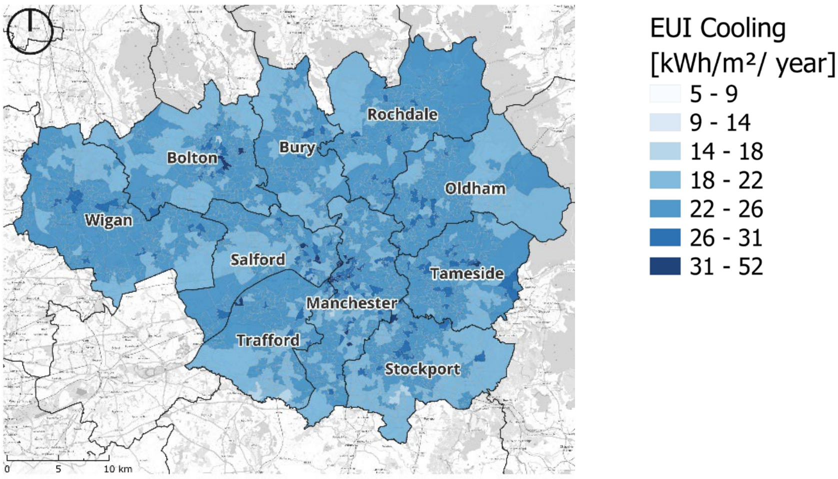
a) 2030 RCP 2.6, b) 2050 RCP 2.6, and c) 2085 RCP 8.5

The average end energy use for the scenarios are 7.7kWh/m2/year, 8.5kWh/m2/year, and 23.7kWh/m2/year respectively.


a)




b)




c)

Figure 3-3: Average projected end energy use for heating under each scenario

a) 2030 RCP 2.6, b) 2050 RCP 2.6, and c) 2085 RCP 8.5

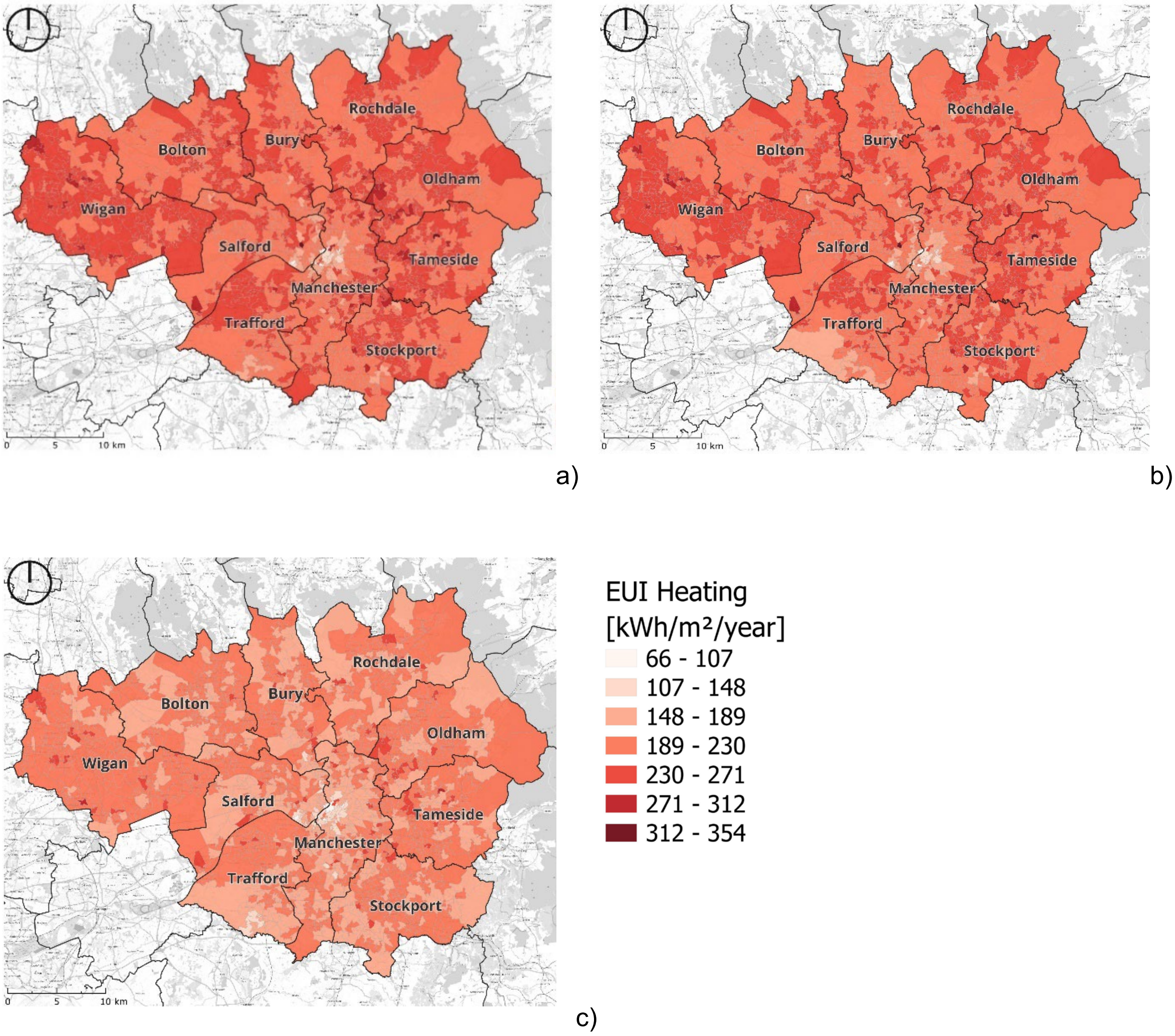
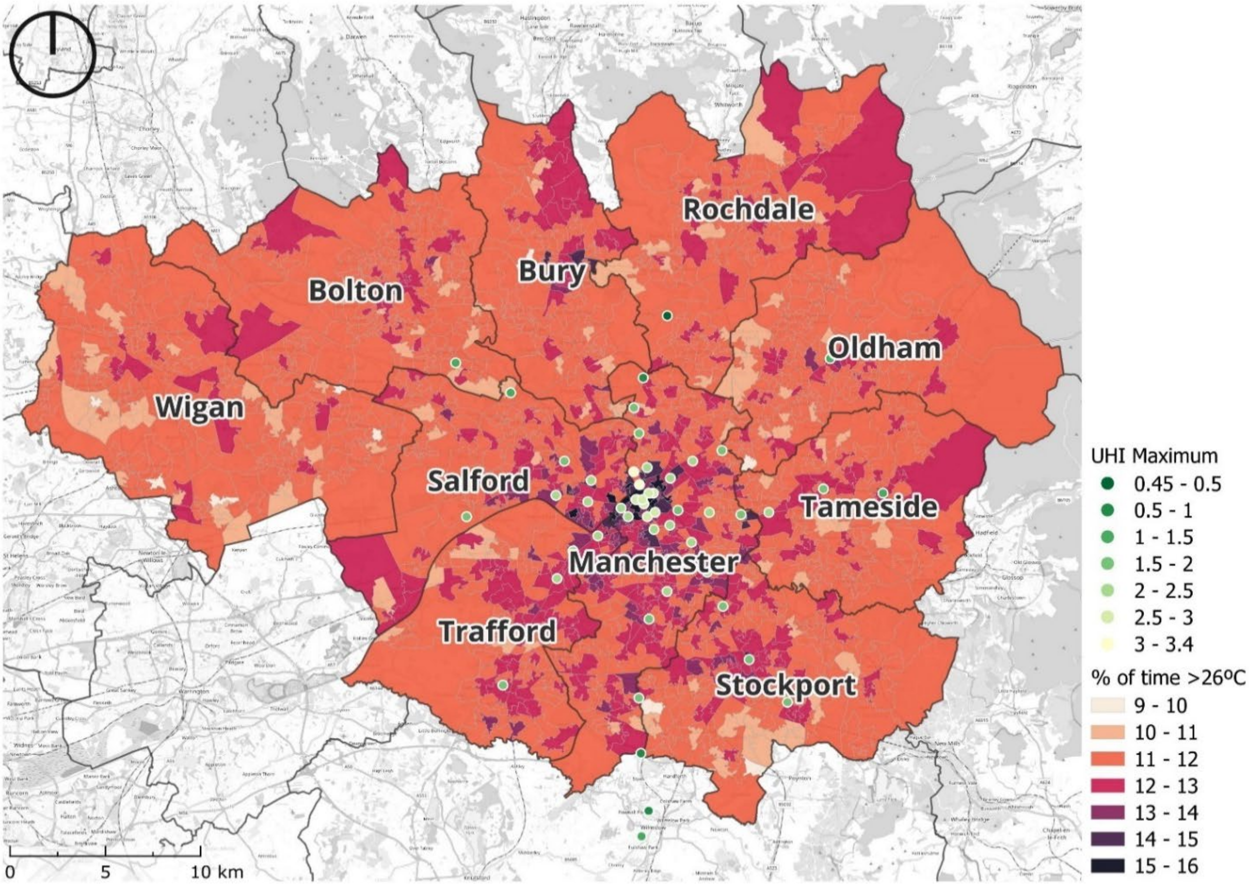


Figure 3-4: Average percentage of time that bedroom temperatures exceed 26°C from 10 pm to 7 am (2030 RCP 2.6 scenario) and maximum UHI effect

The UHI maximum shows the highest temperature difference between the sensor location and the Met Office station at Rostherne during the observation period.




## 3.1.1 Identification of homes prone to heat

The underlying CS-N0W WPD4 building-by-building dataset was analysed aiming to identify the homes and LSOAs that are more sensitive to overheating in the 2030 RCP 2.6 scenario. It was found that building type/geometry is one of the most influential factors for overheating. In Figure 3-5, the distribution of the percentage of time bedroom temperatures exceeded 26ºC for modelled homes in Greater Manchester are presented by type of home, arranged in ascending order based on the median value of each type of home.

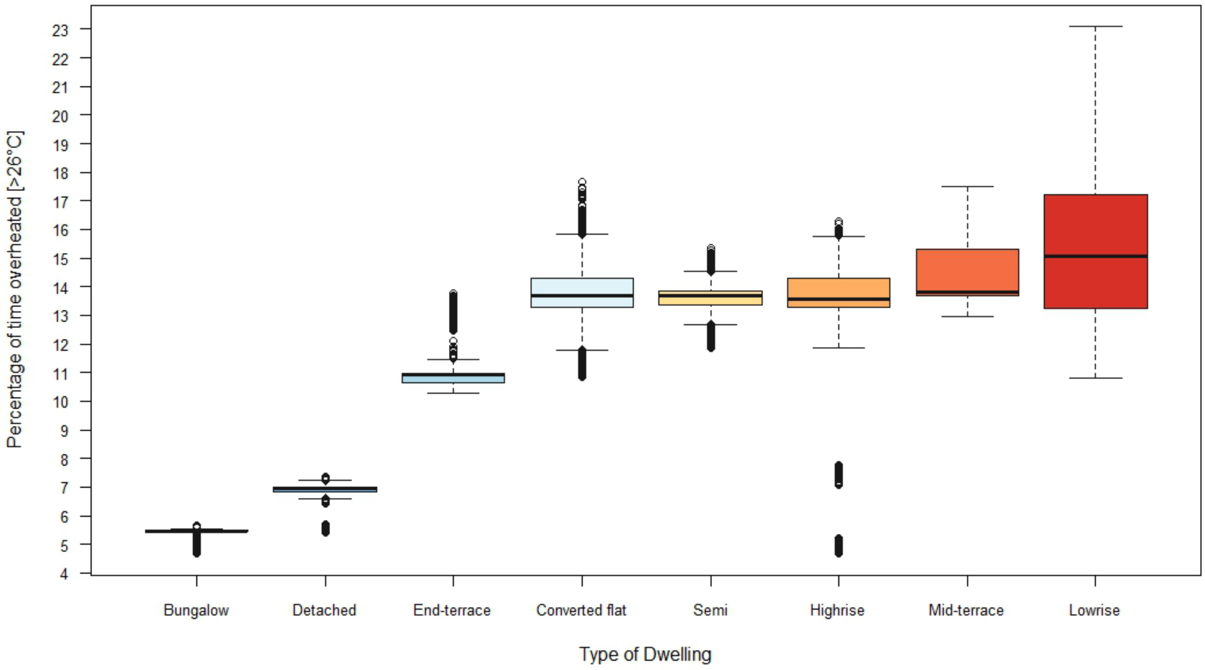
This graph reveals the overall distribution of the homes most sensitive to overheating, coloured in red, dark orange, light orange and yellow, corresponding to low-rise flats, mid-terrace houses, high-rise flats, and semi-detached houses. These findings suggest that physical characteristics, such as the geometry of homes, substantially affect the sensitivity of a home to overheating. Even though the converted flat appears to be one of the most sensitive to overheating, it is important to note that this typology indicates a change of use in the building rather than the physical attributes of the building.[9] Unfortunately, the EPC database does not provide additional useful information to allow further modelling of these types of home.

The prevalence of types of home across the city should be considered. As shown in Figure 3-6, the four most heat sensitive types of home account for almost three quarters of the Greater Manchester housing stock. Specifically, low-rise and high-rise flats, mid-terrace and semi-detached houses comprise 73.8% of the stock.

A further analysis was conducted to investigate a possible connection between the construction age of homes and their sensitivity to overheating in the selected homes, illustrated in Figure 3-7.The relationship of overheating with construction age is less clear compared to the geometry of homes. Based on modelling assumptions, both older and more recently built homes appear to be sensitive to overheating. It is likely that some of the more recently built homes may be more sensitive to overheating due to energy efficiency trends including higher levels of building fabric thermal insulation and airtightness without providing additional cooling means. In Figure 3-7, a similar trend as in Figure 3-5 is observed, with similar values across all construction age bands of the homes, and with limited variation in the median values between construction age bands and overall data distribution. Figure 3-8, illustrates the distribution of homes across different construction age bands in the Greater Manchester Area. The graph shows that over 43% of the homes were constructed before the 1950s, and 78% were built before 1982.

[9] Converted buildings could be, for example, larger houses divided into flats, non-domestic buildings (offices, retail etc.) that were later converted into housing (e.g., through Permitted Development Rights).

Figure 3-5: Box plot of the percentage of time bedroom temperatures exceed 26°C in homes in Greater Manchester by type of home (2030 RCP 2.6 scenario)




As shown in Figure 3-6, the most frequently occurring types of home in the EPC database for Greater Manchester are semi-detached houses, followed by mid-terrace houses and low-rise flats.

Figure 3-6: The percentage of homes by type of home within Greater Manchester

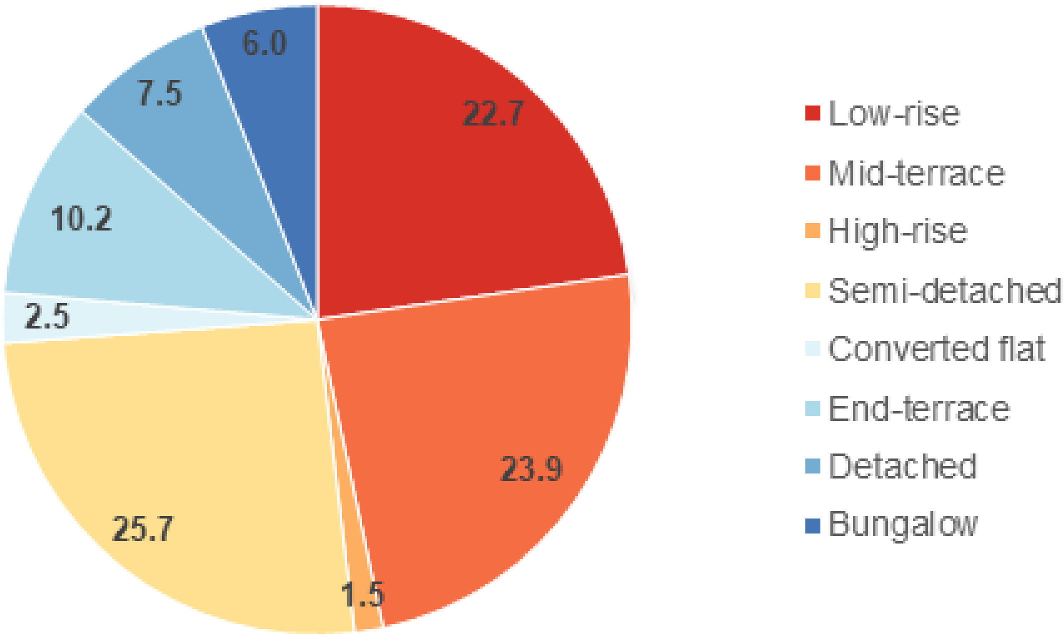


Figure 3-7: Box plot of the percentage of time bedroom temperatures of all homes in Greater Manchester Area exceed 26°C by construction age band of the home (2030 RCP 2.6 scenario)

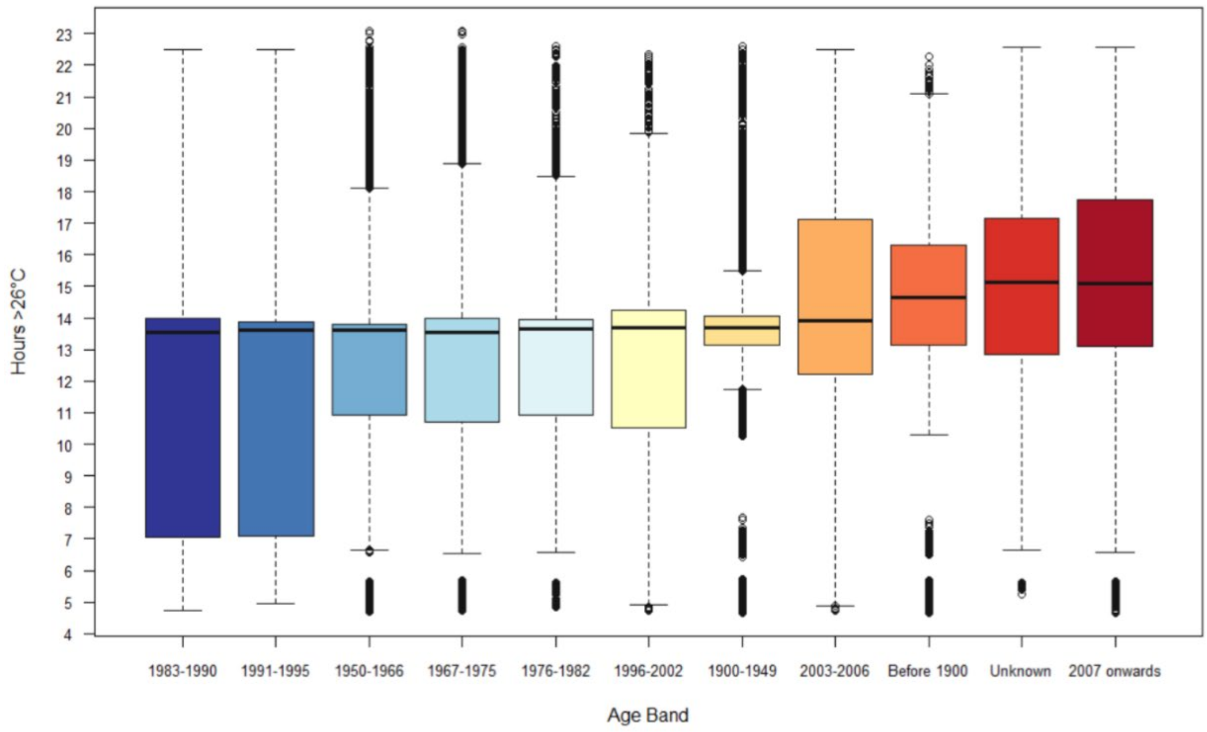
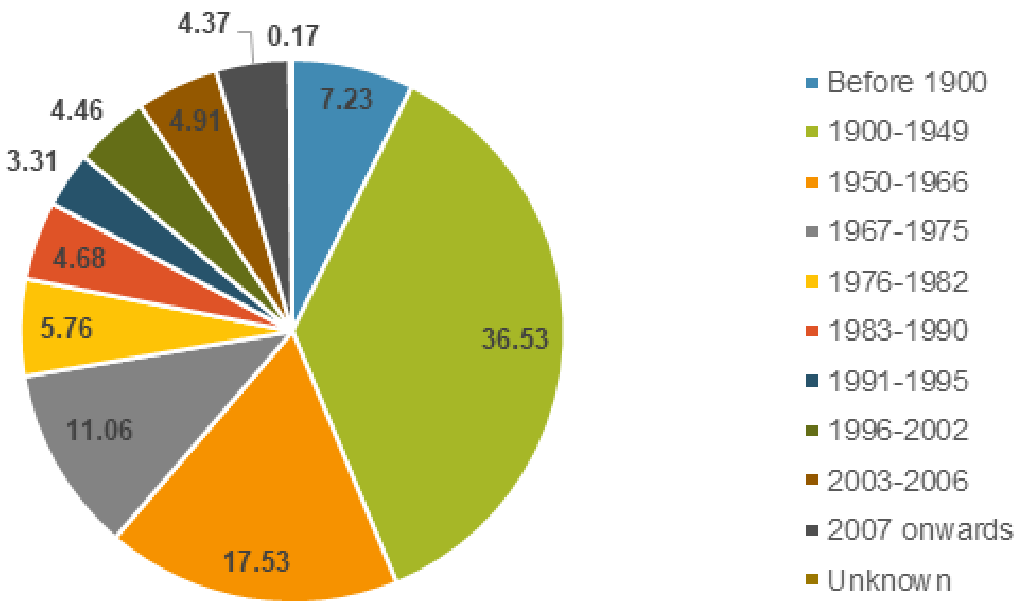



Figure 3-8: The percentage of homes by age band within Greater Manchester



## 3.2 HVI results

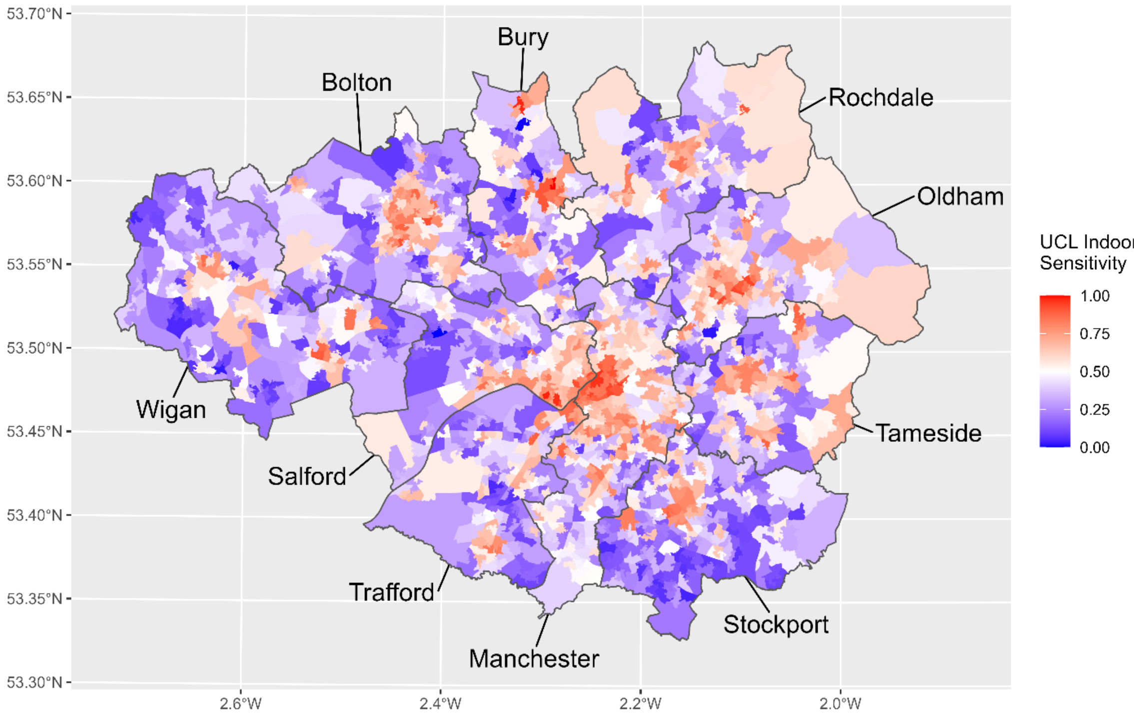
Section 3.2 presents the full results of the UoM HVI described in Section 2.2. The results are presented for each of the four domains. First, for more direct comparison with the UCL model results, the indoor sensitivity domain is presented with only indicators related to building properties included (age and type of home, glazing and roof energy efficiency). The results are then presented for the indoor sensitivity domain *including* the over-occupancy and proximity to greenspace indicators to visualise how this influences overall sensitivity. In section 3.2.3 to 3.2.5 the results for the additional domains of outdoor sensitivity, occupant sensitivity and adaptive capacity are shown. Finally, the results of combining the domains into a single composite Heat vulnerability Index are shown.

Appendix 2 provides additional context for the individual indicator results within each of the four domains.

### 3.2.1 Indoor sensitivity (excluding over-occupancy and NDVI)

Figure 3-9 shows areas of high sensitivity in the urban areas of Wigan, Atherton, Bolton, Bury, Rochdale, Oldham, Ashton Under Lyme, Stockport, Altrincham, and Old Trafford. In general, it also indicates less sensitivity in suburban areas, with exceptions in the east of Greater Manchester. Within Manchester, the picture is more complicated with pockets of high indoor sensitivity within the city centre, to the north and east and along the Oxford/ Wilmslow Road.

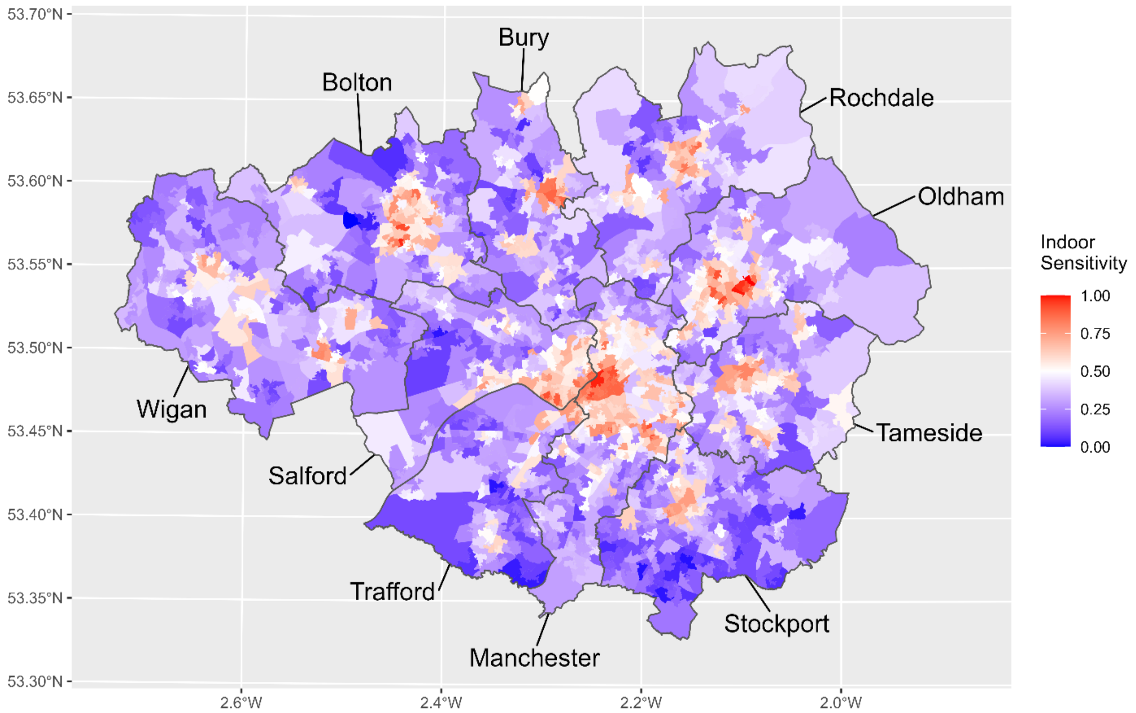
Figure 3-9: A map indicating the relative indoor sensitivity of homes based on their characteristics (excluding over occupancy and NDVI factors) for direct comparison with UCL




## 3.2.2 Indoor sensitivity (including over-occupancy and NDVI)

The indoor sensitivity domain here is different to the indoor sensitivity presented in the previous section because additional factors – removed in section 3.2.1 for consistency in with the UCL model – are included here covering over occupancy and greenspace (NDVI). The indoor sensitivity domain map in Figure 3-10 identifies LSOAs where there is a high concentration of buildings that are more sensitive to overheating (subject to EPC coverage).

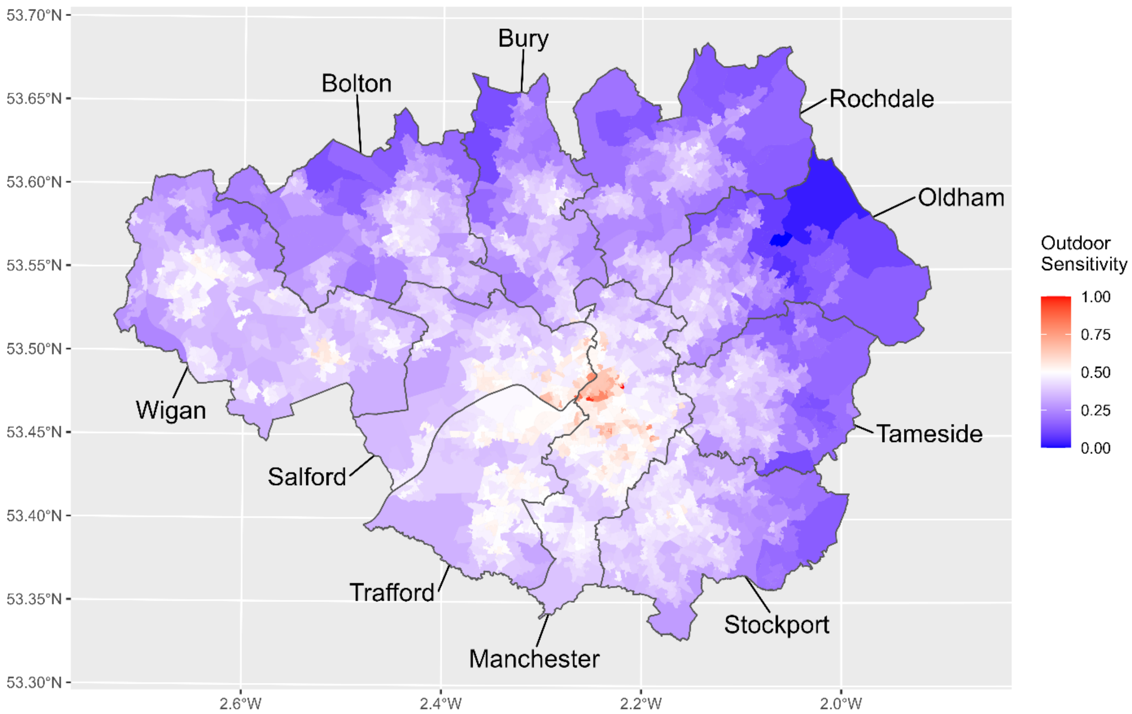
Figure 3-10: A map indicating the relative indoor sensitivity of homes based on all indicators (higher glazing, type of home, age of home, roof insulation, over-occupancy and NDVI factors)




## 3.2.3 Outdoor sensitivity

Figure 3-11 presents the range of normalised domain scores by Greater Manchester councils. For the overall outdoor sensitivity domain score, equal weighting is distributed between building height, elevation, population density, and domains related to ground coverage (NDVI, greenspace, and water coverage). The outdoor sensitivity domain map identifies LSOAs where ambient air temperatures are likely to be elevated compared to their rural equivalents. Interventions here to reduce sensitivity would target increasing green and blue space across the LSOA such as through new parks, green walls and roofs, street level tree planting, re-exposing covered waterways and ensuring existing green-blue space is protected and maintained. Additional interventions include changing the surface albedo of buildings and other surfaces to reduce the absorption of sunlight.

Figure 3-11: Overall domain scores for outdoor sensitivity for each borough

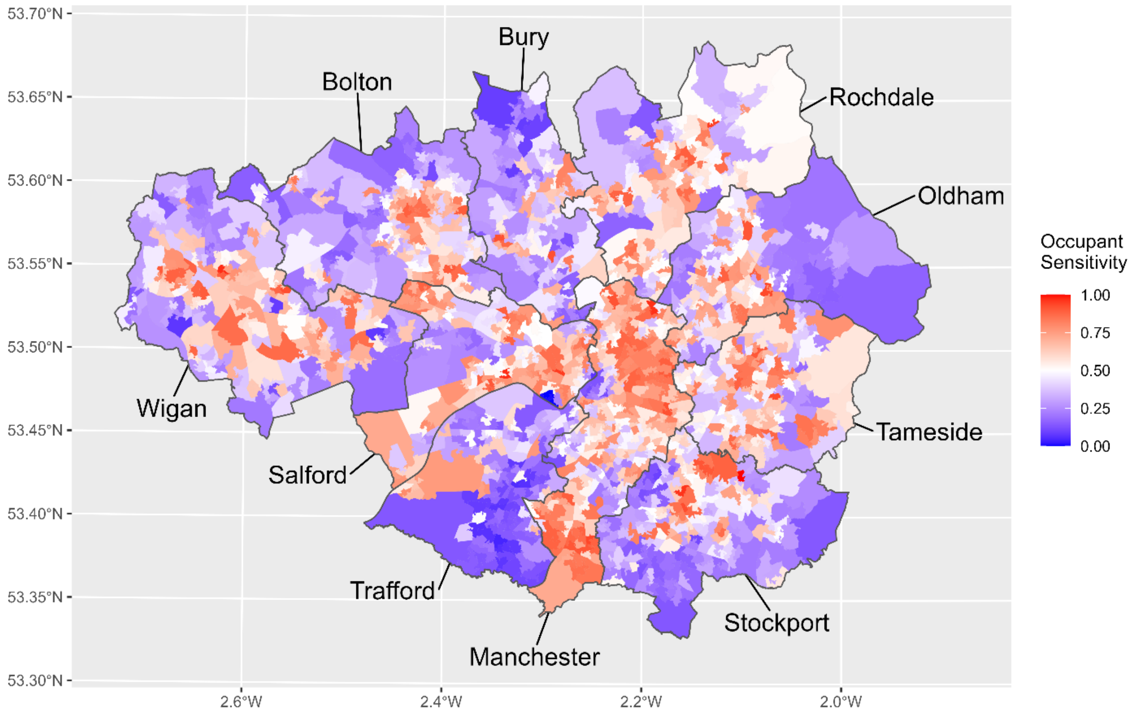



Manchester and Salford have the highest sensitivity according to median domain score and the number of LOSA's falling within the worst 10% across Greater Manchester. This is driven by how urbanised these areas are, having the lowest ground cover of water, woodland, and vegetation, combined with high population density, and high building heights. Trafford also has high sensitivity, likely due to having lowest median woodland cover, low elevation, and relatively high median building heights. No borough has a significantly lower outdoor sensitivity than others; Bolton, Bury, Oldham, Rochdale, Stockport, and Tameside have similar scores, likely as none of them have particularly high or low sensitivity in any of the individual indictors compared.

### 3.2.4 Occupant sensitivity

Figure 3-12 presents the range of normalised domain scores by borough and  presents the highest 10% of LSOAs for occupant sensitivity. Occupant sensitivity maps identify LSOAs where there are high concentration of households with occupants who would be more adversely affected in hot weather. Measures here could include working with existing health care providers and community groups (e.g. those with older people or with disabilities / poor health) to increase their awareness of the risks to their users during heat waves and increase support measures e.g. increased frequency of visits and contact, advice on how to keep occupant's cooler during hot weather, and emergency response plans. Note there will also be sensitive people in LSOAs in otherwise 'low sensitivity' areas who need consideration too.

Figure 3-12: Overall domain scores for occupant sensitivity for each borough

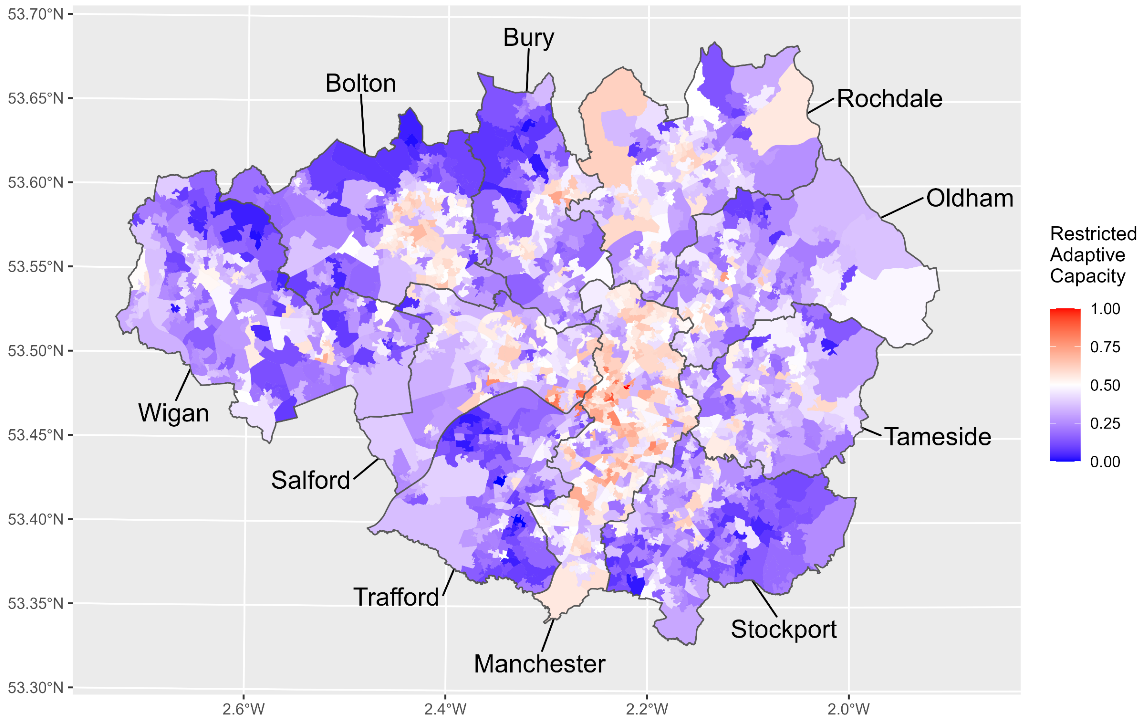



## 3.2.5 Restricted adaptive capacity

Figure 3-13 maps the range of normalised domain scores by borough identifying LSOAs where there is a high concentration of households with poor adaptive capacity.

Manchester has the both the highest median score across its LSOAs and the highest proportion of LSOAs falling into the worst 10% across the whole of Greater Manchester. A high score indicates low or restricted adaptive capacity. Twelve percent of Salford and Bolton's LSOAs also fall in the worst 10%. In contrast, Bury, Tameside, Trafford, Wigan, and Stockport have a very small proportion of LSOAs falling in the worst 10% for adaptive capacity. Manchester's result is particularly striking when combined with the overall results of the outdoor sensitivity domain described above in Section 3.2.3. Manchester borough is most likely to have the highest outdoor temperature and their residents having the least ability to adapt to them.

Figure 3-13: Overall domain scores for restricted adaptive capacity across Greater Manchester

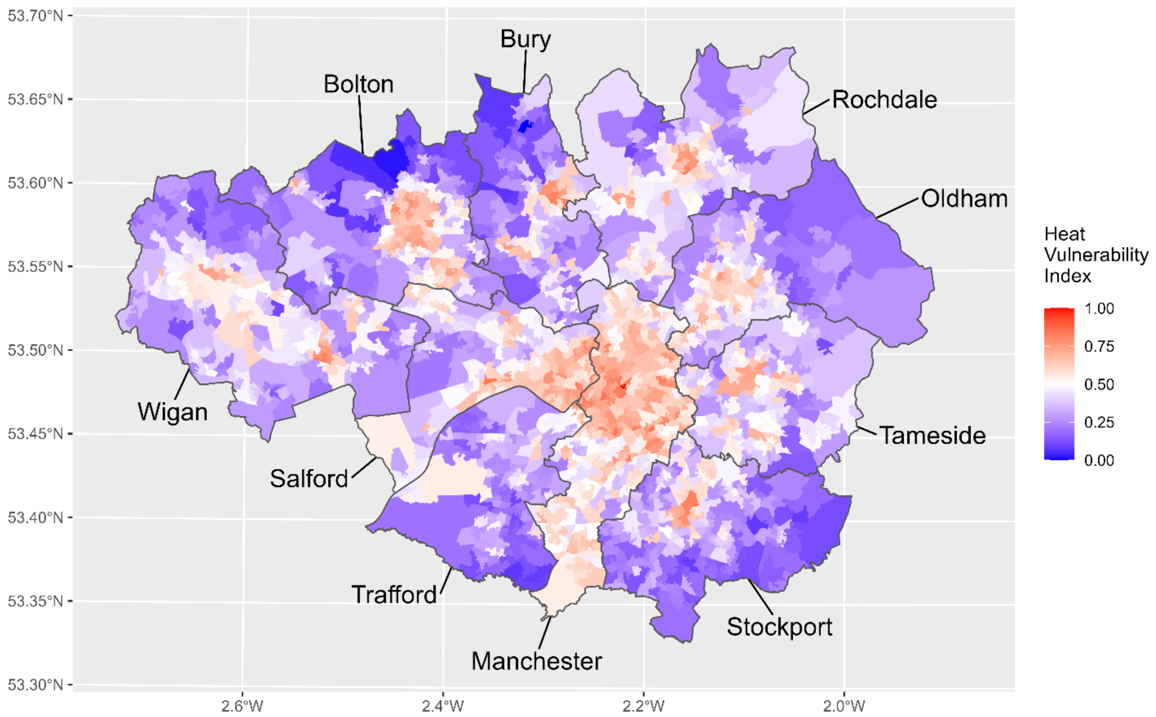



The spatial analysis shows that there is variation in adaptive capacity within each borough, and whilst Manchester is most vulnerable overall, there are LSOAs within each local authority that are vulnerable to overheating due to poorer adaptive capacity. Therefore, whilst Manchester is still clearly the worst performing in terms of adaptive capacity, specific LSOAs within other boroughs should also be considered if implementing any interventions for overheating that are related to this domain.

### 3.2.6 Results of the overall composite heat vulnerability index

This section discusses the results of the overall composite HVI which combines the four presented domains of heat sensitivity (indoor sensitivity (including over-crowding and NDVI), outdoor sensitivity, occupant sensitivity, and adaptive capacity). Figure 3-14 presents a map of the composite HVI scores at LSOA level by borough.

Figure 3-14: Final heat vulnerability index scores combining all domains for each borough (indoor sensitivity, (including over-crowding and NDVI); outdoor sensitivity; occupant sensitivity; and adaptive capacity)




Manchester and Salford have the highest mean and median score for the overall index. Bury, Tameside have the lowest mean and median scores. The map also shows whilst most boroughs have pockets of high vulnerability within larger areas of reduced vulnerability, Manchester's vulnerability is consistently high. There is also higher vulnerability within the city centre area (which is in the north of the borough). The most vulnerable areas for Salford are in the east of the borough; this is also the most urban and built-up area.

# 4. Task 2 Methodology

This section describes the components of the deep-dive analysis:

a. Modelling to quantify the relative potential of the adaptation actions to reduce indoor overheating

b. Analysis of the capital costs and benefits of each adaptation action

c. A socio-technical analysis of the existing barriers that may hinder the implementation of the actions

d. The creation of five infographics to disseminate the results

For a full detailed methodology of each component in the deep-dive analysis, please see Appendix 3.

## 4.1 Modelling

### 4.1.1 Method used

Different types of homes and adaptation actions were modelled using EnergyPlus, a widely tested and validated building thermal and energy performance simulation software (US DoE, 2024). Simulations were run using UK Climate Projections 2018 (UKCP18) 2030 and 2050, RCP 2.6 and 8.5 (50$^{th}$ percentile) weather files for Manchester. Overheating was assessed by the method set by CIBSE in TM59 using Criterion 1, according to which the number of hours during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3% of occupied hours. ΔT is defined as the difference between the operative temperature in the room at any time and the limiting maximum acceptable temperature[10]. The Energy Use Intensity (EUI) for in kWh/m² per year for heating and cooling was calculated for each type of home, adaptation action, and climate scenario. The season from October to April was considered for heating, and from May to September for cooling, using an electric heater/cooler sized for each room. Cooling was operated during the daytime when the indoor temperature exceeded 26°C in homes that adopted air conditioning. Similarly, heating was operated at 20.4°C during occupancy hours. Windows were assumed to remain closed when a cooling system was switched on, therefore the adaptive actions related to window opening are not included in the subsequent analysis. The EUI for heating was calculated to identify potential impacts of the overheating reduction strategies during winter.

[10] According to CIBSE TM52, it is recommended that for newbuilds, major refurbishments and adaptation strategies, the maximum acceptable temperature ($T_{max}$) should be calculated as a function of the running mean of the outdoor temperature ($T_{rm}$) using the equation: $T_{max} = 0.33\ T_{rm} + 21.8$, where Tmax is the maximum acceptable temperature (°C). By way of illustration, for a constant outdoor temperature of 30°C, $T_{max}$ = 0.33 x 30°C + 21.8°C = 31.7°C, therefore the % of occupied hours the room experiences temperatures greater than or equal to one degree (K) above 31.7 °C, i.e. greater than or equal to 32.7 °C, would be recorded.

Results from the building performance simulations were analysed to quantify the percentage of occupied hours during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive. The actions were ranked in ascending order based on their effectiveness in reducing overheating levels, based on this criterion. Further details about the modelling methods are provided in Appendix 3.

## 4.2 Cost-benefit analysis (CBA)

### 4.2.1 Method used

To produce the cost-benefit analysis, costs were gathered for the adaptation actions, including capital and/or maintenance costs. Quotes were sourced from five different suppliers with a preference for Greater Manchester suppliers, where available. Costs were gathered for the materials and installation for each action, some quotations grouped these together. The actions costed included: installing internal shading (white and blackout); installing external shading devices (shutters); upgrading or replacing windows to increase their openable area; modifying the reflectivity of homes (painting in light colours); and the combinations of these actions. The determined benefit was the total number of additional hours spent in thermal comfort above the base case level of comfort for each type of home with no adaptation actions installed. This information was provided by the modelling.

The cost-benefit analysis was calculated as a ratio of the total costs (capital and maintenance) and the total additional hours spent in thermal comfort to provide a cost per additional hour in thermal comfort. The cost-benefit ratio was calculated for 1 year and 5 years.

The full methodology can be found in Appendix 3 and sources for the costs gathered can be found in Appendix 5.

## 4.3 Socio-technical analysis

### 4.3.1 Literature review

A literature review was carried out to understand what research had already been conducted on actions to adapt to indoor overheating and related barriers. In total, the literature review consulted 21 academic papers, 4 grey literature documents, 7 institutional documents, and 2 project reports (34 documents in total).

### 4.3.2 Stakeholder survey and interviews

As part of the stakeholder consultation 55 in-person interviews were held in addition to an online survey.

The survey and interviews included a set of questions that aimed to gather insights on the demographics of individuals consulted in the study. Participants were invited to share whether they or any of the people in their households were vulnerable to hot weather, how many people lived in their households, if they were renters or owned their own homes, and how long they had resided in their properties.

To identify any barriers and opportunities for Greater Manchester's residents to address overheating in their homes, a list of adaptation actions was explored with survey respondents and interviewees that could be implemented by residents to alleviate overheating. The adaptation actions explored in this stakeholder consultation are consistent with the series of adaptation actions used to quantify reduction in indoor temperatures in the modelling and cost-benefit analysis sections of this study.

Participants were asked to consider which actions they had implemented previously and rank their perception of their effectiveness. To understand the potential barriers to implementing these behaviours or actions, participants provided their reasoning for why they might not undertake or install these adaptation actions. The adaptation actions explored were the following:

- Opening windows
- Keeping internal blinds closed during the day
- Keeping external shutters closed during the day
- Using a ceiling/desk/floor fan
- Using air conditioning
- Painting external surfaces in light colours
- Shading from external structures
- Applying films to windows

## 4.4 Infographics

To disseminate the results, infographics were developed for the public as a clear and simple form of communication.

Several infographic styles were reviewed, and a graphic format was chosen which adapted an existing BBC infographic on how to keep homes cool.[11] Wording for the simple advice included on the infographics was reviewed by the Greater Manchester Steering Group for Heatwave Communications.

# 5. Task 2 Results

## 5.1 Comparative evaluation of the effectiveness of individual actions

The effectiveness of individual adaptation actions, listed in Table 5-1, and their combinations on reducing overheating were quantified. It is worth noting here that, for the action covering the modifications to window opening/closing behaviour based on indoor/outdoor temperatures, it was assumed that occupants already operated windows in the base case as this was deemed a more realistic scenario. In contrast, for all other

[11] How to keep your home cool in hot weather - BBC News

actions tested, the base case did not include the corresponding action. Therefore, when comparing the relative effectiveness of individual actions, the results of this study may appear to underestimate the effectiveness of opening windows (when compared to the base case).

Table 5-2 provides a summary ranking of adaptive, behavioural, non-structural actions across the five types of homes, highlighting that the two most effective actions reduce solar heat gains through windows using internal shading systems. The ranking of strategies was found to be the same for all homes. Table 5-3 provides a summary ranking of passive, structural actions, where the most effective actions overall are those that block or minimise solar heat gains entering the building, such as systems that shade the windows (for example, external shutters) or building walls (for example, vegetation or other structures). Increasing the area of windows that could be opened, and therefore, ventilation rates, may be particularly beneficial for flats, possibly due to their limited existing indoor-outdoor air exchange rates. Semi-detached houses appear to also benefit from increasing external wall reflectivity, potentially due to the larger influence of the external wall area compared to other types of home. Table 5-4 summarises key findings on the impact each action has on the effectiveness of cooling.

Table 5-1: Actions tested for reducing overheating

| Action description | Type of action | Base case | Additional settings | Total number of additional iterations | Impact |
|---|---|---|---|---|---|
| Reducing internal heat gains from equipment and lighting | Adaptive (non-structural) | 100% | 66%, 33% | 2 | Time in comfort and EUI for cooling and heating |
| Internal window shading (using white or blackout curtains) | Adaptive (non-structural) | No curtains | Shading closed between: 6 am - 10 pm, 7 am - 9 pm, 8 am - 8 pm, 9 am - 7 pm 10 am - 6 pm | 10 | Time in comfort and EUI for cooling |
| Modifying window opening and closing behaviour based on indoor and outdoor temperatures | Adaptive (non-structural) | Windows open when the indoor temperature reaches 22°C and close when the outdoor temperature reaches 33°C | Windows open when the indoor temperature reaches 18, 20, 24, 26, 28°C and close when the external temperature reaches, 24, 26, 28, 30°C | | Time in comfort |
| Modifying the area of windows that could be opened | Passive (structural) | Area of windows that could be opened set at 33% | 20%, 40%, 60%, 80% | 4 | Time in comfort |
| External window shading (using shutters) | Passive (structural) | No external shading | Shading closed between: 6 am - 10 pm, 7 am - 9 pm, 8 am - 8 pm, 9 am - 7 pm 10 am - 6 pm | 5 | Time in comfort and EUI for cooling |
| External wall shading (using vegetation or other structures of varying translucency levels) | Passive (structural) | No shading | Blocking the total incident solar radiation by 75%, 50%, 25% | 3 | Time in comfort and EUI for cooling |
| Increasing the reflectivity of external walls | Passive (structural) | Thermal reflectivity 0.25 | Thermal reflectivity 0.80, 0.60, 0.40 | 3 | Time in comfort, EUI for cooling and heating |

Table 5-2: Ranking of adaptive, behavioural, non-structural actions based on their effectiveness to reduce overheating across all types of homes based on the median percentage of occupied overheating hours (CIBSE TM59 Criterion 1).

1: most effective, 5: less effective in reducing overheating

| Ranking | All types of homes |
|---|---|
| 1 | Internal window shading (using white curtains) |
| 2 | Internal window shading (using blackout curtains) |
| 3 | Reducing internal heat gains from equipment and lighting |
| 4 | Modifying the window opening indoor temperature threshold (compared to the base case with opening the window if indoor temperature exceeds 22°C) |
| 5 | Modifying the window closing outdoor temperature threshold (compared to the base case with closing the window if outdoor temperature exceeds 33°C) |

Table 5-3: Ranking of passive, structural cooling actions based on their effectiveness to reduce overheating across the five types of homes based on the median percentage of occupied overheating hours (CIBSE TM59 Criterion 1.

1: most effective, 5: less effective in reducing overheating

| Ranking | High-rise post-2010s flats | High-rise pre-2010s flats | Low-rise flats | Mid-terrace houses | Semi-detached houses |
|---|---|---|---|---|---|
| 1 | External window shading (using shutters) | External window shading (using shutters) | External window shading (using shutters) | External window shading (using shutters) | External window shading (using shutters) |
| 2 | External wall shading (using vegetation or other structures of varying translucency levels) | External wall shading (using vegetation or other structures of varying translucency levels) | External wall shading (using vegetation or other structures of varying translucency levels) | External wall shading (using vegetation or other structures of varying translucency levels) | External wall shading (using vegetation or other structures of varying translucency levels) |
| 3 | Modifying the area of windows that could be opened | Modifying the area of windows that could be opened | Modifying the area of windows that could be opened | Modifying the area of windows that could be opened | Increasing the reflectivity of external walls |
| 4 | Increasing the reflectivity of external walls | Increasing the reflectivity of external walls | Increasing the reflectivity of external walls | Increasing the reflectivity of external walls | Modifying the area of windows that could be opened |

Table 5-4: Summary of key findings on the effectiveness of cooling actions

| Action | Impact on Indoor temperature |
|---|---|
| Internal window shading using curtains | Although not as effective as external shading, this measure can be beneficial in the short term. For the tested climate scenarios, better results were achieved when the curtains were closed from 6 am to 10 pm. |
| External window shading using shutters | Overall, this was found to be the most effective strategy in reducing overheating. This measure may be more effective in homes with large, glazed areas. |
| Shading the buildings' external walls, for example by using different structures or vegetation | Indoor overheating reduced as a function of shading translucency from the base case with no external shading to a scenario in which external shading allowed only 25% of direct solar radiation to penetrate. This measure may be more effective in homes with large, exposed wall areas. |
| Varying the area of windows that could be opened | This measure may be more effective in more sheltered or energy efficient homes as they might have higher needs for ventilation due to their smaller surface area exposed to the outdoors, and in recently built flats with increased levels of building fabric airtightness. |

### Comparative evaluation of the effectiveness of combined actions

Table 5-5 shows four different combinations of the actions that were tested to investigate their combined effect.

Table 5-5: Summary of the combinations of actions tested

| |
|---|
| **Combination A - Only adaptive, behavioural, non-structural actions** |
| Changing the window opening indoor temperature threshold from 22°C to 18°C |
| Applying internal window shading (white curtains) between 6 am - 10 pm |
| Reducing heat gains from equipment and lighting to 66% |
| **Combination B - Only passive, structural actions** |
| Increasing the area of windows that could be opened from 33% to 60% |
| Applying external window shading (shutters) to windows between 8 am - 8 pm |
| Modifying the absorptance of external walls from 0.75 to 0.6 |
| Applying external wall shading allowing only 75% of total solar direct solar gains |

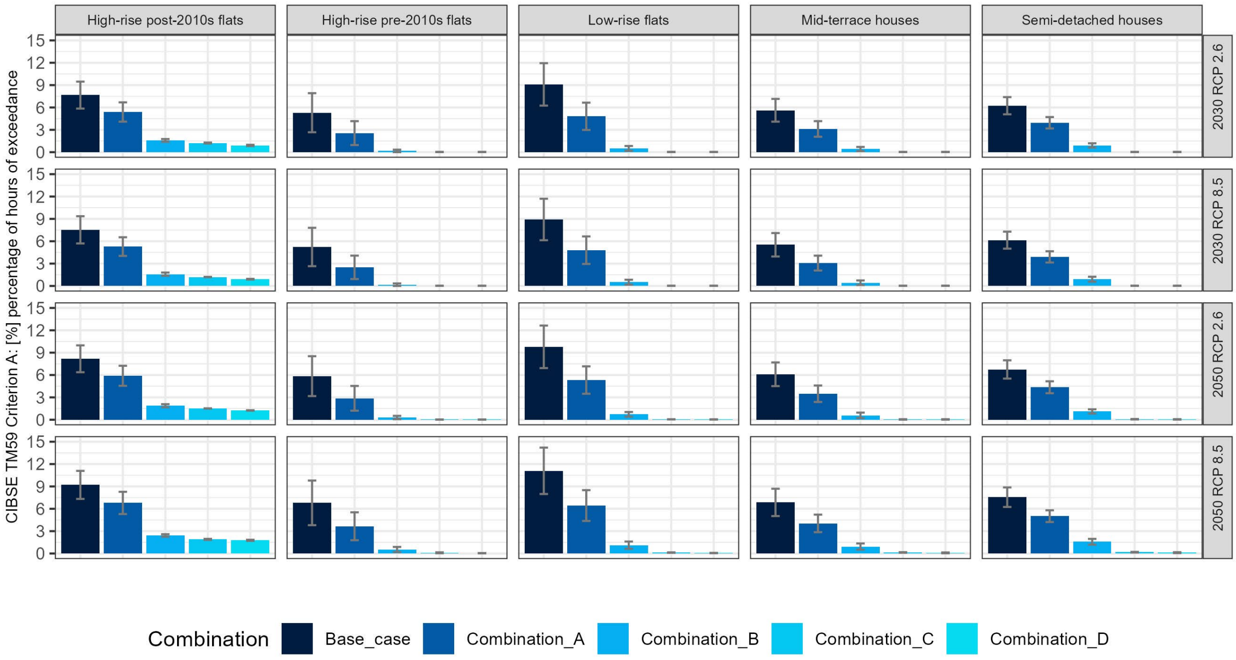
| |
|---|
| **Combination C - Only passive structural actions (More Extensive)** |
| Increasing the area of windows that could be opened from 33% to 80% |
| Applying external window shading (shutters) to windows between 6 am - 10 pm |
| Modifying the absorptance of external walls from 0.75 to 0.2 |
| Applying external wall shading allowing only 50% of total direct solar gains |
| **Combination D – Adaptive, behavioural and passive, structural actions** |
| Changing the window opening indoor temperature threshold from 22°C to 18°C |
| Reducing heat gains of equipment and lighting to 66% |
| Increasing the area of windows that could be opened from 33% to 80% |
| Applying external window shading (shutters) between 6 am - 10 pm |
| Modifying the absorptance of external walls from 0.75 to 0.2 |
| Applying external wall shading allowing only 50% of total direct solar gains |

In Figure 5-1, a summary of the results for each type of home, climate scenario, and combination of actions is presented. Under the 2050 RCP 8.5 (50$^{th}$ percentile), when compared to the base case, Combination A reduced the median percentage of occupied hours during which ΔT is greater than or equal to one degree (K) from around 10% to 7% in the high-rise post-2010s flats, from 8% to 4% in the high-rise pre-2010s flats, from 11% to 6% in the low-rise flats, and from 7% to 4% in the mid-terrace houses and from 7% to 5% in the semi-detached houses. Despite these reductions, absolute percentages of exceedance were above 3% in the modelled homes, thus failing the CIBSE TM59 Criterion 1. Combination B, which consists of moderately applied passive, structural actions, achieved around double the reduction in % hours of exceedance that Combination A achieved compared to the base case. Under the 2050 RCP 8.5 (50$^{th}$ percentile), the absolute percentages of exceedance fell below 3% on average in all the homes for Combination B. Combination C, which consists of passive, structural actions applied more extensively, yielded significantly greater reductions in overheating. For the same climate scenario, when compared to the base case, Combination C reduced the percentage of occupied hours during which ΔT is greater than or equal to one degree (K) from around 10% to 2% in the high-rise post-2010s flats, from 8% to 0% in the high-rise pre-2010s flats, from 11% to 0% in the low-rise flats, from 7% to 0% in the mid-terrace houses, and from 7% to 0% in the semi-detached houses. Combination D, which combined passive and adaptive actions, resulted in slight further improvements compared to Combination C.

Please note that the earlier analysis suggests that there are some differences across types of homes when individual strategies are applied (in terms of which action may be more effective). This part of the analysis includes combinations of actions, therefore the potential differences across types of homes are much smaller.

Figure 5-15: Percentage of occupied hours during which ΔT is greater than or equal to one degree (K) during the period May to September following the application of combined actions

Each bar height corresponds to the median value obtained when the home is modelled at four different orientations; error bars correspond to the minimum and maximum values




In summary, the findings suggest that the largest reduction in overheating hours is achieved by a combination of passive actions applied extensively combined with adaptive/behavioural actions (Combination D).

## 5.2 CBA Results

The results of the cost-benefit analysis presented in this section are for each of the actions and combinations of actions modelled in Section 5. that have associated capital costs of structural adaptations and/or retrofitting. These results are presented by type of home.

Table 5-6 to Table 5-10 present the results of the cost-benefit analysis for each action and combination of actions by type of home. They include:

- Average capital cost - Year 1 only (£).
- Average additional thermal comfort (hours).
- Cost-benefit ratio - first year only (£ per additional hour in thermal comfort).
- Cost-benefit ratio - first five years only (£ per additional hour in thermal comfort).

For high-rise pre-2010 flats (Table 5-6), the baseline level of comfort (with no adaptation actions applied), when assessing using CIBSE TM59 Criterion 1, was 3,422 hours (93%) out of the 3,672 hours from May to September. The most cost-efficient of the individual actions considered, was installation of internal shading using light shading devices (as opposed to blackout). This resulted in a 3% increase in total time spent in thermal comfort from May to September at a cost of £2.87 per additional hour in thermal comfort in the first year, or £0.57 per additional hour in thermal comfort spread over the first five years. The action with the lowest cost-efficiency was replacing windows to increase the extent to which they could be opened.

Combination A, which included adaptive, behavioural actions, such as changing window opening timings, reducing internal heat gains, and utilising internal shading, such as white curtains, for most of the day, was the most cost-efficient of the combinations of actions for high-rise pre-2010 flats. It resulted in a 3% increase in total time in thermal comfort from May to September at a cost £0.46 per additional hour in thermal comfort in the first year and £0.28 per additional hour in thermal comfort spread over the first five years. This is because Combination A mainly comprised of behavioural actions that were assumed to have zero cost, except for the installation of white curtains. Adding actions with associated capital costs of structural adaptations and/or retrofitting increased the time in thermal comfort from May to September. Combination B, where only passive, structural actions were implemented, increased the total time in thermal comfort by 6% from May to September but had the lowest cost-efficiency of the combinations of actions. Combination B and C both include passive, more invasive retrofit actions with substantial capital costs. However, Combination C included the most effective passive actions, so this increased the total time in thermal comfort to 100% from May to September and made it more cost-efficient than Combination B. The cost-efficiency of Combination D was similar to Combination C, as the only additional action included with an associated capital cost was the installation of internal shading and, alongside zero-cost behavioural actions, this slightly increased the cost and the percentage of total time spent in thermal comfort.

For all the other types of home (high-rise post-2010 flats - Table 5-7, low-rise flats - Table 5-8, mid-terrace - Table 5-9, and semi-detached houses - Table 5-10), internal shading using light shading devices was, again, the most cost-efficient single action. This could cost between £261- £364 and deliver between 58-150 additional hours of thermal comfort depending on the type of home. While external shutters were more effective, delivering between 172-316 additional hours of thermal comfort, costs were considerably higher, ranging from £2,363-£5,745 depending on the type of home. Equally, replacing windows to increase the extent to which they could be opened had the lowest cost-efficiency for each of these types of homes. Across all homes, Combination A is the most cost-efficient in contrast to Combinations B, C, and D with their more costly passive, structural actions for the additional hours of thermal comfort gained.

Table 5-6: Cost-benefit analysis for high-rise pre-2010 flat

| Adaptation action | Average capital cost Year 1 only (£) | | Average additional thermal comfort (hours) | Cost-benefit - first year only (£ per additional hour in thermal comfort) | | Cost-benefit - first five years only (£ per additional hour in thermal comfort) | |
|---|---|---|---|---|---|---|---|
| | Min | Max | | Min | Max | Min | Max |
| Baseline | 0 | | 0 | 0 | | 0 | |
| 2.A Internal shading - white curtains | 261 | | 91 | 2.87 | | 0.57 | |
| 2.B Internal shading - blackout curtains | 308 | | 76 | 4.04 | | 0.81 | |
| 4. Openable window area - repair | 1523 | 2087 | 115 | 13.27 | 18.19 | 2.65 | 3.64 |
| 4. Openable window area - replacement | 3254 | 13493 | 115 | 28.35 | 117.59 | 5.67 | 23.52 |
| 5. External shutter | 2364 | | 210 | 11.25 | | 2.25 | |
| 7. Modifying reflectivity | 928 | | 44 | 21.07 | | 4.22 | |
| Combination A | 261 | | 115 | 2.27 | | 0.46 | |
| Combination B | 4815 | 16785 | 230 | 20.96 | 73.06 | 4.19 | 14.61 |
| Combination C | 4815 | 16785 | 246 | 19.58 | 68.26 | 3.92 | 13.65 |
| Combination D | 5076 | 17045 | 248 | 20.47 | 68.73 | 4.10 | 13.75 |

Table 5-7: Cost-benefit analysis for high-rise post-2010 flat

| Adaptation action | Average capital cost Year 1 only (£) | | Average additional thermal comfort (hours) | Cost-benefit - first year only (£ per additional hour in thermal comfort) | | Cost-benefit - first five years only (£ per additional hour in thermal comfort) | |
|---|---|---|---|---|---|---|---|
| | Min | Max | | Min | Max | Min | Max |
| Baseline | 0 | | 0 | 0 | | 0 | |
| 2.A Internal shading - white curtains | 261 | | 58 | 4.51 | | 0.90 | |
| 2.B Internal shading - blackout curtains | 308 | | 51 | 5.99 | | 1.20 | |
| 4. Openable window area - repair | 1523 | 2087 | 153 | 9.93 | 13.61 | 1.99 | 2.72 |
| 4. Openable window area - replacement | 3254 | 13493 | 153 | 21.22 | 88.01 | 4.24 | 17.60 |
| 5. External shutter | 2364 | | 202 | 11.71 | | 2.34 | |
| 7. Modifying reflectivity | 928 | | 5 | 202.19 | | 40.45 | |
| Combination A | 261 | | 89 | 2.94 | | 0.59 | |
| Combination B | 4815 | 16785 | 249 | 19.32 | 67.34 | 3.86 | 13.47 |
| Combination C | 4815 | 16785 | 268 | 17.94 | 62.54 | 3.59 | 12.51 |
| Combination D | 5076 | 17045 | 273 | 18.59 | 62.44 | 3.72 | 12.49 |

Table 5-8: Cost-benefit analysis for low-rise flat

| Adaptation action | Average capital cost Year 1 only (£) | | Average additional thermal comfort (hours) | Cost-benefit - first year only (£ per additional hour in thermal comfort) | | Cost-benefit - first five years only (£ per additional hour in thermal comfort) | |
|---|---|---|---|---|---|---|---|
| | Min | Max | | Min | Max | Min | Max |
| Baseline | 0 | | 0 | 0 | | 0 | |
| 2.A Internal shading - white curtains | 310 | | 150 | 2.07 | | 0.41 | |
| 2.B Internal shading - blackout curtains | 366 | | 127 | 2.89 | | 0.58 | |
| 4. Openable window area - repair | 1813 | 2489 | 191 | 9.49 | 13.04 | 1.90 | 2.61 |
| 4. Openable window area - replacement | 3872 | 16058 | 191 | 20.28 | 84.10 | 4.06 | 16.82 |
| 5. External shutter | 2813 | | 316 | 8.91 | | 1.78 | |
| 7. Modifying reflectivity | 1364 | | 84 | 16.33 | | 3.27 | |
| Combination A | 310 | | 171 | 1.81 | | 0.36 | |
| Combination B | 5990 | 20235 | 367 | 16.33 | 55.21 | 3.27 | 11.04 |
| Combination C | 5990 | 20235 | 403 | 14.87 | 50.22 | 2.97 | 10.05 |
| Combination D | 6300 | 20545 | 405 | 15.56 | 50.73 | 3.11 | 10.15 |

Table 5-9: Cost-benefit analysis for mid-terrace home

| Adaptation action | Average capital cost Year 1 only (£) | | Average additional thermal comfort (hours) | Cost-benefit - first year only (£ per additional hour in thermal comfort) | | Cost-benefit - first five years only (£ per additional hour in thermal comfort) | |
|---|---|---|---|---|---|---|---|
| | Min | Max | | Min | Max | Min | Max |
| Baseline | 0 | | 0 | 0 | | 0 | |
| 2.A Internal shading - white curtains | 634 | | 93 | 6.84 | | 1.37 | |
| 2.B Internal shading - blackout curtains | 748 | | 71 | 10.58 | | 2.12 | |
| 4. Openable window area - repair | 3702 | 5072 | 80 | 46.35 | 63.51 | 9.27 | 12.70 |
| 4. Openable window area - replacement | 7909 | 32797 | 80 | 99.03 | 410.65 | 19.81 | 82.13 |
| 5. External shutter | 5745 | | 190 | 30.24 | | 6.06 | |
| 7. Modifying reflectivity | 6304 | | 59 | 107.33 | | 21.49 | |
| Combination A | 634 | | 104 | 6.13 | | 1.23 | |
| Combination B | 15752 | 44847 | 218 | 72.44 | 206.21 | 14.50 | 41.26 |
| Combination C | 15752 | 44847 | 247 | 63.90 | 181.91 | 12.79 | 36.40 |
| Combination D | 16386 | 45481 | 249 | 65.95 | 183.04 | 13.20 | 36.62 |

Table 5-10: Cost-benefit analysis for semi-detached home

| Adaptation action | Average capital cost Year 1 only (£) | | Average additional thermal comfort (hours) | Cost-benefit - first year only (£ per additional hour in thermal comfort) | | Cost-benefit - first five years only (£ per additional hour in thermal comfort) | |
|---|---|---|---|---|---|---|---|
| | Min | Max | | Min | Max | Min | Max |
| Baseline | 0 | | 0 | 0 | | 0 | |
| 2.A Internal shading - white curtains | 634 | | 84 | 7.51 | | 1.50 | |
| 2.B Internal shading - blackout curtains | 748 | | 63 | 11.81 | | 2.36 | |
| 4. Openable window area - repair | 3702 | 5072 | 86 | 42.90 | 58.78 | 8.58 | 11.76 |
| 4. Openable window area - replacement | 7909 | 32797 | 86 | 91.65 | 380.07 | 18.33 | 76.01 |
| 5. External shutter | 5745 | | 172 | 33.47 | | 6.69 | |
| 7. Modifying reflectivity | 7890 | | 94 | 84.41 | | 17.00 | |
| Combination A | 634 | | 94 | 6.78 | | 1.36 | |
| Combination B | 17337 | 46432 | 220 | 78.87 | 211.12 | 15.83 | 42.28 |
| Combination C | 17337 | 46432 | 271 | 64.00 | 171.32 | 12.84 | 34.31 |
| Combination D | 17971 | 47066 | 273 | 65.82 | 172.30 | 13.21 | 34.50 |

## 5.3 Socio-technical analysis results: stakeholder engagement

This section presents the results of the stakeholder consultation and literature review. The stakeholder consultation involved 55 in-person interviews, and an online survey, which attracted 32 responses. Overheating is recognised as a problem in Greater Manchester homes, with 70% of participants in this study stating that they have experienced overheating. The following sections present the demographic make-up of the participants and the respondents' perspectives on individual adaptation actions.

### 5.3.1 Literature review results

A range of barriers were identified for the adaptation actions included in this study. See Table 5-11 below.

Table 5-11: Barriers to each adaptation action identified in the literature review

| Adaptation action | Barriers identified in the literature review |
|---|---|
| Windows and natural ventilation | **Physical infrastructure and legislation**: often homes are not designed to prioritise airflow and legislation that promotes energy efficiency by discouraging window opening (Roaf & Nicol, 2020).<br><br>**Security concerns:** Concerns about personal safety when leaving windows open (Wright, et al., 2018) (Taylor, et al., 2018) (Hatvani-Kovacs, et al., 2016).<br><br>**Insects:** Open windows can allow insects and pests to enter the home (Wright, et al., 2018)(Hatvani-Kovacs, et al., 2016).<br><br>**Noise**: Noise from open windows (Taylor, et al., 2018).<br><br>**Awareness and behavioural change:**<br>- Perceptions surrounding the need for adaptation actions for overheating (Wright, et al., 2018).<br>- Lack of knowledge on when to open and close windows (Ascione, et al., 2020) (Hatvani-Kovacs, et al., 2016).<br><br>**Demographics**: Households who are absent from the home during the day are unable to open the windows (Mavrogianni, et al., 2014). |
| Use of air-conditioning | **Health:** Mechanical ventilation was found in some research to reduce indoor air quality and increase access of harmful substances and establishment of moulds (Roaf, et al., 2005) (Palinkas, et al., 2022).<br><br>**High cost:** High cost of electricity from use and high upfront cost (Baborska-Narozny, et al., 2017) (Palinkas, et al., 2022) |

| Adaptation action | Barriers identified in the literature review |
|---|---|
| | **Renting:** Landlord restrictions on the installation of air conditioning in rental properties (Palinkas, et al., 2022). |
| External shading (shutters) | **Leasehold and regulatory constraints:** As shutters involve external changes to the front face of buildings, leaseholders have little control over some changes and landlords are given little incentive to improve the energy efficiency of properties (Green Alliance, 2024). Additionally, there may be local regulations that prevent changes to the external façade (e.g., in listed buildings) (Taylor, et al., 2018).<br><br>**Physical constraints:** Installation of shutters may be less straight-forward in high-rise flats (Taylor, et al., 2018). Windows often open outwards in the UK.<br><br>**Awareness and behavioural change:** Individuals who perceive overheating is a low risk, are less likely to install external shutters (Murtagh, et al., 2019).<br><br>**Personal preference:** Loss of external views and individual preferences on adaptation actions (Porritt, et al., 2012). |
| Shading from external structures | **Leasehold and regulatory constraints:** Historic preservation, local regulations and neighbourhood groups may object to alternative front building façades (Gupta & Gregg, 2012).<br><br>**Physical infrastructure:** Some homes may not have the space, nor control over external structures (Gupta & Gregg, 2012).<br><br>**Cost**: Water bills associated with gardening inhibits some people from having greenery (Hatvani-Kovacs, et al., 2016). |
| Internal shading | **Physical constraints:** Individuals may struggle to access windows in their homes due to space constraints; blinds could also obstruct window opening (Baborska-Narozny, et al., 2017).<br><br>**Personal preference:** Individual lighting preferences, or preference for a view (Baborska-Narozny, et al., 2017) (Porritt, et al., 2012).<br><br>**Awareness and behavioural change:** Lack of knowledge on the efficacy of adaptation techniques, such as shading (Hatvani-Kovacs, et al., 2016). |

Personal preferences in terms of individual lighting preferences were identified as barriers for both internal and external shadings, as these actions impact views from windows. There was a lack of awareness of the need to open of windows or fit external shutters, with individuals across multiple studies not considering overheating a risk. Finally, renting, and regulatory constraints were identified as barriers to more permanent changes to either the inside or external façade of buildings. Renters require the approval of landlords for changes to their homes and some legislation (e.g., regarding cultural heritage) may restrict use of some adaptation actions).

### 5.3.2 Stakeholder engagement results

#### Type of home

Of the most sensitive types of home modelled in this work package, for high-rise flats, semi-detached, and mid-terraces, 70% of occupants in these homes reported they had experienced overheating. For low-rise flats however, this was just 46%.

Table 5-12: Survey respondents and interviewees who had experienced overheating for the most sensitive types of home modelled in this work package

| Type of home | # | Overheating response | | | | | |
|---|---|---|---|---|---|---|---|
| | | Yes - # | % | No - # | % | Limited - # | % |
| High-rise flat[12] | 8 | 6 | 75 | 1 | 13 | 1 | 13 |
| Low-rise flat | 13 | 6 | 46 | 4 | 31 | 3 | 23 |
| Semi-detached | 29 | 21 | 72 | 7 | 24 | 1 | 3 |
| Mid-terrace | 17 | 14 | 82 | 2 | 12 | 1 | 6 |
| Total | 67 | 47 | 70 | 14 | 21 | 6 | 9 |

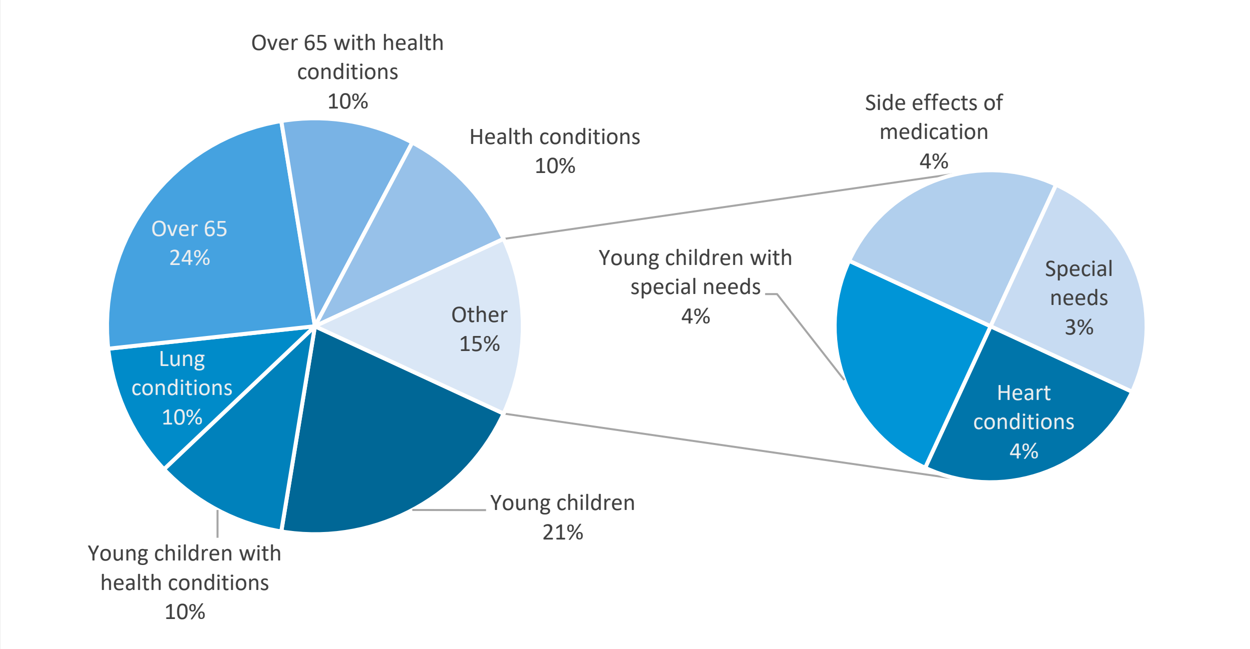
#### Vulnerability

Over a third of survey respondents and interviewees (36%) responded that they considered themselves or someone with whom they resided as vulnerable.[13] Figure 5-2 provides a breakdown of the responses provided by participants. A total of 38% of survey respondents and interviewees stated that they or someone with whom they resided had some kind of health conditions. A total of 34% were over 65 (10% also with a health condition).

[12] The survey and interview did not differentiate between age of the high-rise flat so this data will include modern and pre-2010 homes

[13] Vulnerable people were defined as: children under 5 years old, people over 65, pregnant women, and/or individuals with a health or other condition that could make it difficult for them to stay cool. Participants were asked to provide more information on the vulnerability if they were comfortable.

Figure 5-16: Reasons why survey respondents survey and interviewees considered themselves or someone with whom they resided as vulnerable




## Barriers

Table 5-13 shows the top 3 barriers cited for each adaptation action, and the percentage of survey respondents and interviewees that cited them. The most common barrier cited was 'not required', indicating a large proportion of those interviewed did not see any need for the action, given their perception of need to reduce overheating within their home. It was the number one barrier for 3 of the 8 actions and was one of the top three barriers cited for 7 of them. This indicates the importance of perceptions about whether the risk of overheating warrants people taking specific actions.

Another commonly cited barrier was 'personal preference'. It was cited as a barrier to uptake of 4 of the 8 adaptation actions. This barrier highlights not only the importance of raising people's awareness but also of aesthetic preferences, as adaptation actions, such as painting external surfaces and installing external shutters can change the appearance of a home. The number one barrier for 'light painting on external walls' was found to be the need for permission by a landlord. It was also cited as one of the top three barriers for the installation of external shutters.

Table 5-13: The three most cited barriers to people adopting specific adaptation actions.

| Ranking | Film on Windows | Shading from external surfaces | Light-colour painting on external walls | Use of air conditioning | Use of fans | External shutters | Close blinds | Open windows |
|---|---|---|---|---|---|---|---|---|
| 1 | Personal preference (33%) | Physical constraint - may not be possible to install (47%) | Renting – would need permission (43%) | Not required (45%) | Not required (62%) | Personal preference (46%) | Not required (57%) | Security concerns (33%) |
| 2 | Not Required (33%) | Physical constraint – high rise flat (27%) | Personal preference (38%) | Financial concern (41%) | Do not own one (29%) | Not required (29%) | Concern regarding light (43%) | Not required (33%) |
| 3 | Unaware of solution (33%) | Not considered action as an option (27%) | Not required (19%) | Personal preference (14%) | Previous experience – ineffective (10%) | Renting – would need permission (24%) | Not applicable | Believe windows let hot air in (33%) |

The stakeholder consultation also revealed that some adaptation actions had unique barriers. For example, one of the barriers cited to opening windows was security concerns about increased vulnerability to burglaries and intrusions, which is in line with findings from the literature review (see Table 5-11). Other barriers cited included concerns about health, noise, impact of use of air-conditioning on climate change, and physical constraints on external shading (e.g., lack of outdoor space). Some respondents were also unaware of some adaptation actions.

### 5.3.3 Infographics

Based on the results from the Task 2 modelling, infographics have been developed to show the most effective adaptation actions for the types of home most sensitive to overheating. These are presented below in the following order:

- Low-rise flat
- Mid-terraced house
- Semi-detached house
- Post-2010 high-rise flat
- Pre-2010 high-rise flat.

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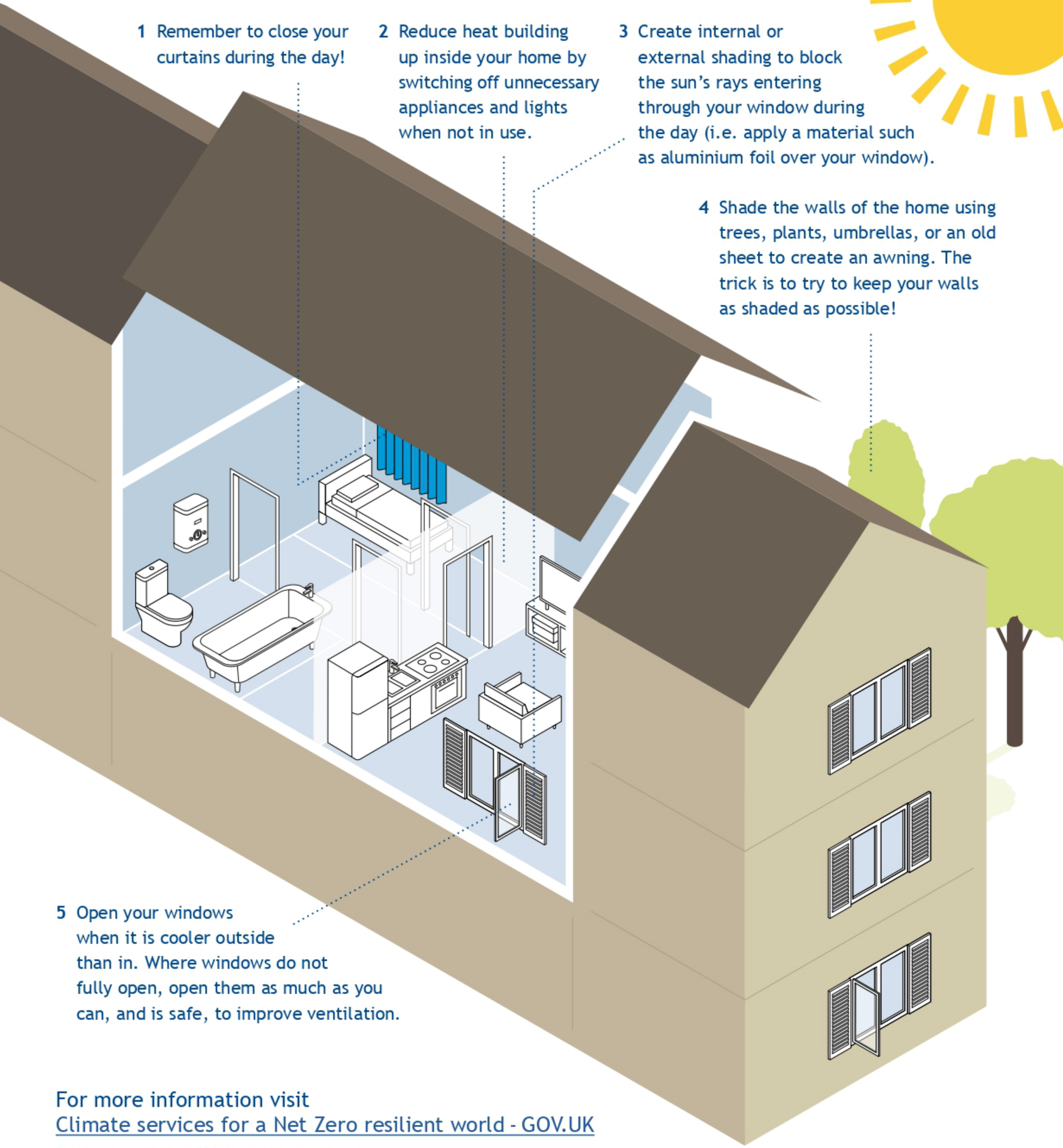
## Low-rise flat

1 Remember to close your curtains during the day!

2 Reduce heat building up inside your home by switching off unnecessary appliances and lights when not in use.

3 Create internal or external shading to block the sun's rays entering through your window during the day (i.e. apply a material such as aluminium foil over your window).

4 Shade the walls of the home using trees, plants, umbrellas, or an old sheet to create an awning. The trick is to try to keep your walls as shaded as possible!



5 Open your windows when it is cooler outside than in. Where windows do not fully open, open them as much as you can, and is safe, to improve ventilation.

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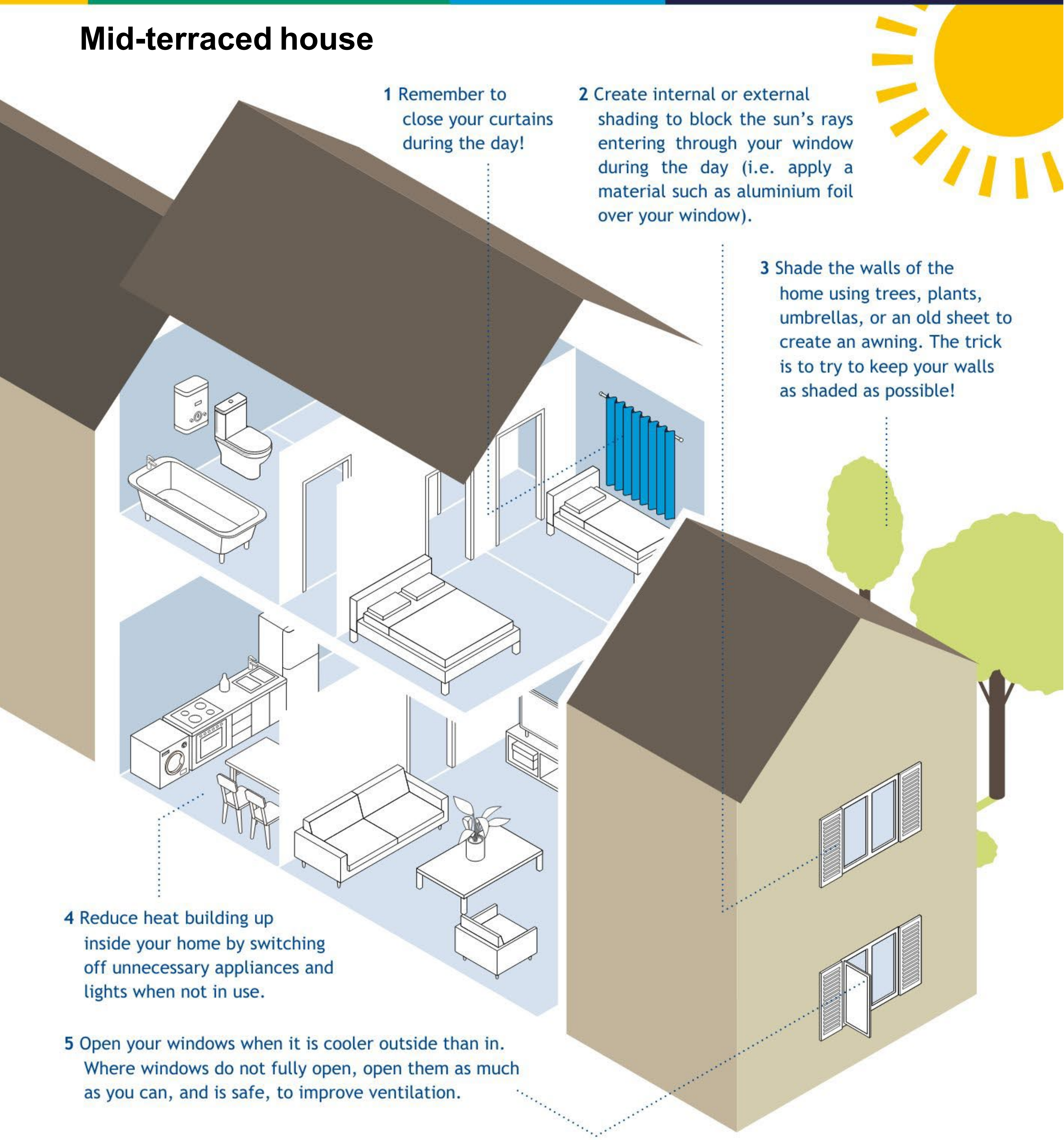
## Mid-terraced house



**1** Remember to close your curtains during the day!

**2** Create internal or external shading to block the sun's rays entering through your window during the day (i.e. apply a material such as aluminium foil over your window).

**3** Shade the walls of the home using trees, plants, umbrellas, or an old sheet to create an awning. The trick is to try to keep your walls as shaded as possible!

**4** Reduce heat building up inside your home by switching off unnecessary appliances and lights when not in use.

**5** Open your windows when it is cooler outside than in. Where windows do not fully open, open them as much as you can, and is safe, to improve ventilation.

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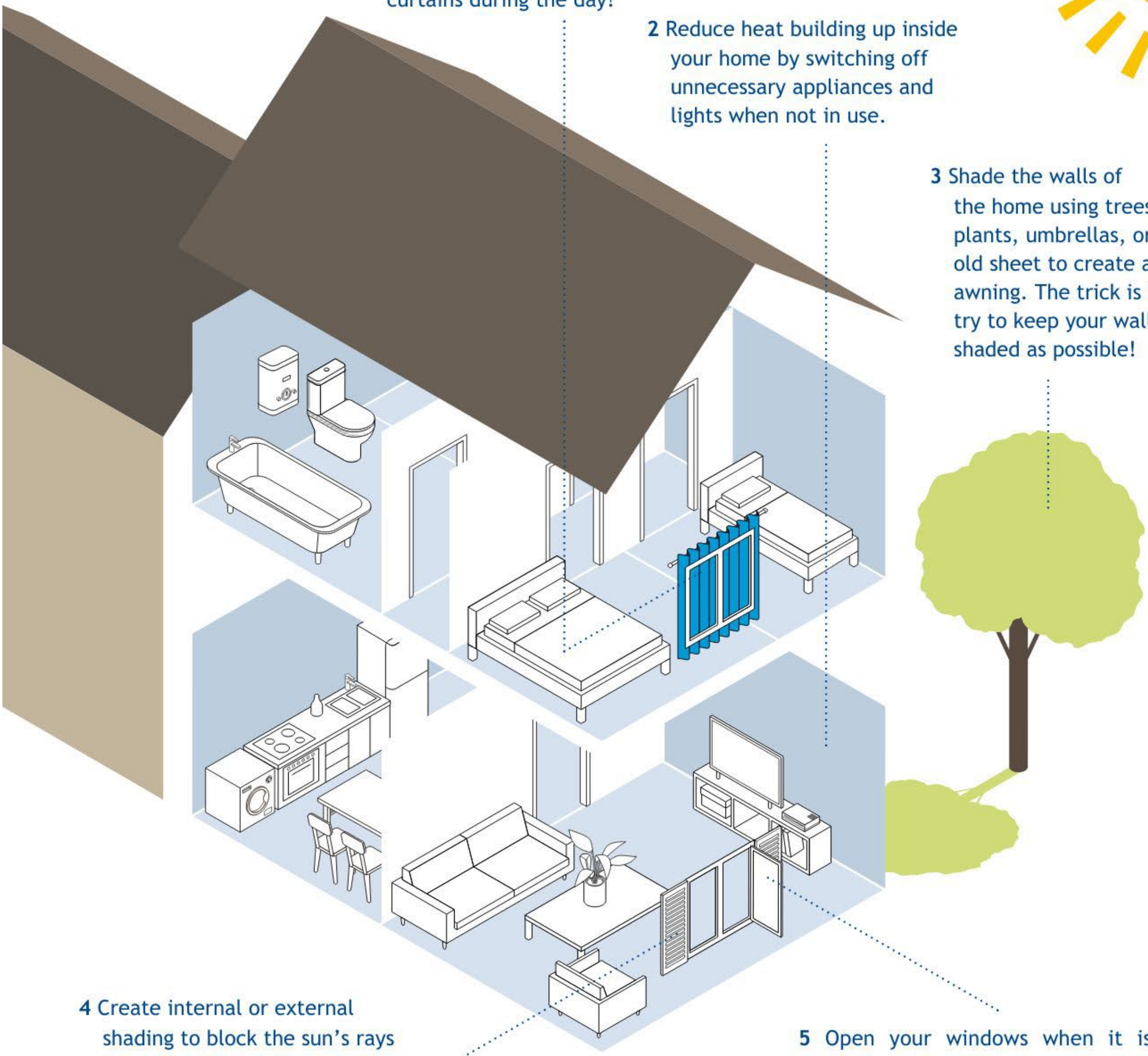
## Semi-detached house

1 Remember to close your curtains during the day!

2 Reduce heat building up inside your home by switching off unnecessary appliances and lights when not in use.

3 Shade the walls of the home using trees, plants, umbrellas, or an old sheet to create an awning. The trick is to try to keep your walls as shaded as possible!



4 Create internal or external shading to block the sun's rays entering through your window during the day (i.e. apply a material such as aluminium foil over your window).

5 Open your windows when it is cooler outside than in. Where windows do not fully open, open them as much as you can, and is safe, to improve ventilation.

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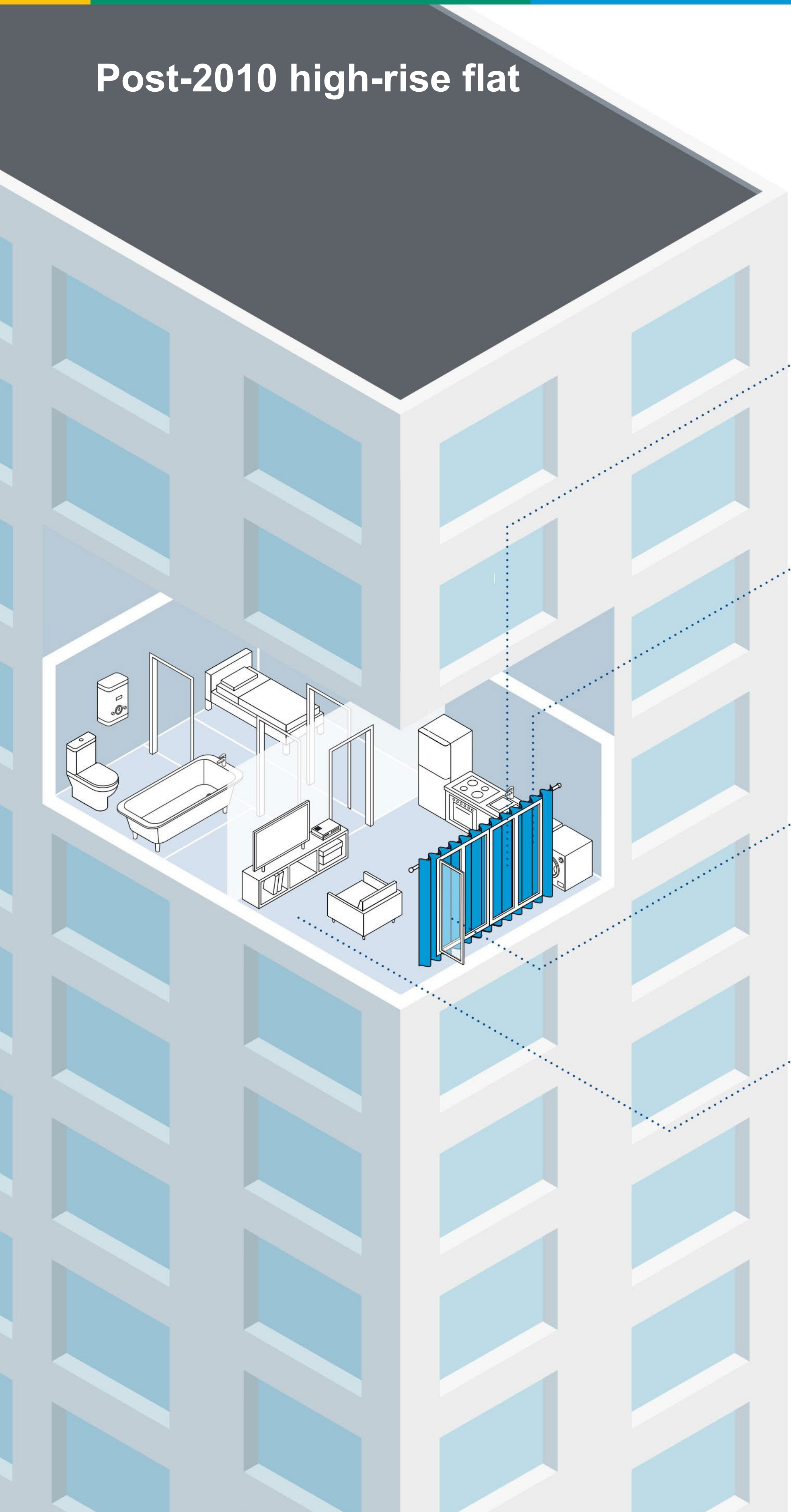
## Post-2010 high-rise flat



1 Remember to close your curtains during the day!

2 Create internal or external shading to block the sun's rays entering through your window during the day (i.e. apply a material such as aluminium foil over your window).

3 Open your windows when it is cooler outside than in. Where windows do not fully open, open them as much as you can, and is safe, to improve ventilation.

4 Reduce heat building up inside your home by switching off unnecessary appliances and lights when not in use.

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Based on a graphic from BBC News at bbc.co.uk/news

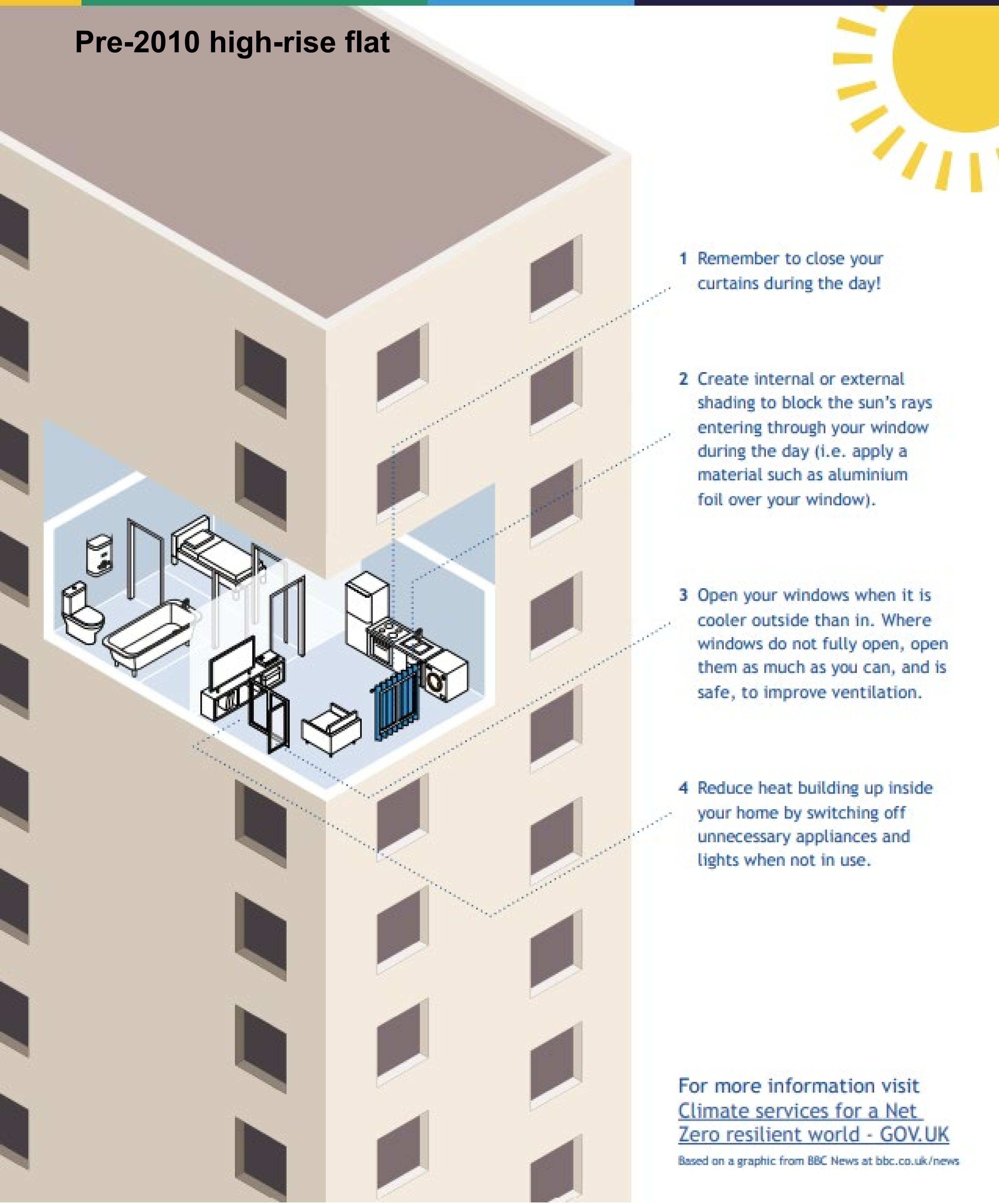
# Adapting Homes to Heat in Greater Manchester

CS NOW

Climate services for a net-zero resilient world

Department for Energy Security & Net Zero

## Pre-2010 high-rise flat



1 Remember to close your curtains during the day!

2 Create internal or external shading to block the sun's rays entering through your window during the day (i.e. apply a material such as aluminium foil over your window).

3 Open your windows when it is cooler outside than in. Where windows do not fully open, open them as much as you can, and is safe, to improve ventilation.

4 Reduce heat building up inside your home by switching off unnecessary appliances and lights when not in use.

For more information visit [Climate services for a Net Zero resilient world - GOV.UK]

Based on a graphic from BBC News at bbc.co.uk/news

# 6. Key limitations and caveats

Task 1 relied on EPC data and there are limitations regarding the extent of data available. Although EPC data are available across the UK their percentage coverage varies substantially. There are uncertainties due to lack of representativeness or errors in the EPC dataset: many older properties that are complex to decarbonise and that may have not been sold or rented in recent years are overlooked in the EPC register. This could result in UCL's model outputs underestimating heating energy demand and may affect the accuracy of UoM's mapping of the concentration of types of home in each LSOA. Hence, it could affect the representativeness of the results from both approaches at the population level, with implications particularly for private renters and older individuals who are more likely to live in properties that are complex to decarbonise and energy inefficient.

UCL's model makes a series of assumptions about individual properties, including human behaviour (ventilation, window opening thresholds, heating and cooling setpoints, and internal gains associated with the use of lighting and appliances). These factors may influence overheating significantly but may differ from actual behaviours in an individual home. Although the model can capture overall trends in the sensitivity of homes to overheating, it cannot project overheating levels in individual homes due to these uncertainties. Therefore, it is strongly recommended that modelling outputs are statistically aggregated for large geographic units (such as LSOAs).

An important limitation of UoM's approach is that it only considers current data and does not project how this may change in the future. This is most pertinent to the occupant sensitivity domain where an individual's sensitivity to heat can change rapidly (e.g. due to pregnancy or illness) and for which the method draws on Census data collected every decade on health and disability. Public health bodies may have more regularly updated statistics on the health indicators, which could be used instead of the Census data. In general, to consider how sensitivities may change, there is a need to consider future population dynamics, particularly age and health, as well as plans for future developments and whether they accommodate greenspace or reduce it further.

A key limitation of the Task 2 approach is that each of the deep-dive components (the modelling, cost-benefit analysis, and stakeholder engagement) were delivered concurrently. As a result, the evidence gathered from stakeholders represents the respondent's *current* prejudices and barriers to adopting the adaptation actions in the absence of knowledge of their respective cost-benefits. A lesson learned to improve the study would be that sequential ordering of the components would have facilitated knowledge sharing with the stakeholders that were engaged in the socio-technical analysis. While this is a limitation, the socio-technical analysis is valuable in providing a baseline assessment of perceived barriers, which can contribute to informing policymakers on areas that will need to be addressed. A proposed next step would be to return to the stakeholders involved in the initial engagement and brief them on the results of the modelling and cost analysis to understand whether these initial perceptions and barriers change.

A key caveat regarding the results of the cost-benefit analysis is that it was assumed that people would fully understand and use the structural adaptations and retrofitting according to the times and thresholds identified in the modelling. In reality, this may not be the case, which could reduce the cost-efficiency of the actions implemented.

In addition, the results of the modelling study should be treated with caution. There are limitations associated with the representation of the Greater Manchester housing stock using a limited number of types of homes. Although established methods to derive building geometry, fabric and systems characteristics were employed, housing-type building modelling approaches are characterised by inherent uncertainties. Another key limitation of any building performance modelling emerges from assumptions made about occupant behaviour inside buildings, in particular the way people operate windows and shading systems, lights and appliances, which can greatly influence indoor thermal conditions. Actual behaviour data is scarce and, therefore, assessing the representativeness of modelling assumptions is challenging. To address this issue, however, a sensitivity analysis was carried out in this study to quantify the impact of different window/shading operation timings on indoor temperatures. Specifically for the action including modifications to window opening/closing behaviour based on indoor/outdoor temperatures, it was assumed that occupants already operated windows in the base case as this was deemed a more realistic scenario. As a result, when comparing the relative effectiveness of individual actions, the results of this study may appear to underestimate the effectiveness of opening windows (when compared to the base case). It is worth noting that, although the present study set out to evaluate the overall potential of behavioural actions to reduce overheating, human behaviour in homes is complex and driven by factors beyond indoor temperature. This report focuses on CIBSE TM59 Criterion 1 rather than a full-scale overheating assessment based on the TM59 methodology using both Criterion 1 and 2. Lastly, there are also uncertainties related to the climate projections used; quantifying the impact of the urban heat island and local microclimatic characteristics were beyond the scope of this study. Green and blue infrastructure, not considered by this study, may also have an important role to play. Tree cover can address the urban heat island effect at neighbourhood to regional scales, primarily through evapotranspiration reducing air temperatures. Indeed, it has been estimated that increasing green cover (e.g. trees, greenspaces and green roofs) by 10% in dense urban areas of Greater Manchester could negate all projected increases in maximum surface temperatures due to climate change in the 2050s (Gill et al., 2007).

# 7. Discussion and conclusion

This section reflects on the findings of the tasks and provides an overall recommendation for end users of the research.

## 7.1 Task 1

Each approach under Task 1 identified similar and expected patterns for the locations across Greater Manchester with homes that are most sensitive to overheating.

**Manchester city centre:** UCL's assessment found that homes in the central parts of Manchester city are more likely to exhibit the highest levels of elevated indoor temperatures and are most prone to overheating. UoM's assessment also identified that homes in Manchester city centre exhibit high levels of sensitivity due to the prevalence of flats and modern homes. Overheating in these areas may be more severe than estimated, as the city centre experiences the UHI effect.

**High-density urban zones:** Across the ten boroughs, there are pockets of homes with higher sensitivities to overheating. These areas, characterized by compact and closely situated housing, show significant heat retention. This may be due to their proximity to hard, human-made surfaces and lower availability of green space. Salford, Stockport, Oldham, and Bury have higher scores across both assessments in their urban areas.

The composite HVI from UoM shows that, as expected, urban areas in Greater Manchester are the most vulnerable, and that this is due to not only housing type and density but also the amount of and proximity to green and blue space, the local environment (noise and air quality), and the socio-economic characteristics (over-occupancy, crime and income) of these areas. In terms of outdoor sensitivity, adaptive capacity and, to a lesser extent, indoor heat sensitivity, green space is a key determinant of vulnerability. As well as increasing expected temperatures, lack of nearby greenspace reduces how well occupants can adapt through seeking cool spaces.

Higher vulnerability in parts of Salford and Manchester, driven by the adaptive capacity domain, also shows the significance of household income, crime prevalence and air pollution. Occupant sensitivity shows how, in addition to the characteristics of urban centres, indicators of sensitivity (such as occupant age, disability, and health) show more distributed clusters of vulnerability across Greater Manchester. This highlights the importance of considering the individual domains, as well as the composite HVI to account for all forms of heat vulnerability.

### 7.1.1 How can the Task 1 methods be used?

The UoM index and UCL modelling approaches together provide a comprehensive framework for policymakers to understand some of the sensitivities of homes and vulnerability of occupants to overheating. The key policy uses of these methods lie in their ability to offer actionable insights that can be directly applied to both strategic planning and targeted interventions, and which sit across policy streams.

The UCL modelling approach isolates how building design (geometry and thermal characteristics, such as insulation) and operation (occupancy patterns, heat emitted by the occupants, lights and appliances, ventilation, and shading) affect heat sensitivity. It identifies which homes are most at risk of overheating and why; showing that the type of home and its geometry, plays a larger role in contributing to the sensitivity of homes to overheating than its construction age. This insight can help policymakers to target energy retrofit programmes, and heat resilience strategies, and determine which households may require targeted advice or support on how to reduce overheating in their homes as a priority.

The UoM approach is valuable for informing policymakers about the distribution of homes that are sensitive to overheating. By identifying the specific factors heightening home sensitivity scores, such as poor roof insulation in one area versus excessive glazing in another, targeted adaptation measures can be prioritized. Importantly, the inclusion of indicators relating to outdoor and individual sensitivity as well as adaptive capacity enables a multi-pronged approach to adaptation. By identifying locations where more occupants are vulnerable and referring to the individual domains and indicators that contribute, policymakers can determine potential adaptation measures that will reduce occupants' sensitivities and/or increase their adaptive capacities and thereby reduce their vulnerability to overheating. For instance, policies can be targeted to enhance green infrastructure if occupant vulnerability is primarily due to a lack of green space, or to address air pollution if high levels in certain areas may restrict occupants from opening their windows. This ability to understand and address the root causes of vulnerability makes the index an essential tool for developing effective climate adaptation strategies. Where retrofitting all homes to reduce heat sensitivities is challenging, policy makers can prioritise homes where occupants are particularly sensitive and/or adaptive capacity is particularly low.

In summary, the UoM index and UCL modelling approaches together offer a powerful toolkit for policymakers. UoM's approach guides the strategic allocation of resources by identifying vulnerable areas and the drivers of that vulnerability, while UCL's modelling approach provides detailed insights into sensitivity to overheating at the building level. These methods can enable policymakers to develop targeted, effective adaptation actions that reduce vulnerability and enhance heat resilience.

## 7.2 Task 2

It was found that low-cost, adaptive, behavioural, non-structural actions can potentially reduce hours of overheating by more than half in homes sensitive to overheating in Greater Manchester. To quantify overheating, CIBSE TM59 Criterion 1 was used, which defines overheating as when the actual operative temperature is equal to or greater than one degree (K) above the limiting maximum acceptable temperature for more than 3% of the occupied hours between May to September. The median percentage was estimated across all types of homes for the current building stock to be between 6% and 9% of the occupied hours under the 2030 scenarios, and between 6% and 11% under the 2050 scenarios. For the 2050 scenarios, this equates to over 110 to 294 occupied hours from May to September where the homes exceed the CIBSE TM59 Criterion 1.[14] When adaptive, behavioural, non-structural actions were applied, the range of median percentage was between 3% and 6% under the 2030 scenarios, and between 3% and 7% under the 2050 scenarios. More substantial, passive, structural actions, such as external wall and window shading, yielded greater reductions in overheating overall and performed slightly better when combined

[14] These are hours *over* the CIBSE Criterion 1 threshold of 3%.

with behavioural actions. When these structural combinations were applied to a greater extent and alongside behavioural actions, the percentage of occupied hours from May to September when the actual operative temperature is equal to or greater than one degree (K) above the limiting maximum acceptable temperature was between 0% and 1% under the 2030 scenarios, and between 0% and 2% under the 2050 scenarios (i.e., CIBSE TM59 Criterion 1 was not exceeded).

Although the cost-benefit analysis was only conducted on actions and strategies which require capital costs, it is clear that there are substantial differences in the cost-efficiency of the least and best performing actions. At a household level, the most cost-efficient action across all types of homes is installing white curtains and using these to provide internal shading. This action does not provide the most benefit overall and nor can it avoid overheating in all types of homes if it is the sole action employed. However, it is comparatively inexpensive and can marginally reduce the time when residents at home experience indoor temperatures above recommended levels. In contrast, the best performing structural actions were found to have relatively low cost-efficiency in terms of additional hours of comfort gained, due to higher capital costs.

As mentioned, for the current state of the building stock, the mean percentage of the occupied hours between May to September when the actual operative temperature is equal to or greater than one degree (K) above the limiting maximum acceptable temperature was estimated to be between 6% and 9% under the 2030 scenarios. This is above the 3% 'allowance' of CIBSE Criterion 1, but not significantly. This may explain why the stakeholder survey revealed that while many respondents experience overheating, they do not perceive it as a pressing concern. As a result, respondents were reluctant to view the installation of adaptation actions as essential. Furthermore, the cost-benefit analysis identified that more costly individual adaptation actions, such as external shutters or modifying the reflectivity of the walls of homes, offer relatively low cost-efficiency in terms of the additional hours of thermal comfort gained across all types of home. This underscores the challenge of demonstrating to households the value of investing in more expensive adaptation actions.

The results of the stakeholder survey and the cost-benefit analysis suggest that government intervention and support would likely be required to encourage people to implement the adaptation actions considered by this study, particularly those with higher capital costs. It is worth noting that not all the modelled actions can be fully applied to every home due to personal, spatial, financial, and legal/planning constraints, including those for listed buildings.

The stakeholder survey also revealed that many people are unaware of the low-cost behavioural measures meaning that education, delivered through effective channels, regarding these types of actions is needed across the Greater Manchester public. Increasing the scope of existing channels that deliver energy advice for winter could be a good solution.

As the climate becomes warmer, meeting overheating criteria will become increasingly challenging without active cooling systems. Nevertheless, adaptive and passive actions may delay the installation or reduce the use of active cooling systems in the future, and the associated capital and operational costs, and carbon emissions. It is recommended that the cost-benefit of the adaptive and passive actions for reducing indoor overheating, and the associated political considerations detailed here, should be considered in future policy planning and decision making at local and national levels.

# 8. References

Aldrich, N., & Benson, W. F. (2008). Peer Reviewed: Disaster Preparedness and the Chronic Disease Needs of Vulnerable Older Adults. *Preventing Chronic Disease*, 5(1). Centre for Disease Control and Prevention. https://doi.org/10.1110/ps.051922406 (Accessed: July 2024).

Aram, F., García, E. H., Solgi, E., & Mansournia, S. (2019). Urban green space cooling effect in cities. *Heliyon*, 5(4), e01339. https://doi.org/10.1016/j.heliyon.2019.e01339.

Arup. (2022). Addressing overheating risk in existing UK homes, London: Arup.

Ascione, F., Bianco, N., De Masi, R.F., Mastellone, M., Mauro, G.M. and Vanoli, G.P. (2020). The role of the occupant behavior in affecting the feasibility of energy refurbishment of residential buildings: Typical effective retrofits compromised by typical wrong habits. *Energy and Buildings*, *223*, p.110217.

Auger, N., Fraser, W. D., Smargiassi, A., & Kosatsky, T. (2015). Ambient heat and sudden infant death: A case-crossover study spanning 30 years in Montreal, Canada. *Environmental Health Perspectives*, 123(7), 712–716. https://doi.org/10.1289/ehp.1307960.

Baborska-Narozny, M., Stevenson, F. & Grudzinska, M. (2017). Overheating in retrofitted flats: occupant practices, learning and interventions. Building Research & Information, 45(1-2).

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

Botti, A., Leach, M., Lawson, M., Hadjidimitriou, N. (2022), Developing a meta-model for early-stage overheating risk assessment for new apartments in London, Energy and Buildings, Volume 254, 2022, 111586, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2021.111586.

BRE, 2024. RdSAP 10 Specification., Warford, UK: Building Research Establishment (BRE).

Brown, C. (2022). Improving spatial assessment of vulnerability to urban heat stress: Developing a Heat Vulnerability Index for Greater Manchester. Doctoral Thesis, University of Manchester, Faculty of Science and Engineering.

Buoite Stella, A., Filingeri, D., Ravanelli, N., Morrison, S. A., Ajčević, M., Furlanis, G., & Manganotti, P. (2021). Heat risk exacerbation potential for neurology patients during the COVID-19 pandemic and related isolation. *International Journal of Biometeorology*, 65(4), 627–630. https://doi.org/10.1007/s00484-020-02044-2.

CIBSE. (2017). TM59 Design methodology for the assessment of overheating risk in homes, s.l.: CIBSE.

Calver, P., & Simcock, N. (2021). Demand response and energy justice: A critical overview of ethical risks and opportunities within digital, decentralised, and decarbonised futures. Energy Policy, 151, 112198. https://doi.org/10.1016/j.enpol.2021.112198.

Climate Change Committee. (2021). Independent Assessment of UK Climate Risk. Westminster: CCC. Available at: Independent Assessment of UK Climate Risk - Climate Change Committee (theccc.org.uk) (Accessed: July 2024).

Climate Change Committee. (2022). Risks to health, wellbeing and productivity from overheating in buildings. Westminster: Climate Change Committee. Available at: Risks to health, wellbeing and productivity from overheating in buildings - Climate Change Committee (theccc.org.uk) (Accessed: July 2024).

Crawley, J., Wang, X., Ogunrin, S., Vorushlyo, I., & Taneja, S. (2020). Domestic Air Conditioning in 2050 - Increasing Visibility of Underrepresented Groups in Energy Research (IVUGER) Report.

Conti, S., Meli, P., Minelli, G., Solimini, R., Toccaceli, V., Vichi, M., Beltrano, C. and Perini, L. (2005). Epidemiologic study of mortality during the Summer 2003 heat wave in Italy. *Environmental Research*, 98(3), 390–399. https://doi.org/10.1016/j.envres.2004.10.009.

Copernicus Global Land Service. (2024). Sentinel-2 Global Mosaic Service. Available at: Sentinel-2 Global Mosaic service | Home (copernicus.eu) (Accessed: July 2024).

Corcuera Hotz, I., & Hajat, S. (2020). The Effects of Temperature on Accident and Emergency Department Attendances in London: A Time-Series Regression Analysis. *International Journal of Environmental Research and Public Health*, 17(6), 1957. https://doi.org/10.3390/ijerph17061957.

Curriero, F.C., Heiner, K.S., Samet, J.M., Zeger, S.L., Strug, L. and Patz, J.A. (2002). Temperature and Mortality in 11 Cities of the Eastern United States. American Journal of Epidemiology, 155(1), 80–87. https://doi.org/10.1093/aje/155.1.80.

Defra. (2019). Road Noise - Lden - England Round 3 (data.gov.uk). Available at: Road Noise - Lden - England Round 3 (data.gov.uk) (Accessed: July 2024).

Defra. (2024). Modelled background pollution data annual mean 2022 PM2.5 and NOx (as NO2) in µg m-3. Available at: [Modelled background pollution data - Defra, UK] (Accessed: July 2024).

Department for Levelling Up, Housing and Communities. (2024). Energy performance of buildings data: England and Wales. Available at: [Energy Performance of Buildings Data England and Wales] (Accessed: July 2024).

Eames, M. E., Xie, H., Mylona, A., Shilston, R., & Hacker, J. (2024). A revised morphing algorithm for creating future weather for building performance evaluation. Building Services Engineering Research & Technology, 45(1), 5-20.

Fang, Y., & Gu, K. (2022). Exploring coupling effect between urban heat island effect and PM2.5 concentrations from the perspective of spatial environment. *Environmental Engineering Research*, 27(2), 200559-0. https://doi.org/10.4491/eer.2020.559.

Ferguson, L., Mavrogianni, A., Symonds, P., Davies, M., & Ruyssevelt, P. (2023, November). Inequalities in exposure to indoor environmental hazards across England and Wales–can more energy efficient homes help?. In *Journal of Physics: Conference Series* (Vol. 2600, No. 14, p. 142002). IOP Publishing.

Ferguson, L., & Mavrogianni, A. (2024). The impact of heat adaptation on socioeconomically vulnerable populations. In Mitigation and Adaptation of Urban Overheating: The Impact of Warmer Cities on Climate, Energy, Health, Environmental Quality, Economy, and Quality of Life (pp. 277–293). https://doi.org/10.1016/B978-0-443-13502-6.00010-5.

Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guihenneuc-Jouyaux, C., Clavel, J., Jougla, E. and Hémon, D. (2006). Excess mortality related to the August 2003 heat wave in France. International Archives of Occupational and Environmental Health, 80(1), 16–24. https://doi.org/10.1007/s00420-006-0089-4.

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. Built Environment, 33(1), 115-133. https://doi.org/10.2148/benv.33.1.115

Green Alliance. (2024). Climate Adaptation in UK Homes - Energy suppliers' roles in preparing customers, London: Green Alliance.

Green Alliance. (2024). Climate adaptation in UK homes: Energy suppliers' role in preparing customers, s.l.: s.n.

Gupta, R. & Gregg, M. (2012). Using UK climate change projections to adapt existing English homes for a warming climate. Building and Environment, Volume 55, pp. 20-42.

Hankey, S., & Marshall, J. D. (2017). Urban Form, Air Pollution, and Health. *Current Environmental Health Reports*, 4(4), 491–503. https://doi.org/10.1007/s40572-017-0167-7.

Hatvani-Kovacs, G., Belusko, M., Skinner, N., Pockett, J., & Boland, J. (2016). Heat stress risk and resilience in the urban environment. Sustainable Cities and Society, Volume 26, pp. 278-288.

HM Government. (2021). The building regulations 2010: overheating. Westminster: HM Government. Available at: [Overheating: Approved Document O - GOV.UK (www.gov.uk)] (Accessed: July 2024).

Hutter, H. P., Moshammer, H., Wallner, P., Leitner, B., & Kundi, M. (2007). Heatwaves in Vienna: Effects on mortality. Wiener Klinische Wochenschrift, 119(7–8), 223–227. https://doi.org/10.1007/s00508-006-0747-0

Kaiser, R., Rubin, C. H., Henderson, A. K., Wolfe, M. I., Kieszak, S., Parrott, C. L., & Adcock, M. (2001). Heat-related death and mental illness during the 1999 Cincinnati heat wave. The American Journal of Forensic Medicine and Pathology, 22(3), 303–307. https://doi.org/10.1097/00000433-200109000-00022

Kang, Y., Baek, I., & Park, J. (2024). Assessing heatwave effects on disabled persons in South Korea. Scientific Reports, 14(3459). https://doi.org/10.1038/s41598-024-54015-x

Kim, Y., & Joh, J. (2006). A vulnerability study of the low-income elderly in the context of high temperature and mortality in Seoul, Korea. Science of the Total Environment, 371(1–3), 82–88. https://doi.org/10.1016/j.scitotenv.2006.08.014

Klein Rosenthal, J., Kinney, P. L., & Metzger, K. B. (2014). Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. Health & Place, 30, 45–60. https://doi.org/10.1016/j.healthplace.2014.07.014

Knowlton, K., Rotkin-Ellman, M., King, G., Margolis, H.G., Smith, D., Solomon, G., Trent, R. and English, P. (2009). The 2006 California heat wave: Impacts on hospitalizations and emergency department visits. Environmental Health Perspectives, 117(1), 61–67. https://doi.org/10.1289/ehp.11594

Kovats, R. S., Hajat, S., & Wilkinson, P. (2004). Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. Occupational and Environmental Medicine, 61(11), 893–898. https://doi.org/10.1136/oem.2003.012047

Layton, J. B., Li, W., Yuan, J., Gilman, J. P., Horton, D. B., & Setoguchi, S. (2020). Heatwaves, medications, and heat-related hospitalization in older Medicare beneficiaries with chronic conditions. PLOS ONE, 15(12), e0243665. https://doi.org/10.1371/journal.pone.0243665

Levermore, G.J., Parkinson, J.B., Laycock, P.J. and Lindley, S. (2014). The Urban Heat Island in Manchester 1996–2011. Building Services Engineering Research and Technology, 36(3), 343–356. https://doi.org/10.1177/0143624414549388

Liu, C., Kershaw, T., Fosas, D., Gonzalez, A.R., Natarajan, S. and Coley, D.A. (2017). High resolution mapping of overheating and mortality risk. Building and Environment, 122, 1–14. https://doi.org/10.1016/j.buildenv.2017.05.028

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

Lomas, K. J., Watson, S., Allinson, D., Fateh, A., Beaumont, A., Allen, J., Foster, H., & Garrett, H. (2021). Dwelling and household characteristics' influence on reported and measured summertime overheating: A glimpse of a mild climate in the 2050's. Building and Environment, 201, 107986. https://doi.org/10.1016/J.BUILDENV.2021.107986

Madrigano, J., Ito, K., Johnson, S., Kinney, P. L., & Matte, T. (2015). A case-only study of vulnerability to heat wave–related mortality in New York City (2000–2011). Environmental Health Perspectives, 123(7), 672. https://doi.org/10.1289/ehp.1408178

Malmquist, A., Lundgren, T., Hjerpe, M., Glaas, E., Turner, E., & Storbjörk, S. (2021). Vulnerability and adaptation to heat waves in preschools: Experiences, impacts and responses by unit heads, educators and parents. Climate Risk Management, 31, 100271. https://doi.org/10.1016/j.crm.2020.100271

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P., & Oikonomou, E. (2012). Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. Building and Environment, 55, 117–130. https://doi.org/10.1016/j.buildenv.2011.12.003

Mavrogianni, A., Davies, M., Taylor, J., Chalabi, Z., Biddulph, P., Oikonomou, E., Das, P. and Jones, B. (2014). The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments. Building and Environment, Volume 78, pp. 183-198.

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

McGill, G., Oyedele, L. O., & McAllister, K. (2015). An investigation of indoor air quality, thermal comfort and sick building syndrome symptoms in UK energy efficient homes. Smart and Sustainable Built Environment. https://doi.org/10.1108/SASBE-10-2014-0054

McGeehin, M. A., & Mirabelli, M. (2001). The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. Environmental Health Perspectives, 109(Suppl 2), 185. https://doi.org/10.1289/ehp.109-1240665

McLachlan, C., Glynn, S., Hill, F., Edwards, R., Kuriakose, J., Wood, R., & Manchester, T. (2016). Air conditioning demand assessment. Tyndall Manchester. Available at: https://www.enwl.co.uk/globalassets/innovation/enwl001-demand-scenarios–atlas/enwl. Accessed August 2024

Meier, A., Rainer, L., Daken, A., Ueno, T., Pritoni, M., & Baldewicz, D. (2019). What can connected thermostats tell us about American heating and cooling habits? UC Davis.

Met Office Hadley Centre. (2018). UKCP18 Probabilistic Climate Projections., s.l.: Centre for Environmental Data Analysis .

Met Office. (2022). Manchester heat pack. UK Climate Resilience. Available at: CSSP_city_pack_MANCHESTER (metoffice.gov.uk). Accessed July 2024

Ministry of Housing, Communities and Local Government. (2019). English indices of deprivation. Available at: https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019 Accessed July 2024.

Morton, D., Marston, C., O'Neil, A., & Rowland, C. (2024). Land Cover Map 2023 (10m classified pixels, GB). NERC EDS Environmental Information Data Centre.

Murtagh, N., Gatersleben, B. & Fife-Schaw, C. (2019). Occupants' motivation to protect residential building stock from climate-related overheating: A study in southern England. Journal of Cleaner Production, Volume 226, pp. 186-194.

Mujan, I., Anđelković, A. S., Munćan, V., Kljajić, M., & Ružić, D. (2019). Influence of indoor environmental quality on human health and productivity: A review. Journal of Cleaner Production, 217, 646-657. https://doi.org/10.1016/j.jclepro.2019.01.307

Murage, P., Kovats, S., Sarran, C., Taylor, T., McInnes,R., Hajat, S (2020) What individual and neighbourhood-level factors increase the risk of heat-related mortality? A case-crossover study of over 185,000 deaths in London using high-resolution climate datasets, Environment International, Volume 134, 2020, 105292, ISSN 0160-4120, https://doi.org/10.1016/j.envint.2019.105292.

Naughton, M.P., Henderson, A., Mirabelli, M.C., Kaiser, R., Wilhelm, J.L., Kieszak, S.M., Rubin, C.H. and McGeehin, M.A. (2002). Heat-related mortality during a 1999 heat wave in Chicago. American Journal of Preventive Medicine, 22(4), 221–227. https://doi.org/10.1016/s0749-3797(02)00421-x

Oikonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P. and Kolokotroni, M.(2012). Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. Building and Environment, Volume 57, pp. 223-238.

O'Neill, M. S., & Ebi, K. L. (2009). Temperature extremes and health: Impacts of climate variability and change in the United States. Journal of Occupational and Environmental Medicine, 51(1), 13–25. https://doi.org/10.1097/jom.0b013e318173e122

Office for National Statistics (ONS). (2024a). Nomis official labour and Census statistics. Available at: Dataset Selection - Query - Nomis - Official Census and Labour Market Statistics (nomisweb.co.uk) Accessed July 2024.

Office for National Statistics (ONS). (2024b). Open Geography Portal Postcode to 2021 LSOA look-up tables. Available at: Open Geography Portal (statistics.gov.uk) Accessed July 2024.

Office for National Statistics (ONS) (2024c) Estimates by single year of age and sex for 2021 LSOA, mid-2022. Available at: Lower layer Super Output Area population estimates (Accredited official statistics) - Office for National Statistics (ons.gov.uk) Accessed July 2024

Ordnance Survey (2024a). OS Mastermap Topography Layer. Available at: OS MasterMap Topography Layer | Data Products | OS (ordnancesurvey.co.uk) Accessed July 2024

Ordnance Survey (2024b). OS Mastermap Building Height Attribute. Available at: OS MasterMap Building Height Attribute | Data Products | OS (ordnancesurvey.co.uk) Accessed July 2024

Ordnance Survey (2024c). OS Open Greenspace Data Products. Available at: OS Open Greenspace | Data Products | OS (ordnancesurvey.co.uk) Accessed July 2024

Palinkas, L. A., Hurlburt, M. S., Fernandez, C. & De Leon, J., 2022. Vulnerable, Resilient, or Both? A qualitative study of adaptation resources and behaviours to heat waves and health outcomes of low-income residents of urban heat islands. International Journal of Environmental Research and Public Health, 19(17).

Petrou, G., Symonds, P., Mavrogianni, A., Mylona, A. and Davies, M. (2019). The summer indoor temperatures of the English housing stock: Exploring the influence of dwelling and household characteristics. Building Services Engineering Research and Technology, 40(4), 492-511. https://doi.org/10.1177/0143624419847621

Porritt, S., Cropper, P., Shao, L. & Goodier, C. (2012). Ranking of interventions to reduce dwelling overheating during heat waves. Energy and Buildings, Volume 55, pp. 16-27.

Public Health England. (2020). PHE heatwave mortality monitoring reports (2016 to 2020): Heatwave mortality monitoring report: 2020. Available at: Heatwave mortality monitoring report: 2020 - GOV.UK (www.gov.uk). Accessed July 2024

Rakoto, P., Deliami, K., Hurley, J., Amati, M., Sun, Q (2021) Revisiting the cooling effects of urban greening: planning implications of vegetation types and spatial configuration. Urban Forestry and Urban Greening 64 127266. https://doi.org/10.1016/j.ufug.2021.127266

Roaf, S., Crichton, D. & Nicol, F. (2005). Adapting buildings and cities for climate change. s.l.:s.n.

Roaf, S. & Nicol, F. (2020). Acceptable Temperatures in Naturally Ventilated Buildings.

Stafoggia, M., Forastiere, F., Agostini, D., Caranci, N., De'Donato, F., Demaria, M., Michelozzi, P., Miglio, R., Rognoni, M., Russo, A. and Perucci, C.A.. (2008). Factors affecting in-hospital heat-related mortality: A multi-city case-crossover analysis. Journal of Epidemiology and Community Health, 62(3), 209-215. https://doi.org/10.1136/jech.2007.060715

Schifano, P., Cappai, G., De Sario, M., Michelozzi, P., Marino, C., Bargagli, A. M., & Perucci, C. A. (2009). Susceptibility to heat wave-related mortality: A follow-up study of a cohort of elderly in Rome. Environmental Health, 8(1), 50. https://doi.org/10.1186/1476-069X-8-50

Smithers, R.J.; Doick, K.J.; Burton, A.; Sibille, R.; Steinbach, D.; Harris, R.; Groves, L. and Blicharska, M. (2018) Comparing the relative abilities of tree species to cool the urban environment. Urban Ecosystems, 21(5): 851-862.

Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban form and extreme heat events: Are sprawling cities more vulnerable to climate change than compact cities? Environmental Health Perspectives, 118(10), 1425-1428. https://doi.org/10.1289/ehp.0901879

Tan, J. (2008). Commentary: People's vulnerability to heat wave. International Journal of Epidemiology, 37(2), 318-320. https://doi.org/10.1093/ije/dyn023

Taylor, J., Mavrogianni, A., Davies, M., Das, P., Shrubsole, C., Biddulph, P., & Oikonomou, E. (2015). Understanding and mitigating overheating and indoor PM2.5 risks using coupled temperature and indoor air quality models. Building Services Engineering Research and Technology, 36(2), 275-289. https://doi.org/10.1177/0143624414566474

Taylor, J., Davies, M., Mavrogianni, A., Shrubsole, C., Hamilton, I., Das, P., Jones, B., Oikonomou, E. and Biddulph, P. (2016). Mapping indoor overheating and air pollution risk modification across Great Britain: A modelling study. Building and Environment, 99, 1-12. https://doi.org/10.1016/j.buildenv.2016.01.010

Taylor, J., Symonds, P., Wilkinson, P., Heaviside, C., Macintyre, H., Davies, M., Mavrogianni, A. and Hutchinson, E. (2018). Estimating the Influence of Housing Energy Efficiency and Overheating Adaptations on Heat-Related Mortality in the West Midlands, UK. Atmosphere, 9(5).

Thompson, R., Landeg, O., Kar-Purkayastha, I., Hajat, S., Kovats, S., & O'connell, E. (2022). Heatwave mortality in summer 2020 in England: An observational study. International Journal of Environmental Research and Public Health, 19(10), 6123. https://doi.org/10.3390/ijerph19106123

UKHSA. (2023). Heat mortality monitoring report: 2022. Available at: Heat mortality monitoring report: 2022 - GOV.UK (www.gov.uk). Accessed July 2024

Willand, N., Ridley, I., & Pears, A. (2016). Relationship of thermal performance rating, summer indoor temperatures and cooling energy use in 107 homes in Melbourne, Australia. Energy and Buildings, 113, 159-168. https://doi.org/10.1016/j.enbuild.2015.12.032

Woodland, L., Ratwatte, P., Phalkey, R., & Gillingham, E. L. (2023). Investigating the health impacts of climate change among people with pre-existing mental health problems: A scoping review. International Journal of Environmental Research and Public Health, 20(8), 5563. https://doi.org/10.3390/ijerph20085563

World Health Organisation. (2021). Climate change and health vulnerability and adaptation assessment. Geneva: World Health Organization. Available at: 9789240036383-eng.pdf (who.int). Accessed July 2024

Wright, D. L., Haines, V. J. & Lomas, K. J. (2018). Overheating in UK Homes: Adaptive opportunities, actions and barriers. s.l., s.n.

Wright, M. K., Hondula, D. M., Chakalian, P. M., Kurtz, L. C., Watkins, L., Gronlund, C. J. & Harlan, S. L. (2020). Social and behavioral determinants of indoor temperatures in air-conditioned homes. Building and Environment, 183, 107187. https://doi.org/10.1016/j.buildenv.2020.107187

Xu, Z., Crooks, J. L., Black, D., Hu, W., & Tong, S. (2017). Heatwave and infants' hospital admissions under different heatwave definitions. Environmental Pollution, 229, 525-530. https://doi.org/10.1016/j.envpol.2017.06.030

# Appendices

## Appendix 1. Task 1 Detailed Methodologies

*This appendix provides additional detail for the Task 1 methodologies, including further information on EPC coverage in Greater Manchester and collection and use of the HVI indicators by UoM.*

### Supporting tables

The EPC data coverage at local authority and regional level, compared to the national average, is presented in Table A-1.

Table A-1: Percentage of homes covered by an EPC in England, in the North West region, and per borough in Greater Manchester according to the 2021 Census data (Office for National Statistics).

| Area name | All homes | Detached | Semi-detached | Terraced | Flats and Maisonettes |
|---|---|---|---|---|---|
| England | **59.3** | **52.4** | **54.9** | **60.3** | **72.1** |
| North West | **59.2** | **52.1** | **53.5** | **62.0** | **75.2** |
| Bolton | 57.9 | 51.4 | 52.3 | 60.3 | 74.1 |
| Bury | 55.7 | 48.9 | 50.3 | 59.8 | 70.0 |
| Manchester | 70.8 | 64.3 | 62.1 | 67.1 | 81.8 |
| Oldham | 59.6 | 51.4 | 53.3 | 64.0 | 71.9 |
| Rochdale | 59.7 | 53.2 | 55.8 | 61.2 | 73.7 |
| Salford | 70.4 | 59.1 | 60.0 | 69.2 | 85.0 |
| Stockport | 56.7 | 47.6 | 51.9 | 60.8 | 74.6 |
| Tameside | 58.6 | 51.3 | 53.2 | 60.8 | 72.5 |
| Trafford | 57.7 | 48.6 | 49.4 | 62.3 | 76.5 |
| Wigan | 56.3 | 51.9 | 51.0 | 61.8 | 75.3 |

### Production of UoM Heat Vulnerability Index

Table A-2 presents a summary of the indicators used within the UoM HVI. These indicators were collected for each LSOA in Greater Manchester (where raw data was not already available at LSOA). Weightings for individual indicators (such as greenspace), and then domains within the composite index, are applied so that an indicator with more contributing factors than others, and indicators included in more than one domain, are not overrepresented and skew the results. For example, roof insulation and window glazing are both factors of how building insulation contributes to indoor sensitivity to warmer weather, and these are weighted so as to be a combined single value rather than representing building insulation twice in the scoring. No weightings are made on relative importance or significance of an indicator, as at this stage there is no evidence to support a determination on this. To produce the index the following steps were then taken:

1. The data for each of the indicators in Table  was normalised with a value from (0-1).
2. Weighting was applied to the normalised score for each indicator, by default this was 1. Where the same component of vulnerability was represented by more than 1 indicator, the weightings were summed to 1 instead. Where this is the case, it is explained in Table A-1.
3. The weighted score of each indicator within each domain was summed to give a domain score for each LSOA.
4. The normalised scores for each of the four domains for each LSOA were summed to give the final index, with no weightings, therefore all domains were weighted equally.

Table A-2: A summary of the indicators, the data sources, processing methodology and their relationship with heat vulnerability

| Indicator | | Data Source and Methodology | Relationship with vulnerability | Weighting within the domain |
|---|---|---|---|---|
| Outdoor Sensitivity | Average elevation (m) | OS Topography Layer (2024a)<br>Average elevation calculated by joining the topography layer with the LSOA boundaries. | Elevation and ambient air temperatures are related, as temperatures change with altitude. Higher elevations relate to lower temperatures. | 1 |
| | Average building height (m) | OS MasterMap Building Height Attribute joined with the OS Topography Layer (OS,2024a; OS, 2024b)<br>Building height information (RelHMax) averaged within each LSOA. | Regression analysis with Greater Manchester temperature monitoring data indicates a strong relationship with UHI (Brown, 2022).<br>Tall buildings can trap heat in street canyons, limiting heat dissipation. Taller average building heights increase heat sensitivity. | 1 |
| | Population density people/m$^2$ | Census 2021<br>Direct download | Population density is a proxy indicator for anthropogenic heat emissions. Heat emissions include exhaust heat from vehicles, heating, Ventilation, and Air Conditioning systems and hot water provision. Thus, the higher the population density, the greater the sensitivity. | 1 |
| | Average NDVI in the LSOA | Sentinel-2 Mosaic Data (Copernicus Global land service, 2024).<br>The average NDVI in summer months is calculated for each LSOA. | Regression analysis with Greater Manchester temperature monitoring data indicates a strong relationship with UHI (Brown, 2022). The Normalised Difference Vegetation Index (NDVI) is an indicator of the amount of greenspace within an area, which can provide cooling, particularly due to evapotranspiration. LSOAs with a lower average NDVI are more sensitive to heat. | The landcover indicators sum to 1. Each is weighted based on its relative relationship with air temperature based on previous regression modelling (Brown, 2022).<br>0.4 NDVI.<br>0.2 each for land cover type to represent landcover and its contribution to the UHI. |
| | % Woodland | UK CEH Landcover maps (Morton, 2024)<br>The % of land space within each LSOA covered in woodland. | Tree canopy cover provides cooling through evapotranspiration, as well as shade and differences in Albedo as compared with the built environment. Regression analysis demonstrates a relationship with UHI in Greater Manchester (Brown, 2022). While the NDVI showed the strongest relationship with ambient air temperatures, land surface cover type is useful to inform planning decisions. Wider evidence demonstrates differences in the cooling effect both between tree species and different forms of vegetation (Smithers *et a*l., 2018; Rakoto *et al.*, 2020) In this index assumes that LSOAs with a higher percentage of woodland cover have a lower sensitivity to heat. Landcover maps will omit small parcels of vegetation, such as urban gardens and street trees; however, these are captured within the NDVI. | |
| | % Grassland | UK CEH Landcover maps (Morton, 2024) | Grassland cover can also provide cooling through evapotranspiration, although in hotter temperatures this service is reduced as soil dries out and grass yellows. | |
| | % Water (fresh) | UK CEH Landcover map (Morton, 2024) | Bodies of water provide cooling by absorbing heat. Greater Manchester has a limited amount of water bodies, and none were near the temperature sensors used to conduct the regression analysis, therefore, they didn't show a strong relation with the temperature measurements. However, water cover is demonstrably an important feature in mediating the UHI as demonstrated by other studies and is therefore included here. | |
| Indoor Sensitivity | % homes classified as overcrowded | 2021 Census TS052 "Occupancy rating for bedrooms"<br>% of homes with an occupancy rating of bedrooms classified as -1 or -2 or less. | Overcrowding increases internal heat gains from occupants. Over-occupied bedrooms are likely to be warmer overnight. Nighttime temperatures are correlated with higher adverse health outcomes. The higher the percentage of homes that are overcrowded, the higher the indoor sensitivity of the LSOA. | 1 |
| | % households classified as living in flats or terraces | 2021 Census TS044 "Accommodation type"<br>% households classified as living in terraces, purpose-built block of flats or tenement, part of converted house or bedsit, part of another converted building or in a commercial building, e.g., hotel or over a shop. | Evidence suggests flats are more prone to overheating than other building types, particularly top floor flats (Mavrogianni *et a*l., 2012; Beizaee *et al*., 2013; Lomas and Kane, 2013; Taylor *et al*., 2015; Taylor *et* al., 2016; Liu *et* al., 2017; Petrou *et al*., 2019; Lomas *et* al., 2021). Flats or rooms (e.g., bedsits or hotel rooms) without cross ventilation are also particularly vulnerable). Around two thirds of overheating living rooms nationally were in flats, with the monitored and reported prevalence of overheating in flats being double that for other types of homes (Lomas *et al.,* 2021)<br>Terrace homes have been shown to overheat more than semi-detached or detached (Beizaee *et al*., 2013; Gupta and Gregg, 2012), particularly mid-terrace homes, which are less likely to have a "safe haven" from overheating within the homes than semi-detached and detached buildings (Drury *et al*., 2021). Terrace homes are often smaller than other building types, The prevalence of overheating in small homes may be four times higher than in homes over 100m$^2$ (Lomas *et al*., 2021). The higher the % of flats and terraces within an LSOA | 0.5 each<br>Reflects equal weighting between building types both known to be more likely to overheat compared to detached and |

| Indicator | | Data Source and Methodology | Relationship with vulnerability | Weighting within the domain |
|---|---|---|---|---|
| | | | the higher the rank of the LSOA under this indicator. The analysis by UCL in this report indicates mid terraces and flats have similar levels of sensitivity to overheating, and end-terraces slightly lower. | semi-detached houses. |
| | % of homes with poor or very poor roof energy efficiency | EPC download July 2024<br><br>Each postcode is assigned to an LSOA. Duplicate EPCs are removed. Sum all homes classified as 'poor' or 'very poor' roof energy efficiency in the LSOA | Homes with poor roof insulation have been found to be more vulnerable to overheating, due to heat gains through the roof (Mavrogianni et al., 2012; Petrou *et al.,* 2019). The prevalence of reported overheating in living rooms was significantly less in homes with 50mm or more of loft insulation (Lomas *et al*., 2021). The higher the % of homes with poor or very poor roof energy efficiency, the higher the indoor sensitivity rank for the LSOA under this indicator. | 0.5 each<br><br>Reflects equal weighting across the indicators representing building fabric. Combined this will equal 1. |
| | % of homes with higher glazing areas | EPC download July 2024<br><br>Sum all homes classified as more than typical or much more than typical glazing area in the LSOA | Homes with larger windows are more vulnerable to solar heat gains (Baborska-Narożny *et al*., 2017). Building design features such as glazing, and solar radiation per area of glazing impact overheating (Gupta and Gregg, 2020*)* The higher the percentage of homes with higher glazing area than typical the higher the vulnerability rank for the LSOA under this indicator. | |
| | % of homes that are built after 2007 or pre1900 | EPC July 2024 Download<br><br>Sum all homes built after 2007 or pre 1900. | The analysis by UCL considered in this study indicates homes built after 2007 or pre 1900 within Greater Manchester are more sensitive to overheating. This is supported by other evidence that identifies homes that have higher internal temperatures include those built after the 1980s (Taylor *et al*., 2015; Beizaee *et al.,* 2013) and 'newer' homes generally (McGill *et a*l., 2017).<br><br>The higher the percentage of homes built after 2007 or before 1900 in an LSOA the higher its indoor sensitivity rank for this indicator. | 0.5 for each age group |
| | Average NDVI within 20m of homes | Sentinel-2 Mosaic data; Address Code Data; UPRN Dataset.<br><br>The average NDVI calculated in the 20m around each residential property listed in the EPC database. | Low levels of greenspace immediately around a building can increase internal temperatures compared with those with more immediate greenspace. Green space cools surrounding areas (Aram *et al*., 2019) and green vegetation in the vicinity was associated with lower temperatures in bedrooms in a study of 113 homes in 2 cities the Netherlands (Zuurbier *et al.,* 2021). A case study of heat related deaths in London finds that urban vegetation within the same postcode spatial unit can modify the mortality risk associated with heat exposure (Muraje *et al*., 2020). Here a low average NDVI correlates to higher indoor sensitivity. | 1 |
| Occupant Sensitivity | % residents reporting Disability - limited a little | TS038 Disability 2021 Census (ONS, 2021) | People living with a disability are more sensitive to overheating than the general population (Kovats *et al*., 2004; Stafoggia *et a*l., 2008). Disabled people, especially younger individuals with disabilities can be more exposed to the high temperatures (Kang, Y., *et al* 2024).<br><br>The weightings assume that people who are limited a lot are more sensitive to heat than those who are limited a little. | 0.125 |
| | % residents reporting Disability - limited a lot | TS038 Disability 2021 Census (ONS, 2021) | | 0.375 |
| | % residents reporting Bad health | TS037 General Health 2021 Census (ONS, 2021) | People living with poor health can be more sensitive to overheating than the general population. The weighting assumes that people declaring 'very bad' health are more sensitive to heat than those declaring 'bad' health. Pre-existing health conditions have been identified as leading to susceptibility to heat-related illnesses and mortality (Kovats *et al.,* 2004; Schifano *et al*., 2009; Buoite *et al*., 2020; Layton *et al*., 2020). Specific illnesses linked with exposure to heat include: diabetes (Konkel, 2020); cardio vascular conditions (Yin and Wang, 2017); kidney disease, nervous disorders, emphysema, and epilepsy (Semenza *et al*., 1999); cardiovascular and respiratory diseases, Alzheimer's and dementia in over 65s (Thompson *et al.,* 2022) Impacts on those already suffering from mental health conditions have also been identified (Stafoggia *et al*., 2008; Cusack *et al*., 2011; Woodland *et al.,* 2023). | 0.125 |
| | % residents reporting Very bad health | TS037 General Health Census (ONS, 2021) | | 0.375<br><br>The weights for Census indicators- disability and health sum to 1. |
| | Rank position within GM of the health deprivation and disability domain | English indices of multiple deprivation 2019 (CLG, 2019). | The health and deprivation index is informed by a wider range of information than declared health and disability and includes access to health services. Analysis of the places of deaths during warm weather or extreme heat, has found that deaths are more likely in homes, as compared to a hospital setting, suggesting that access to medical care is another factor that increases vulnerability to overheating (O'Neill *et al*., 2003; Madrigano *et al.,* 2015*).* | 1 |

| Indicator | | Data Source and Methodology | Relationship with vulnerability | Weighting within the domain |
|---|---|---|---|---|
| | % residents aged 0-5 | ONS Population Estimates by 2021 LSOA (ONS, 2024c) | Young children are more sensitive to high temperatures than the general population (McGeehin and Mirabelli, 2001; Kovats *et al.,* 2004; Xu *et al.,* 2017; Malmquist *et al*., 2021). There is a positive association between increasing temperatures and London A&E department attendance, which appears to be most significant in children (Corcuera Hotz *et al*., 2020). Evidence from other countries also links heatwaves to increases in hospital emissions among this age group (Xu *et al*., 2017), as well as to increases in infant mortality (Auger *et al*., 2015). Little evidence has been found on the causes of infant sensitivity. However, it has been suggested this is a result of infants having underdeveloped thermoregulation and immune systems, as well as their very low understanding and self-care ability (Xu *et al*., 2017; cited by Brown, 2022). | 1 |
| | % residents aged 65+ | ONS Population Estimates by 2021 LSOA (ONS, 2024c) | All cause excess mortality is higher in the 65+ age groups during heat events and increases with age (PHE, 2020; UKHSA, 2023). This aligns with experience in other countries of a relationship between age and excess mortality and morbidity during heat events (Knowlton *et al*., 2009; Fouillet *et al.,* 2006). The sensitivity of older people to extreme heat is linked to a higher proportions of older individuals living with illness and disability than in the general population (Aldrich and Benson, 2008; Tan, 2008; Klein Rosentha *et al.,* 2014). It is also linked to the physiology of older people and to their relative lack of mobility (Flynn *et al*., 2005). | 1 |
| Restricted Adaptive Capacity | Rank of IMD – Income deprivation domain within GM | English indices of multiple deprivation 2019 (CLG, 2019). | Low income restricts occupants' ability to buy adaptation options, such as fans, insulation and window shading. Numerous studies have linked increased negative impacts during high temperatures with lower levels of income and high deprivation (Kim and Joh, 2006; Madrigano *et al.,* 2015). This indicator has a strong correlation with education and health (Conti *et al*., 2005; Fouillet *et al*., 2006; Hutter *et al.*, 2007; Knowlton *et al*., 2009). Furthermore, an increasing body of literature indicates that low income and social isolation can limit people's capacity to identify heat hazards, reduce exposure, and cope after a heat event (Ferguson and Mavrogianni, 2024). Here a low income gives a higher score as it reduces adaptive capacity, consistent with higher scores within the index causing higher vulnerability. | 1 |
| | % homes privately rented | Census 2021 TS054 – "Tenure" | Privately renting your home prevents occupants from making changes to the fabric of the building that could make their homes cooler, such as roof insulation or window shading. The higher the percentage of privately rented homes in an LSOA gives a higher score. | 1 |
| | Average $PM_{2.5}$ concentration µg $m^{-3}$ | Modelled background pollution data (Defra, 2024)<br><br>Each centroid is allocated to an LSOA, where there is more than 1 the concentration is averaged. Where there's no centroid within an LSOA the nearest reading is chosen. | Window opening and natural ventilation capacity are by far the strongest predictors of overheating of all those considered by a risk assessment completed in London (Botti *et al*., 2022). Air pollution, noise and fear of crime can limit window opening**.**<br><br>Air pollution can inhibit people opening windows. In addition, there is a relationship between heatwaves, a high UHI effect and elevated levels of air pollution (Fang and Gu, 2022). Furthermore, higher exposure to air pollution is linked with negative health outcomes (Hankey and Marshall, 2017) compounding people's sensitivity to hot weather.<br><br>The higher the air pollution (crime or noise), the higher the assumed restriction on an occupants' ability or willingness to open windows. | All factors which restrict window opening ability sum to 1<br><br>0.167 |
| | Average $NO_x$ (as $NO_2$) concentration µg $m^{-3}$ | Modelled background pollution data (Defra, 2024)<br><br>Each centroid is allocated to an LSOA, where there is more than 1 the concentration is averaged. Where there's no centroid within an LSOA the nearest reading is chosen. | | 0.167 |
| | Average road noise exposure [no unit] | Road Noise -Lden- Round 3 (Defra, 2019). The maps provide bands of noise exposure in decibels. Each band is weighted according to the range of decibels accounting for its logarithmic scale. The number of residential properties in each band are counted and multiplied by the band weighting. An average noise exposure for residential properties in the LSOA is calculated. | Noise from roads can also inhibit people from opening windows and is linked with exposure to air pollution above) (Baborska-Narożny *et al*., 2017; Mavrogianni *et al*., 2017). | 0.333 |

| Indicator | | Data Source and Methodology | Relationship with vulnerability | Weighting within the domain |
|---|---|---|---|---|
| | Rank of crime-related deprivation | English indices of multiple deprivation 2019 (CLG, 2019). | Fear of crime inhibits people leaving windows open (Klinenberg, 2002; Hatvani-Kovacs and Boland, 2015) Crime levels increase during heatwaves (Brunsdon *et al*., 2009; Tiihonen *et al*., 2017; Mahendran *et al*., 2021) | 0.333 |
| | Average distance to accessible greenspace in m. | OS Open Greenspace Data Products<br><br>(Ordnance Survey, 2024c)<br><br>The nearest distance function in GIS is used to estimate the closest distance to an accessible green space from each residential building | Greenspace is cooler than other urban land types, so provides cool spaces for residents. Proximity of accessible green spaces can determine whether it is used (Arnberger *et al*., 2017). A high distance to green space reduces adaptive capacity and has a higher score. | 1 |

# Appendix 2. Task 1 Additional Results – UoM Heat Vulnerability Index

*This appendix provides additional results for UoM's HVI as part of Task 1. Details are provided for the individual indicator results for each domain.*

### Indoor sensitivity: individual indicator results (excluding over-occupancy and NDVI)

#### Higer glazing

Higher glazed areas suggest more window coverage, and potentially the presence of conservatories, or ceiling to floor windows. These can impact on a home's likelihood to overheat. For this indicator, no borough has a significantly higher, or lower median ranking compared to others. Oldham, Trafford, and Wigan had the highest percentage of LSOAs that fall within the worst 10% for this metric, however there are no clear patterns. It is likely that high glazed areas are associated with both flats (which are more common in urban areas), and semi-detached or detached housing with gardens, where patio doors or conservatories can be built (this type is more common in suburban areas), therefore data trends will be less obvious. Additionally, the glazed area data is also based on EPC data, which only considers 70% of the homes in Greater Manchester; newer homes are more likely to have EPCs, so this may reflect modern homes with higher glazed areas.

#### Types of home

The types of home most likely to overheat according to previous studies are flats and terraces (Beizaee *et al.*, 2013; Gupta and Gregg, 2012). Therefore, the percentage of both types per LSOA was used as a metric for these two indicators, the higher percentage of these home was seen as having a higher sensitivity to heat.

Oldham, Rochdale, Bolton, and Tameside, have higher percentages of terraced housing, whilst Manchester, Salford and Trafford have higher percentages of flats. The LSOAs with the highest percentage of flats or terraced houses are in Manchester (99.8%) and Trafford (87%), respectively. The LSOA with the highest combined percentage is in Manchester (100%). The LSOA with lowest combined percentage of flats and terraces is in Wigan (0.2%). Manchester therefore has the highest average of both flats and terraces, followed by Salford, then Oldham. Wigan and Stockport have the lowest average, and therefore have more types of home that are less sensitive to overheating.

#### Age of homes

The age of homes is inherently related to their airtightness, ventilation, and energy efficiency which can impact overheating. Homes pre-1900 and post-2007 homes are classed as sensitive to overheating. Oldham, Bury, Rochdale, Tameside and Bolton have LSOAs with the highest median percentage of pre-

1900s homes, Salford, Manchester, and Wigan have LSOAs with the highest median percentage of post 2007 homes.

### Roof energy efficiency

Bury and Oldham have the poorest median roof EPC values; both these boroughs have more terraced houses than flats, with Oldham having the highest median ranking of terraced houses, as well as highest median ranking of homes built pre-1900. Rochdale and Tameside also have some of the highest median rankings for terraced houses, however, they do not have noticeably low roof energy efficiency, suggesting that there are more factors that affect this indicator than just age and type of home. For example, some homes may be retrofitted by owners to improve energy efficiency. EPC coverage may also impact the results. Only 70% of the homes across Greater Manchester have an EPC; older homes that are more likely to have poor roof efficiency but that do not have EPCs may not be represented in this data.

## Indoor sensitivity: individual indicator results (over-occupancy and NDV)

### Over-occupancy

Over-occupancy is included as an indicator as more occupants in a space that is not a suitable size can increase internal heat gains and contribute to hotter indoor temperatures. Here, over-occupancy rate is used as the metric. The average over-occupancy rate for England is 4.4% which is lower than the median rate for Bolton (6%), Manchester (8.0%), Oldham (7.9%), Rochdale (5.9%), and Salford (4.6%), illustrating over-occupancy to be an issue and contributor to heat vulnerability in these boroughs. On the other hand, Bury (3.7%), Stockport (2.5%), Trafford (2.9%), and Wigan (2.3%) are the only local authorities where the median over-occupancy rate is lower than the average across England. When looking at the number of LSOAs per borough that fall in the worst 10% for this metric a similar pattern is seen, with Oldham and Manchester having the highest percentage of worst performing LSOAs. Furthermore, taking Greater Manchester as a whole, 645 out of 1702 LSOAs (38%) have an over-occupancy rate that is higher than the England average, and 209 of these (12%) have an over-occupancy of over 10%. Over-occupancy is on average, highest in Manchester and is likely to be linked to higher population densities, smaller properties (i.e. flats) and more deprivation. According to ONS, terraced houses and flats are more likely to be over occupied than detached or semi-detached homes; this is supported by box and whisker chart for housing type, where the pattern across local authorities follows the same trend as for the chart for over-occupancy. The sensitivity of flats and terraces to overheating is therefore increased; whilst they are also physically more prone to overheating, they are also more likely to be over-occupied by their tenants or owners.

### Average NDVI surrounding homes

Greenspace immediately surrounding a property can cool the very local environment and therefore adjust the microclimate that a property is exposed too. Cooler microclimates surrounding a home can lead to less overheating within the home (Zuurbier *et al.,* 2021). Therefore, properties with gardens, or in greener areas have better cooling potential than ones in denser, urban areas. Average NDVI within 20m radius of a home was used as the metric for greenspace immediately around the home. Manchester had the highest percentage of LSOAs within the worst 10% across Greater Manchester according to surrounding NDVI score. This is significantly higher than other boroughs and is likely tied to the higher concentration of flats and higher population density. Trafford, Bury and Stockport had the least number of LSOAs in the worst 10% for this metric.

## Outdoor sensitivity: individual indicator results

Landcover is an important determinant of local temperature and plays a key role in the development of the UHI effect. Areas with more human-made surfaces and less green or blue space are generally warmer. Overall, all indices related to land cover (NDVI, woodland, vegetation, and water coverage) follow similar trends when looking at the median values for the LSOA ranks across the boroughs. An exception is Trafford which has a disproportionally lower median rank for the indicator of woodland cover, compared to its NDVI, other vegetation, and water coverage median values. Manchester and Salford, being the most urbanised, have consistently the highest proportion of LSOAs which fall into GM's worst 10% for all of the greenspace indicators. The water data is highly skewed as many LSOAs across Greater Manchester have no blue space.

Building heights and urban geometry in general have been linked to the UHI effect. Manchester has by far the highest scores for both median rank and number of LSOAs within the worst 10%. This would be expected with Manchester's city centre and the high-rise homes. Low elevation is also related to higher temperatures, areas within Greater Manchester with low elevation have a higher outdoor sensitivity – these are Trafford, Salford.

## Occupant sensitivity: individual indicator results

### Age of individuals

Both older and younger individuals have been identified in previous work as more vulnerable to heat (McGeehin and Mirabelli, 2001; Kovats *et al*., 2004; Xu *et al*., 2017; Malmquist *et al.,* 2021). For this work, the percentage of the population aged 0-5 and 65 years and over were used as metrics for the age indicators. Concerning age of occupants, there are no boroughs with significantly higher or lower populations between the ages of 0 and 5, the median rank for their LOSA's was found to be consistent. However, for the older individual's indicator, Manchester LSOAs have noticeably lower percentage of the population than all other local authorities; this is likely to be because urban areas tend to have younger populations. Salford's LSOAs also have a lower median percentage of the population aged 65+, whilst Stockport and Wigan LSOAs have slightly higher medians. Manchester had only two LSOAs which fell within Greater Manchester's highest ranked 10% for this indicator, in contrast to Stockport with 37 (19%).

### Disability and health

For both disability and health, no borough has a noticeably high or low median LSOA ranking; this may be as disability and poor health can affect the whole population, regardless of age or location. Bury, Stockport, and Trafford LSOAs have the lowest median rankings for three out of four disability and health indices, whilst Manchester and Tameside and Wigan LSOAs have the highest median indices. Similarly, the worst 10% of LSOAs across Greater Manchester was spread relatively evenly across the 10 boroughs.

There are more decisive patterns for the IMD health and disability rankings; Manchester has higher rankings, whilst Trafford has the lowest. 26% of Manchester's LSOAs also fell within the worst 10% across GM. The differences between boroughs are more pronounced for this dataset, this is as the IMD domain uses a different method for quantifying health and disability than just the data provided by the Census, which considers years of potential life lost, comparative illness and disability ratio based on age and sex, acute morbidity, and mood and anxiety disorders (Ministry of Housing, 2019).

## Restricted adaptive capacity: individual indicator results

Income is a key determinant of an individual's ability to adapt. Income is needed to travel to cool spaces such as air-conditioned locations, buy and run temporary measures such as fans, and be able to add more permanent measures such as shutters to homes. Income is represented here by the IMD income sub domain. In terms of median LSOA rank, Manchester is the highest for income deprivation. Manchester also has the highest number of LSOAs within the worst 10% across GM for this indicator. Trafford has both the lowest median LSOA rank and is one of three LSOAs with only 4% of their total LSOAs falling in the worst 10% across GM, the other LAs are Tameside, Trafford, and Wigan.

Whether an individual owns or rents a home can be a limiting factor in their ability to adapt. Renters are generally unable or not allowed to add permanent physical measures to their rented homes, for example measures such as shutters or shading that may help reduce heat gains. Therefore, Tenure is also included as an indicator. In terms of both median LSOA rank and the percentage of LSOAs in the worst 10%, Manchester and Salford score the highest for this indicator. Stockport has both the lowest median LSOA rank, with Rochdale and Oldham having only 2% of their LSOAs fall within the worst 10% for this indicator.

Four indicators act as proxies to represent individuals' likelihood to open windows are night. Opening windows is a key mechanism for cooling a home, and some characteristics of the local environment can act as a deterrent for opening windows. This includes $PM_{2.5}$ and $NO_x$ emissions (poor air quality), the risk of crime, and noise. All of which are represented within the index.

### Air pollution ($PM_{2.5}$ and $NO_x$)

Air pollution is represented by $NO_x$ and $PM_{2.5}$, Manchester again has the highest median LSOA PM2.5 concentration, while Salford has the highest median LSOA NOx concentration. Wigan and Tameside's both also have high median LSOA $PM_{2.5}$ concentrations. Notably, 32% of Salford's LSOAs fall within GM's worst

10% for $NO_x$. Trafford has the median $PM_{2.5}$ concentration. Whereas Wigan has by far the lowest median $NO_x$ concentration.

### Crime

Crime was represented using the LSOAs rank from the IMD's crime sub-domain. When considering the median LSOA rank for this indicator Manchester was highest, followed by Rochdale, and Oldham. Manchester also had the highest percentage of LSOAs falling into GM's worst 10% (24%). Trafford had the lowest median LSOA ranking for crime and no LSOAs falling into GM' worst 10%.

### Noise

Noise is calculated via a scale of the average decibels, with a threshold being assigned to indicate if on average the homes in the LSOA would be disturbed by noise and so be deterred from opening windows or not. Salford has the highest percentage of disturbed LSOAs at 98 %. However, all boroughs do have a significant proportion of their LSOAs that are classed as disturbed in this analysis, ranging from 75 to 98%.

### Green space

Greenspace within a city often acts a cool area, grass heats up at a lower rate than concrete and asphalt, and parks with trees provide shade on sunny days. They therefore provide a "cool space" for local residents during the day and can offer some relief from extreme temperatures. Going to a green area due to its cooling properties is a form of adaption. However, access to greenspace varies significantly. This was represented by calculating the average distance to greenspace. Bury had the highest number of LSOAs that are more than 300m on average from greenspace (14%) whilst Rochdale has the lowest (8%). Oldham has the highest number of LSOAs with an average distance of homes to greenspace of less than 9m (18%), whilst Trafford has the lowest (4%).

# Appendix 3. Task 2 Detailed Methodologies

*This appendix presents the detailed methodologies for each component of Task 2.*

The deep dive analysis consisted of a mix-method approach including modelling of adaptation actions, a cost-benefit assessment, and stakeholder engagement and analysis to understand socio-technical barriers. The detailed methodologies are as follows:

## Modelling

Different types of homes and adaptation actions were modelled using EnergyPlus, a widely tested and validated building thermal and energy performance simulation software (US DoE, 2024). Past work on the CS-N0W project carried out UK-wide modelling using a limited number of weather files. The Manchester housing stock, in particular, was modelled using London climate files as Manchester data were not available at the time. For the purposes of the present study, a new generation of future climate files[15] were used, which were developed for building performance simulation specifically for Greater Manchester. These files were created using the latest UK Climate Projections, UKCP18 (Met Office Hadley Centre, 2018) (Eames, et al., 2023) by employing a morphing method in line with the climate scenarios (Representative Concentration Pathways – RCPs), which project future greenhouse gas concentrations and radiative forcing proposed by the Intergovernmental Panel on Climate Change (IPCC). Simulations were performed using Design Summer Year (DSY) weather files for four time points: 2030 RCP 2.6, 2050 RCP 2.6, 2030 RCP 8.5 and 2050 RCP 8.5. The 50$^{th}$ percentile of the UKCP18 probability distribution was used for all tested climate scenarios. It is worth noting that the use of central projections only, may not capture the potential effects of more extreme scenarios (90$^{th}$ percentile). However, this modelling work focuses on the assessment of the relative effectiveness of different overheating reduction actions to inform public health guidance rather than the quantification of overheating levels under the full range of UKCP18 scenarios. Outdoor air temperature of the four selected climate scenarios during the hottest week of the year (27 July – 2 August) is shown in Figure A-1. It should be pointed out that the Urban Heat Island effect is not factored in in these projections. The outdoor temperature difference between the years 2030 and 2050 for the two climate scenarios during the same week is shown in Figure A-2.

[15] Design Summer Year (DSY) weather files (specifically designed for overheating assessment): https://www.cibse.org/weatherdata

Figure A-1: External air temperature during the hottest week of the year (27 July 27 - 2 August) under the four different climate change scenarios selected for Greater Manchester (Design Summer Year, RCP 2.6 2030, RCP 2.6 2050, RCP 8.5 2030, RCP 8.5 2050, 50th percentile)

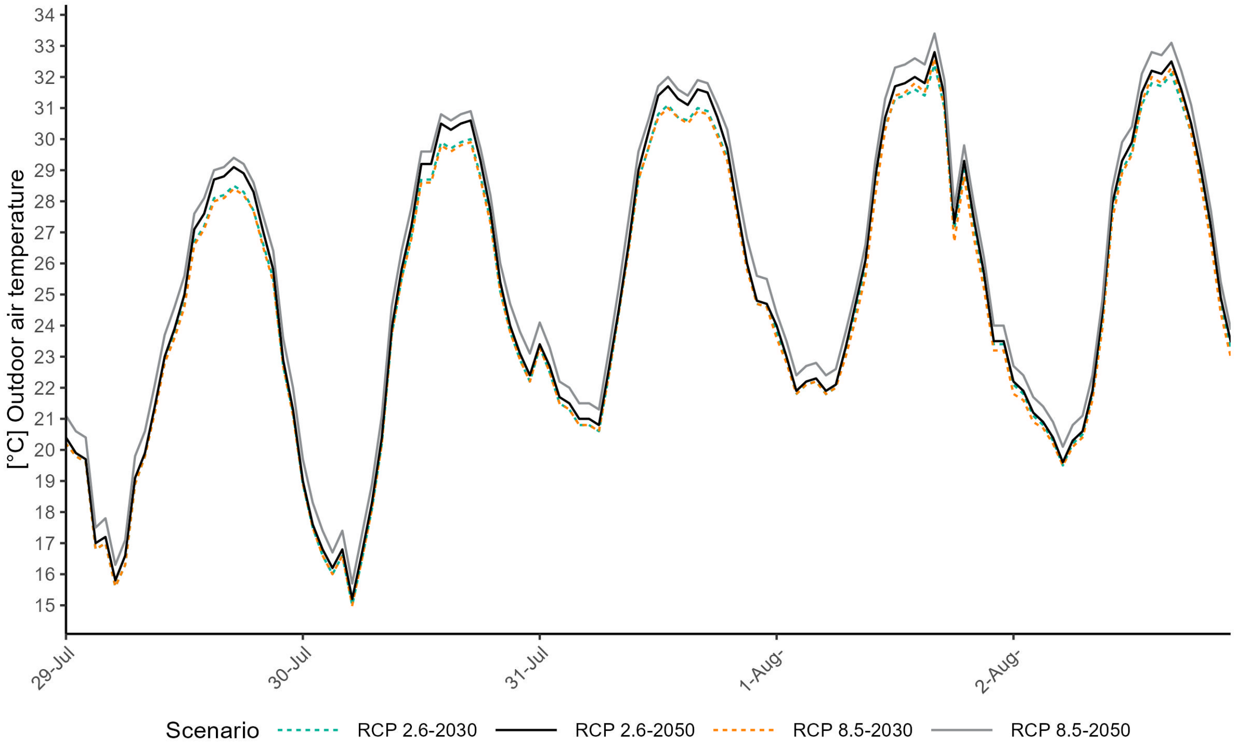
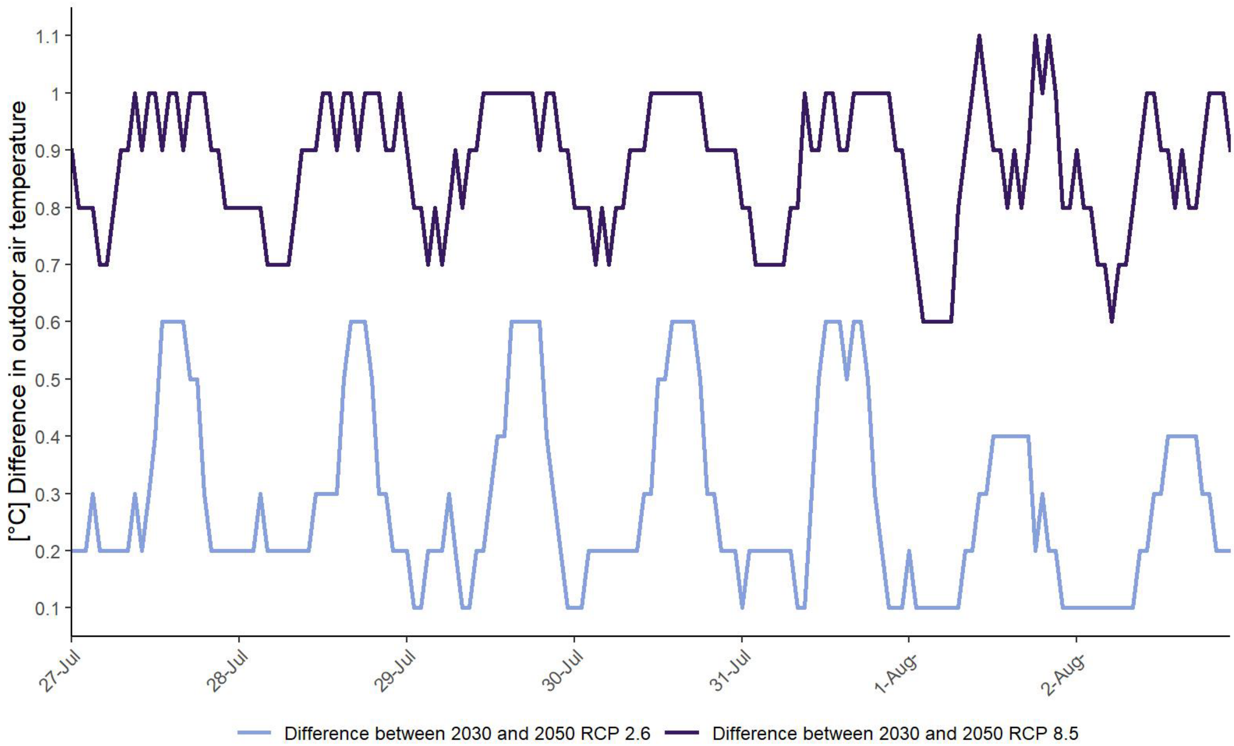


Figure A-2: Temperature difference between the Design Summer Years 2030 and 2050 (RCP 2.6 and RCP 8.5, 50th percentile) for the hottest week of the year (27 July - 2 August) for the selected climate change scenarios

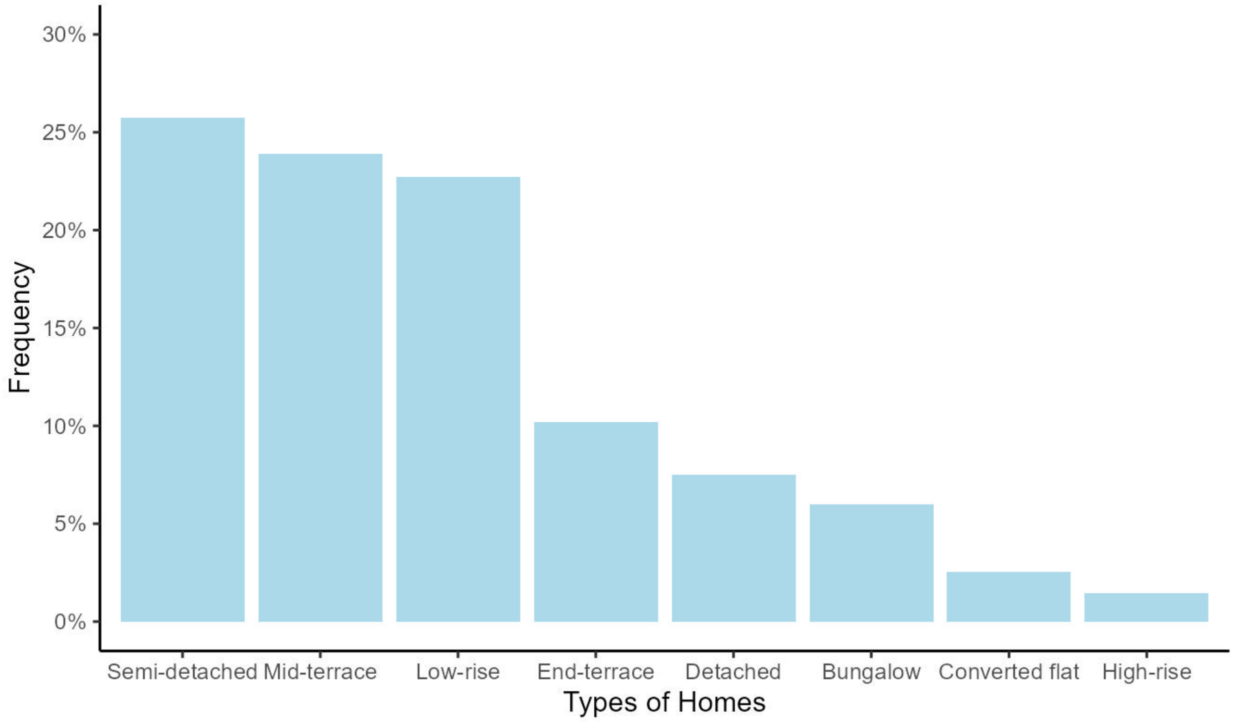



The types of homes in Greater Manchester that are most sensitive to overheating were identified using data generated in the context of a previous CS-N0W study, led by UCL (Ferguson, et al., 2023)2023). This earlier study produced estimates of indoor overheating, and heating and cooling energy demand, individually for each home address listed in the Energy Performance Certificate (EPC) database for the UK, using a metamodel of EnergyPlus. Based on the analysis of this existing dataset for Greater Manchester, five types of home were selected for more detailed analysis of their sensitivity to overheating:

1) Three types of flats: a) high-rise post-2010s flats, representative of newbuilds and to be built high-rise flats; b) high-rise pre-2010s flats, representative of the majority of existing high-rise flats; and c) low-rise flats, representative of the existing stock.
2) Two types of houses: mid-terrace and semi-detached houses, representative of the existing stock.

High-rise and low-rise flats, and mid-terrace and semi-detached houses, in total, represent over 73% of the Greater Manchester housing stock (1.5%, 22.7%, 23.9% and 25.7%, respectively). Findings on semi-detached houses will apply to some degree to end-terrace houses, given the potential similarities in their building geometry. Despite high-rise flats representing a small proportion of the stock, special emphasis was given to them in the present study due to their high sensitivity to overheating, especially top-floor flats, according to previous empirical studies (Salagnac, 2011). They are also common in new construction developments in the Greater Manchester Area. The frequency of occurrence of different types of homes across the Greater Manchester housing stock is shown in Figure A-3.

Figure A-3: Frequency of occurrence of types of home in the Greater Manchester Area according to the EPC database




The physical dimensions and architectural configurations of the homes were developed following prior analysis of the entire UK housing stock database using EPC data (Ferguson, et al., 2023). The models (Figure A-4) were divided into thermal zones, distinguishing between zones primarily occupied in the daytime and nighttime. Table A-3 presents the physical characteristics of the modelled homes.

Figure A-4: 3D Visualizations corresponding to five simulated models

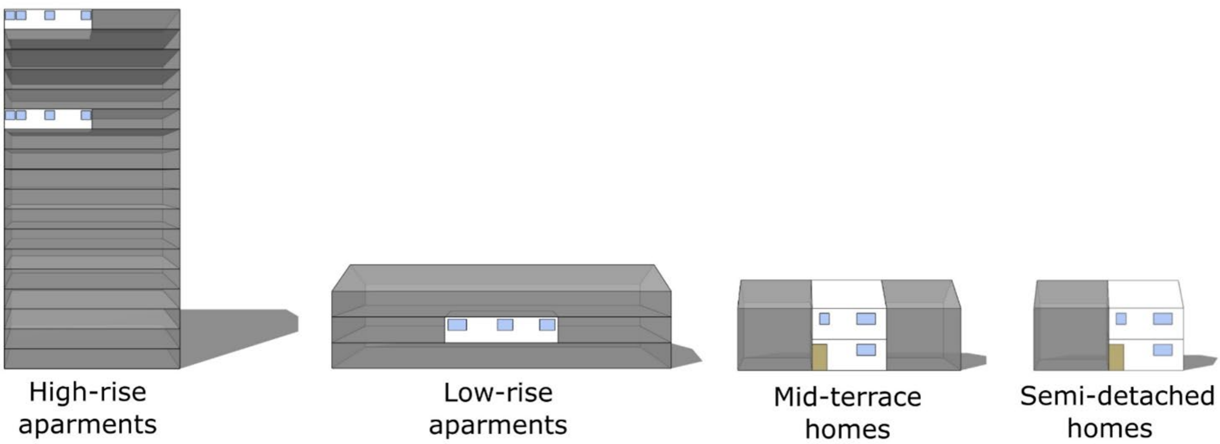


Table A-3: Physical characteristics of homes

| | High-rise post-2010s flat | High-rise pre-2010s flat | Low-rise flat | Mid-terrace house | Semi-detached house |
|---|---|---|---|---|---|
| Total area (m²) | 75 | 75 | 65 | 120 | 120 |
| Daytime area (m²) | 45 | 45 | 41 | 60 | 60 |
| Nighttime area (m²) | 30 | 30 | 24 | 60 | 60 |
| Internal height (m) | 2.8 | 2.8 | 2.7 | 2.7 | 2.7 |
| Total window area (m²) | 10.0 | 10 | 11.8 | 19.2 | 19.2 |

The **high-rise flat** was simulated with one externally exposed façade, allowing only single-side ventilation, while the other five sides were assumed to be adiabatic (i.e., not losing or gaining heat from the adjoining property).

The **low-rise flat** was simulated with externally exposed front and back façades, allowing cross-ventilation, with the remaining sides configured as adiabatic.

The **mid-terrace house** was simulated with externally exposed front and back façades, roof, and floor, and with two adiabatic side walls.

The **semi-detached house** was simulated similarly to the mid-terrace house but with three externally exposed façades, roof and floor, and only one adiabatic side wall.

All external walls featured window sizes typical for each type of home. Building construction thermal properties were assigned to each type of home following the method developed by Mavrogianni et al. (2012). This method uses the approximate construction age of the building to assign construction materials and building energy efficiency levels for different architectural eras based on the Reduced data Standard Assessment Procedure (RdSAP) (BRE, 2024) and other relevant sources. The assumed thermal transmittance values (U-values) of walls, roofs, floors and windows for the base case scenario of each type of home are shown in Table A-4.

Table A-42: Thermal transmittance of modelled construction elements (base case)

| | High-rise post-2010s flat | High-rise pre-2010s flat | Low-rise flat | Mid-terrace house | Semi-detached house |
|---|---|---|---|---|---|
| | U-values (W/m²K) | | | | |
| Exterior wall | 0.15 | 1.60 | 2.10 | 2.10 | 2.10 |
| Exterior roof | 0.10 | 0.40 | 2.30 | 2.30 | 2.30 |
| Ground floor | 0.15 | 1.20 | 1.20 | 1.20 | 1.20 |
| Interior wall | 2.10 | 2.10 | 3.20 | 3.20 | 3.20 |
| Interior floor/ceiling | 0.69 | 0.69 | 1.30 | 1.30 | 1.30 |
| Windows | 0.57 | 3.10 | 4.80 | 4.80 | 4.80 |

An algorithm for windows was configured and integrated into the model according to CIBSE (2017). Windows in each thermal zone were controlled independently and programmed to open when the indoor temperature exceeded 22°C and the room was occupied. Additionally, windows were closed whenever the outdoor temperature rose above 33°C and the indoor temperature fell below that outdoors. Internal conditions were modelled according to CIBSE's TM59 design methodology for assessing overheating risk in homes (CIBSE, 2017).

Thermal comfort was assessed from May to September following CIBSE TM59 (CIBSE, 2017). Criterion 1 for living rooms, kitchens and bedrooms was chosen as the primary criterion to assess the sensitivity of buildings to overheating. According to this criterion, to maintain thermal comfort during the summer period, the number of hours during which ΔT (defined as the difference between the actual operative temperature in the room at any time and the limiting maximum acceptable temperature, which is a function of the running mean of the outdoor temperature) is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3% of occupied hours (CIBSE TM52 Criterion 1: Hours of exceedance).

The individual and cumulative effects of adaptive and passive actions aiming to reduce overheating were quantified.

**Adaptive, behavioural, non-structural actions** can increase occupant adaptive capacity. These actions can possibly empower occupants by creating a sense of control over their environment, allowing them to adjust their surroundings to suit their personal preferences.

**Passive, structural cooling actions** are low/medium-cost, low-carbon actions that rely on natural processes, such as natural ventilation and shading, rather than mechanical means, to achieve thermal comfort indoors. They may potentially also reduce operational carbon emissions and costs.

A total of eight passive and adaptive actions were tested earlier in Table 5-1 including the assumptions used in the base case, the variables tested for each strategy, and the total number of iterations obtained for each set of results.

## Cost-benefit analysis

A cost-benefit analysis was undertaken and considered:

- The capital costs of structural adaptations and retrofitting associated with each of the actions and combined actions modelled.
- The benefits of those actions obtained from the modelling results.

It was assumed that home occupiers would understand and apply the structural adaptations and retrofitting actions according to the times and thresholds identified in the modelling. The following methodology was applied:

1. The actions were identified that would have capital costs: applying internal window shading with white curtains (Action 2); applying internal window shading with blackout curtains (Action 3); increasing the extent which windows could be opened through repairs, such as restriction removal (Action 5); replacing faulty windows to increase the extent to which windows could be opened to 80% (Action 5); applying external window shutters (Action 6); and increasing the reflectivity of external walls by painting them a light colour (Action 8). How each of these actions could be achieved was also considered. For example, Action 5 window repair and replacement can be achieved utilising different materials, such as wood, aluminium, or uPVC.
2. Data on capital costs were gathered for each action from five suppliers and a minimum of three installers with a priority for suppliers in the Greater Manchester area where this was possible. All total capital costs included materials, installation, and labour. The costs were converted to unit costs in £/$m^2$. The total capital cost per type of home was estimated by multiplying this cost by the area of windows and walls for each type of home where the actions would be applied. Area details are provided in Table A-5 and match those used in the modelling (Table A-3).
3. The benefits of each individual action and the combined strategies were obtained from the results of the modelling. The metric used to assess the benefits from each of the adaptation actions was the hours of thermal comfort compared to the base case (where no adaptation actions were applied).
4. The cost-benefit analysis calculated the cost per additional hour in thermal comfort resulting from each individual action and combination of actions for the first year and for the first five years.
5. Associated assumptions are listed in Table A-6 and Appendix 5 shows the sources of costs for each action.

Table A-53: Total area of windows, walls and roofs for each type of home

| Type of home | Windows $m^2$ | Walls and roofs $m^2$ |
|---|---|---|
| High-rise (pre-2010s) flats | 10 | 23 |
| High-rise (post-2010s) flat | 10 | 98 |
| Low-rise flat | 12 | 34 |
| Mid-terrace house | 24 | 159 |
| Semi-detached house | 24 | 199 |

*Numbers are rounded to the nearest whole number

Table A-64: Assumptions made during the researching of costs

| Action | Assumption |
|---|---|
| All actions | • People have full understanding of how to implement and/or use the structural adaptations and retrofitting associated with each of the actions.<br>• The measures are installed by professionals<br>• All capital costs are incurred in year 1 |
| Internal shading and external shutters | • The windows are standard and easy to access<br>• There are no operational costs (such as cleaning) |
| Window repair – restriction removal and window replacement | • The windows are standard and easy to access<br>• The windows require basic preparation<br>• There are no operational costs (such as cleaning) |
| Modifying reflectivity | • The walls are easy to access and require basic preparation and standard scaffolding.<br>• The cost includes paint, scaffolding (assembly, dismantling, rental fee) and labour (painting and preliminary work, such as cleaning, plastering, masking)<br>• The cost of paint is not dependent on the selected colour<br>• There are no operational costs (such as cleaning) |
| Electricity for heating and cooling | • Electricity unit and standing rates are Ofgem's January-March 2025 rates |

## Socio-technical analysis and stakeholder engagement

A combination of methods were used to determine whether occupants of homes have socio-technical barriers that affect their ability to implement the adaptation actions intended to reduce overheating. A literature review was conducted to understand what barriers associated with the use of the adaptation actions had already been identified. An online survey and in-person semi-structured interviews with passers-by were carried out with individuals living in Greater Manchester to understand any context specific barriers based on the individual's existing perceptions of the adaptation actions.

### Literature review

Desk-based research was conducted of socio-technical barriers to the proposed adaptation actions being modelled. The findings of the review helped identify trends in the research as well as existing knowledge gaps, both of which were used to inform the survey and interview design.

The literature review covered what adaptation actions for overheating were already studied (e.g., window opening, internal/external shadings, green cover etc.), how effective these adaptation actions were found to be, and what evidence, if any, was found to explain barriers to adaptation. Categorisations were used to classify the barriers: financial, public perception/knowledge, regulatory/policy barriers, physical constraints, and others. In total, the literature review consulted 21 academic papers, four grey literature documents, seven institutional documents, and two project-outcome papers (total 34 sources).

### Stakeholder engagement: surveys and semi-structured interviews

The stakeholder engagement aimed to gather a contextual understanding of barriers perceived by the occupants of homes in Greater Manchester to adoption of the adaptation actions proposed in this study.

To ensure that the survey and interviews were unbiased, open-ended, and allowed for maximum engagement in a short period of time:

- A survey and interview guide were developed. Its purpose was to ensure that a diverse and large sample of respondents was reached. Questions were designed in such a way that they could be answered online or in-person.
- The survey and interview materials were designed to prevent response bias by ensuring questions were open-ended and allowed for varied responses. Likert scales were used to establish a basis for comparison between questions.
- Internal testing was applied to the survey and interview guide to check coherence.

### Survey and interview delivery

The project was supported by GMCA's Local Energy Advice Demonstrator project (LEAD) to enable in-person delivery. LEAD consists of 10 delivery partners providing energy advice to local communities across Greater Manchester through community events. The CS-N0W project team attended six events in collaboration with the LEAD partners, which enabled in-person interviews.

### Survey and semi-structured interview analysis

The interview and survey outputs were analysed, using thematic qualitative analysis, to identify recurring patterns in the data. Responses were tagged with short phrase 'codes', which represented different themes, such as a barrier to adaptation. The 'codes' were then counted and summed to show the regularity of each occurring in the data set, exposing the commonest responses. Quantitative data analysis was used where numerical responses were recorded, (e.g., for effectiveness scores of different adaptation actions). Weighted averages were applied to prevent the data from being skewed by data outliers.

# Appendix 4. Task 2 Additional Results – UCL EUI Calculations for Heating and Cooling

*This appendix provides additional modelling results as part of Task 2.*

As part of the modelling element of Task 2, the Energy Use Intensity (EUI) in kWh/m² per year for heating and cooling was calculated for each type of home, adaptation action, and climate scenario. The EUI for heating was calculated to identify potential impacts of the overheating reduction strategies during winter and the EUI for cooling was calculated to identify potential impacts on space cooling during summer for homes with air-conditioning.

The assumptions were:

- The season from October to April was considered for heating using an electric heater sized for each room
- The season from May to September was considered for cooling, using an electric cooler sized for each room
- Cooling was operated during the daytime when the indoor temperature exceeded 26°C in homes that adopted air conditioning
- Heating was operated at 20.4°C during occupancy hours

Windows were assumed to remain closed when a cooling system was switched on, therefore the adaptive actions related to window opening are not included in the subsequent analysis.

It was found that two overheating reduction actions may increase space heating energy consumption during winter: reducing internal heat gains and increasing the reflectivity of external walls (Figure A-5). For space cooling, it was found that across all types of home, external wall shading contributed to the most significant reduction in space cooling demand (Figure A-6 to Figure A-10). For high-rise pre-2010 and post-2010 and low-rise flats, external window shading also resulted in substantial reductions.

Figure A-1: Heating EUI in the mid-terrace (top) and semi-detached (bottom) houses under the 2050 RCP 8.5 scenario

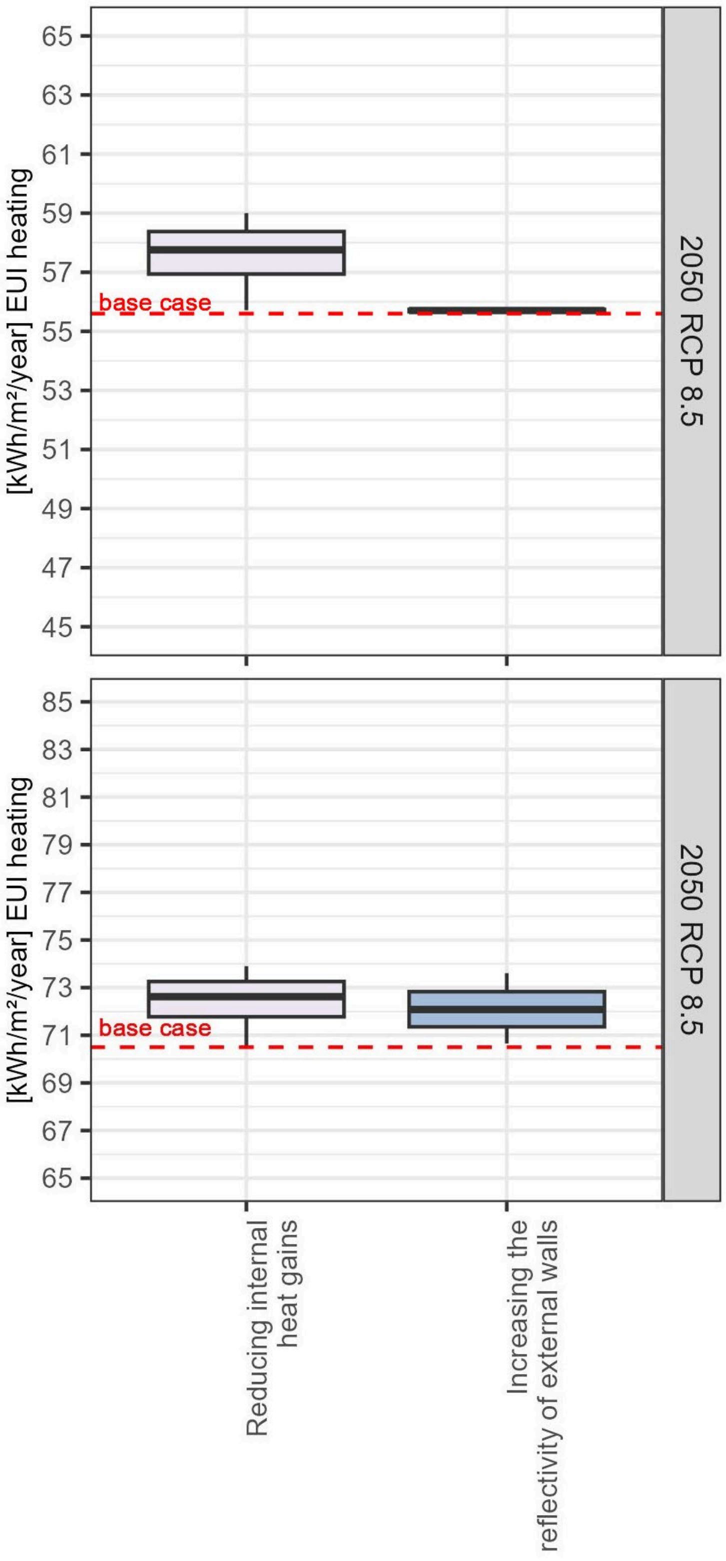


Figure A-2: Cooling EUI following the application of individual actions to the high-rise post-2010s flat under the 2050 RCP 8.5 scenario

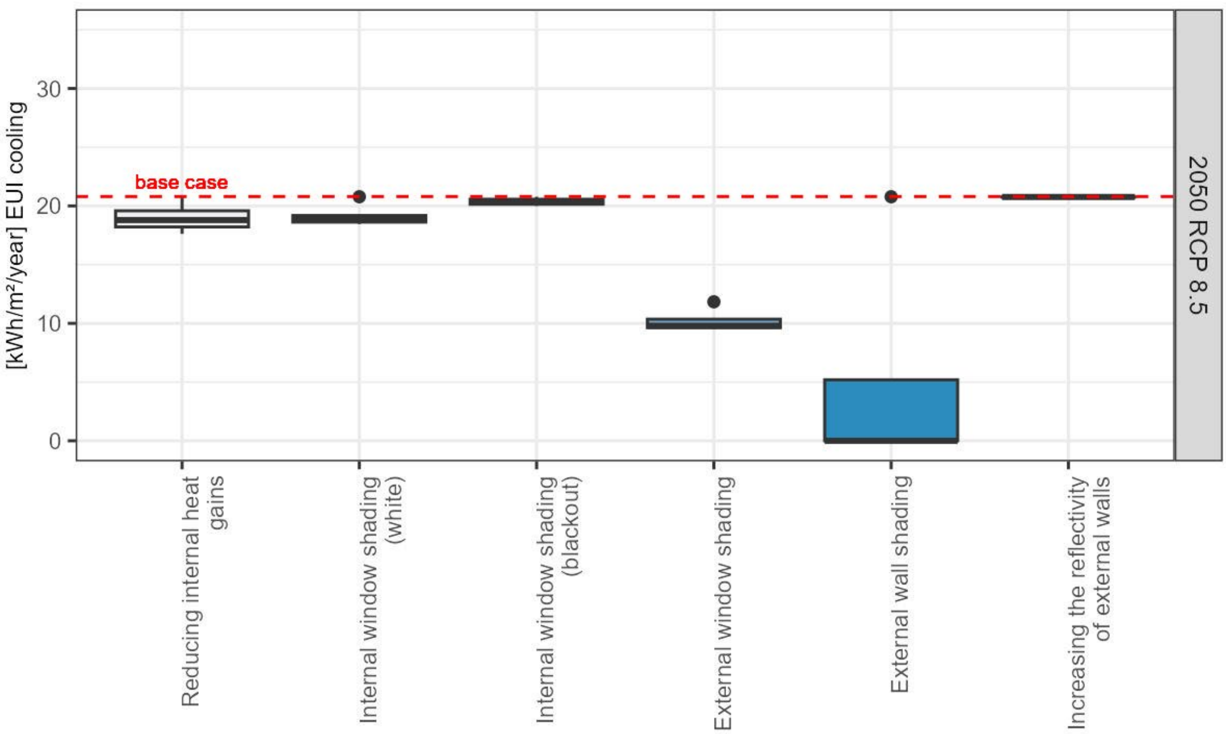


Figure A-3: Cooling EUI following the application of individual actions to the high-rise pre-2010s flat under the 2050 RCP 8.5 scenario

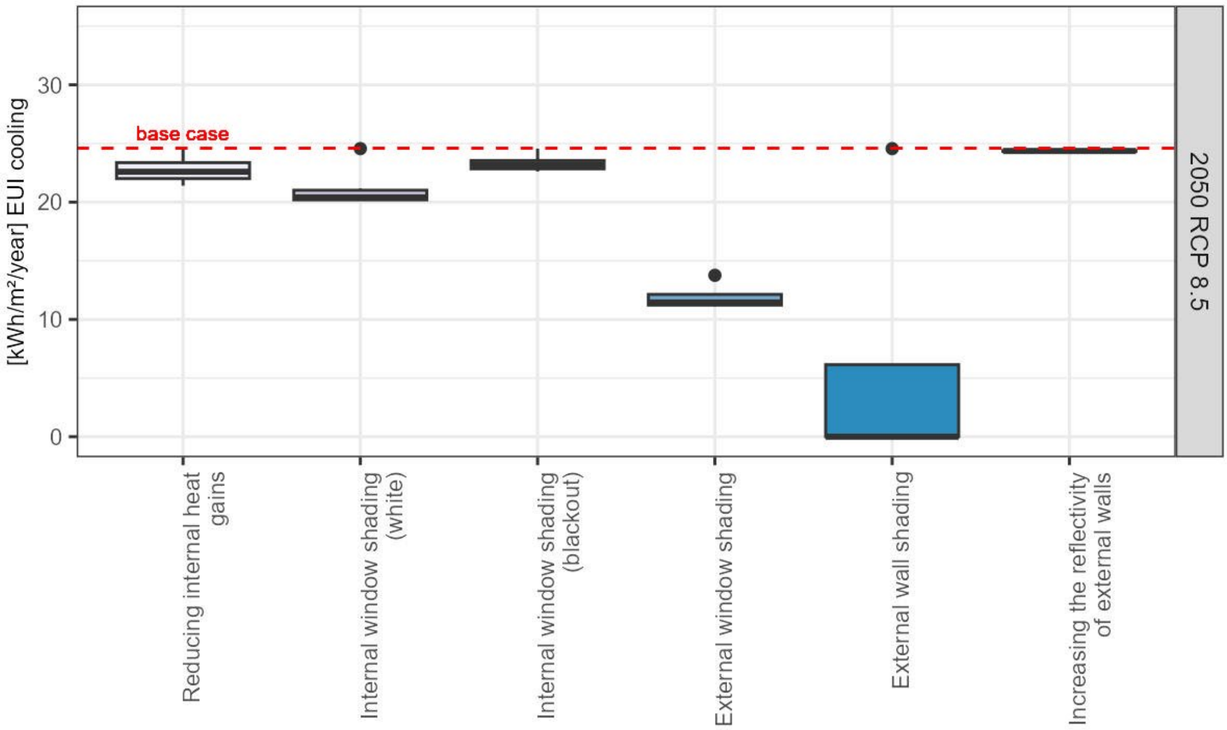


Figure A-4: Cooling EUI following the application of individual actions to the low-rise flat under the 2050 RCP 8.5 scenario

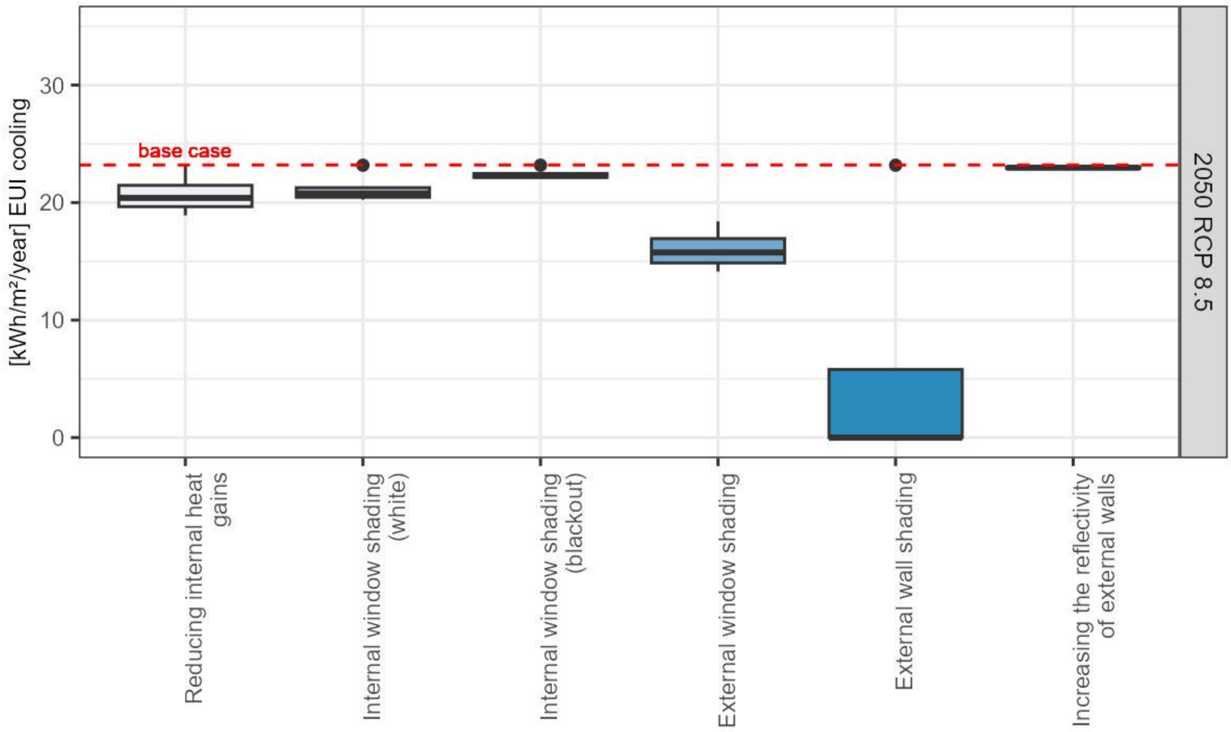


Figure A-9: Cooling EUI following the application of individual actions to the mid-terraced house under the 2050 RCP 8.5 scenario

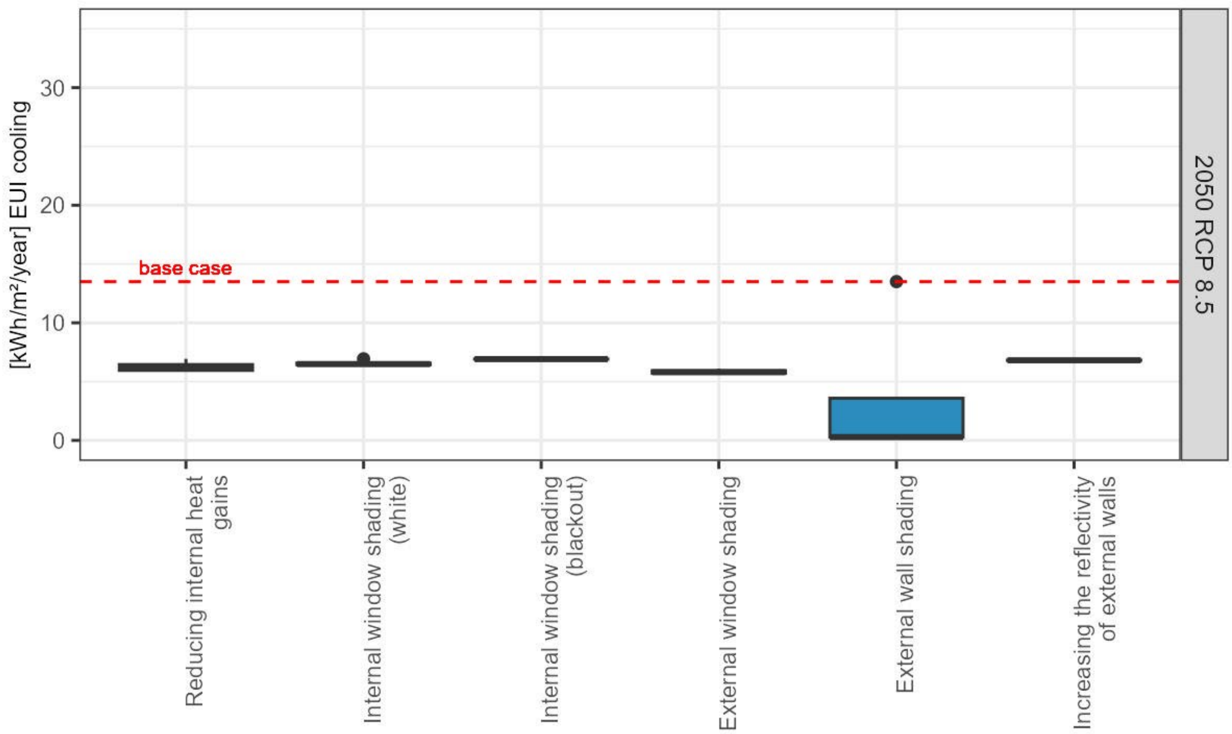
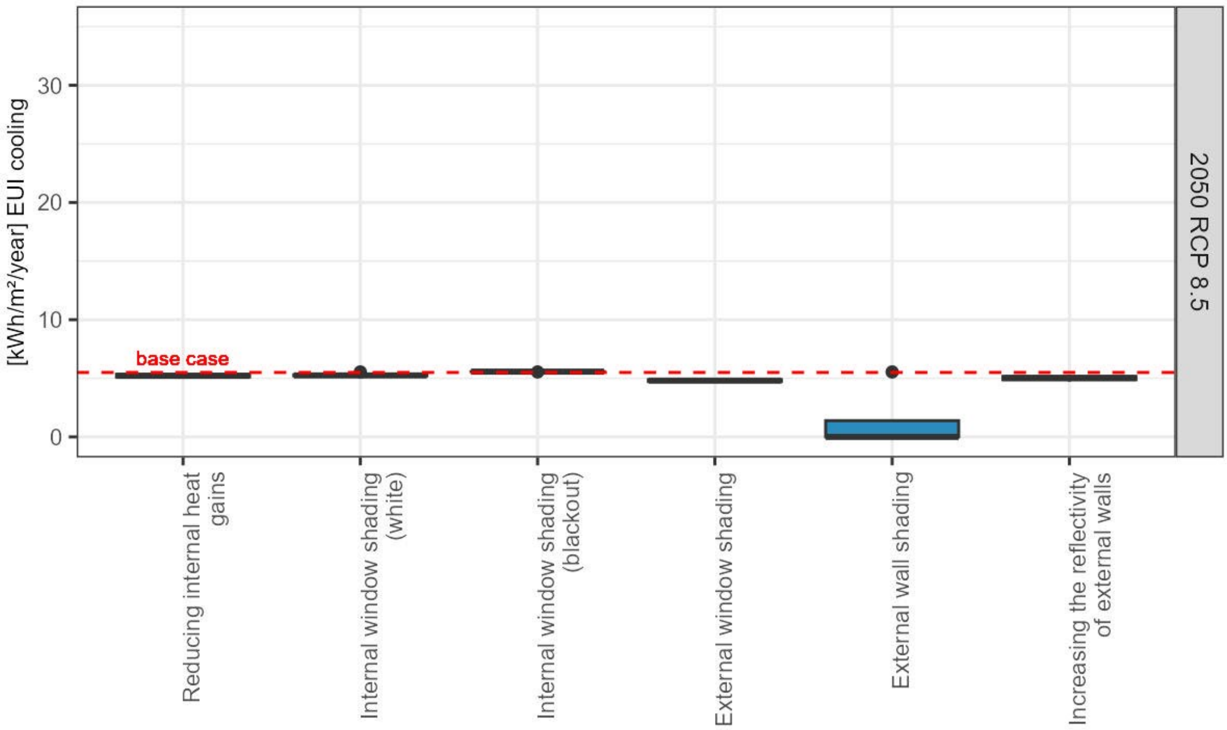


Figure A-10: Cooling EUI following the application of individual actions to the semi-detached house under the 2050 RCP 8.5 scenario



# Appendix 5. Task 2 – Cost-benefit Analysis – Capital Cost Sources

*This appendix shows the sources used for the CBA to calculate the final capital costs for each adaptation action per housing type.*

Table A-7 presents the range of sources and costs gathered for each adaptation action and the steps taken to convert these to an average (or minimum/maximum) £/m2 cost for the CBA.

Table A-8 presents the final costs (£/m2) used for the CBA for each action (also visible in the final column of Table A-7).

Table A-9 presents the total costs used for each adaptation action per housing type, whereby the final cost (£/m2) was multiplied by the total area (m2) of the windows/walls (as relevant for the adaptation action) per housing type. The area figures were consistent with those used in the modelling (Table A-3).

Table A-75: Source used to calculate the cost (£/m2) for each adaptation options which were used in the CBA

| Adaptation Action | Company | Date accessed | Product name | Price, £ | Width, cm | Height, cm | Quoted Area, cm2 | Cost £/m2 | Average Cost £/m2 | Installation Cost, £/m2 | Final Cost used in CBA, £/m2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Internal Shading - Blackout curtains | Dunelm | Nov-24 | Dunelm - Isla Ultra Blackout Eyelet Curtains | 45 | 117 | 137 | 16029 | 28.07 | 15.49 | 15.63 | **31.12** |
| | | | | 55 | 117 | 182 | 21294 | 25.83 | | | |
| | | | | 75 | 168 | 182 | 30576 | 24.53 | | | |
| | | | | 110 | 228 | 228 | 51984 | 21.16 | | | |
| | Dunelm | Nov-24 | Dunelm - Berlin Blackout Eyelet Curtains | 15 | 117 | 137 | 16029 | 9.36 | | | |
| | | | | 18 | 117 | 182 | 21294 | 8.45 | | | |
| | | | | 30 | 168 | 182 | 30576 | 9.81 | | | |
| | | | | 40 | 228 | 228 | 51984 | 7.69 | | | |
| | | | | 55 | 228 | 274 | 62472 | 8.80 | | | |
| | The Range | Nov-24 | The Range - Heavy Weight Textured Blackout Lined Curtain | 70 | 167 | 182 | 30394 | 23.03 | | | |
| | | | | 80 | 228 | 182 | 41496 | 19.28 | | | |
| | The Range | Nov-24 | The Range - Blackout Eyelet Curtains | 32 | 168 | 137 | 23016 | 13.90 | | | |
| | | | | 37 | 168 | 183 | 30744 | 12.03 | | | |
| | | | | 47 | 168 | 229 | 38472 | 12.22 | | | |
| | | | | 57 | 229 | 229 | 52441 | 10.87 | | | |
| | Wilko | Nov-24 | Velvet Blackout Curtains | 37 | 168 | 137 | 23016 | 16.08 | | | |
| | | | | 64 | 229 | 229 | 52441 | 12.20 | | | |
| | Dunelm | Nov-24 | Dunelm - Unlined Tab Top Curtains | 30 | 117 | 137 | 16029 | 18.72 | 10.75 | 15.63 | **26.38** |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Internal shading - Light coloured curtains | | | | 40 | 117 | 182 | 21294 | 18.78 | | | |
| | | | | 50 | 168 | 182 | 30576 | 16.35 | | | |
| | | | | 70 | 228 | 228 | 51984 | 13.47 | | | |
| | Dunelm | Nov-24 | Dunelm - Single Voile Panel Curtains | 6 | 150 | 122 | 18300 | 3.28 | | | |
| | | | | 8 | 150 | 182 | 27300 | 2.93 | | | |
| | | | | 12 | 300 | 122 | 36600 | 3.28 | | | |
| | | | | 18 | 300 | 228 | 68400 | 2.63 | | | |
| | The Range | Nov-24 | Eyelet Curtain | 16 | 168 | 137 | 23016 | 6.95 | | | |
| | | | | 20 | 168 | 183 | 30744 | 6.51 | | | |
| | | | | 28 | 229 | 229 | 52441 | 5.34 | | | |
| | The Range | Nov-24 | Pencil Pleat Fiji Curtains - light | 25 | 117 | 137 | 16029 | 15.60 | | | |
| | | | | 30 | 117 | 183 | 21411 | 14.01 | | | |
| | | | | 48 | 168 | 229 | 38472 | 12.48 | | | |
| | | | | 80 | 229 | 274 | 62746 | 12.75 | | | |
| | The Range | Nov-24 | Pencil Pleat Taped Top Curtains - Light | 25 | 117 | 137 | 16029 | 15.60 | | | |
| | | | | 30 | 117 | 183 | 21411 | 14.01 | | | |
| External Shading - Shutters | Robert Dyas | Nov-24 | vidaXL Roller Shutter Aluminium 70x100 cm Anthracite \| Robert Dyas | 124 | 70 | 100 | 7000 | 177.14 | 188.98 | 50.00 | **238.98** |
| | Robert Dyas | Nov-24 | vidaXL Roller Shutter Aluminium 100x100 cm Anthracite \| vidaXL.co.uk | 148 | 100 | 100 | 10000 | 148.00 | | | |
| | | | | 348 | 160 | 150 | 24000 | 145.00 | | | |
| | | | | 280 | 110 | 220 | 24200 | 115.70 | | | |
| | Simply Shutters | Nov-24 | The Carbrooke - Open Louvre Pine Decorative Exterior Window Shutters - Simply Shutters | 310 | 100 | 100 | 10000 | 310.00 | | | |
| | Simply Shutters | Nov-24 | The Carbrooke - Open Louvre Faux Wood Decorative Exterior Window Shutters - Simply Shutters | 230 | 100 | 100 | 10000 | 230.00 | | | |
| | The Green Blind | Nov-24 | Outdoor Wooden Roller Blinds – thegreenblind | 475 | 180 | 150 | 27000 | 175.93 | | | |
| | | | | 395 | 120 | 150 | 18000 | 219.44 | | | |
| | | | | 449 | 100 | 250 | 25000 | 179.60 | | | |

Climate services for a net-zero resilient world

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Surface Albedo Modification | Check a Trade | Nov-24 | Cost guides- Painter/Decorator | x | x | x | x | 20.00 | 39.67 | Already included in quote | **39.67** |
| | Smart Spender | Nov-24 | UK \| Exterior House Painting Cost | x | x | x | x | 33.00 | | | |
| | Hamuch | Nov-24 | Trade rates for painter & decorators around Manchester | x | x | x | x | 66.00 | | | |
| Windows Replace - uPVC (low cost) | Check a Trade | Nov-24 | New Windows Cost in 2025 \| Checkatrade | 200 | x | x | 5400 | 370.37 | 328.98 | Already included in quote | **328.98** |
| | | | | 500 | x | x | 10800 | 462.96 | | | |
| | | | | 450 | x | x | 14400 | 312.50 | | | |
| | | | | 230 | x | x | 19600 | 117.35 | | | |
| | | | | 650 | x | x | 19600 | 331.63 | | | |
| | Federation of Master Builders | Nov-24 | How much do new windows cost in the UK? | 160 | x | x | 5400 | 296.30 | | | |
| | | | | 200 | x | x | 10800 | 185.19 | | | |
| | | | | 300 | x | x | 5400 | 555.56 | | | |
| Windows Replace - uPVC (high cost) | Check a Trade | Nov-24 | New Windows Cost in 2025 \| Checkatrade | 400 | x | x | 5400 | 740.74 | 791.28 | Already included in quote | **791.28** |
| | | | | 600 | x | x | 10800 | 555.56 | | | |
| | | | | 400 | x | x | 5400 | 740.74 | | | |
| | | | | 550 | x | x | 14400 | 381.94 | | | |
| | | | | 900 | x | x | 19600 | 459.18 | | | |
| | Federation of Master Builders | Nov-24 | How much do new windows cost in the UK? | 990 | x | x | 5400 | 1833.33 | | | |
| | | | | 1065 | x | x | 10800 | 986.11 | | | |
| | | | | 1240 | x | x | 19600 | 632.65 | | | |
| Windows replace - timber (low cost) | Check a Trade | Nov-24 | New Windows Cost in 2025 \| Checkatrade | 800 | x | x | 5400 | 1481.48 | 952.79 | Already included in quote | **952.79** |
| | | | | 1350 | x | x | 10800 | 1250.00 | | | |
| | | | | 1350 | x | x | 19600 | 688.78 | | | |
| | | | | 550 | x | x | 5400 | 1018.52 | | | |
| | | | | 650 | x | x | 10800 | 601.85 | | | |
| | Federation of Master Builders | Nov-24 | How much do new windows cost in the UK? | 850 | x | x | 5400 | 1574.07 | | | |
| | | | | 750 | x | x | 19600 | 382.65 | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 900 | x | x | 14400 | 625.00 | | | |
| Windows replace - timber (high cost) | Check a Trade | Nov-24 | New Windows Cost in 2025 \| Checkatrade | 1485 | x | x | 5400 | 2750.00 | 1351.39 | Already included in quote | **1351.39** |
| | | | | 1600 | x | x | 10800 | 1481.48 | | | |
| | | | | 1860 | x | x | 19600 | 948.98 | | | |
| | | | | 750 | x | x | 5400 | 1388.89 | | | |
| | | | | 850 | x | x | 10800 | 787.04 | | | |
| | Federation of Master Builders | Nov-24 | How much do new windows cost in the UK? | 1100 | x | x | 19600 | 561.22 | | | |
| | | | | 1000 | x | x | 5400 | 1851.85 | | | |
| | | | | 1500 | x | x | 14400 | 1041.67 | | | |
| Windows replace - Aluminium (low cost) | Check a Trade | Nov-24 | New Windows Cost in 2025 \| Checkatrade | 240 | x | x | 5400 | 444.44 | 332.73 | Already included in quote | **332.73** |
| | | | | 300 | x | x | 10800 | 277.78 | | | |
| | | | | 345 | x | x | 19600 | 176.02 | | | |
| | | | | 210 | x | x | 5400 | 388.89 | | | |
| | Federation of Master Builders | Nov-24 | How much do new windows cost in the UK? | 260 | x | x | 10800 | 240.74 | | | |
| | | | | 350 | x | x | 5400 | 648.15 | | | |
| | | | | 300 | x | x | 19600 | 153.06 | | | |
| Windows replace - Aluminium (high cost) | Check a Trade | Nov-24 | New Windows Cost in 2025 \| Checkatrade | 1000 | x | x | 5400 | 1851.85 | 1364.28 | Already included in quote | **1364.28** |
| | | | | 1400 | x | x | 10800 | 1296.30 | | | |
| | | | | 1550 | x | x | 19600 | 790.82 | | | |
| | | | | 1290 | x | x | 5400 | 2388.89 | | | |
| | Federation of Master Builders | Nov-24 | How much do new windows cost in the UK? | 1390 | x | x | 10800 | 1287.04 | | | |
| | | | | 1615 | x | x | 19600 | 823.98 | | | |
| | | | | 600 | x | x | 5400 | 1111.11 | | | |

Table A-86: Final costs (£/m2) used in the CBA derived from sources in Table 5-12

| Adaptation Option | | Values for Analysis, £/m2 |
|---|---|---|
| **Internal Shading** | White Average | 26.38 |
| | Blackout Average | 31.12 |
| **Window repair** | Min | 154.00 |
| | Max | 211.00 |
| **Window replacement** | Min | 328.98 |
| | Max | 1364.28 |
| **External shading** | Average | 238.98 |
| **Modifying the albedo** | Average | 39.67 |

Table A-97: Final capital costs included in the CBA per housing type for the studied adaptation actions

| Housing Type | Cost range | Internal shad - White, £ | Internal shad - Blackout, £ | Window repair, £ | Window replacement, £ | External shading, £ | Modifying albedo, £ |
|---|---|---|---|---|---|---|---|
| **High-rise (in stock)** | Min | x | x | 1523 | 3254 | x | x |
| | Max | x | x | 2087 | 13493 | x | x |
| | Average | 261 | 308 | 1805 | 8373 | 2364 | 928 |
| **High-rise (NZEB)** | Min | x | x | 1523 | 3254 | X | x |
| | Max | x | x | 2087 | 13493 | X | x |
| | Average | 261 | 308 | 1805 | 8373 | 2364 | 928 |
| **Low-rise apartment** | Min | x | x | 1813 | 3872 | X | x |
| | Max | x | x | 2483 | 16058 | x | x |
| | Average | 310 | 366 | 2148 | 9965 | 2813 | 1364 |
| **Mid-terrace home** | Min | x | x | 3702 | 7909 | X | x |
| | Max | x | x | 5072 | 32797 | X | x |
| | Average | 634 | 748 | 4387 | 20353 | 5745 | 6304 |
| **Semi-Detached home** | Min | x | x | 3702 | 7909 | X | x |
| | Max | x | x | 5072 | 32797 | X | x |
| | Average | 634 | 748 | 4387 | 20353 | 5745 | 7890 |

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