Assessing the future heating and cooling needs of the UK housing stock

April, 2023

UK Government

CS-NOW

Climate services for a net zero resilient world

Author(s)	Dr Lauren Ferguson, University College London Professor Anna Mavrogianni, University College London Dr Phil Symonds, University College London Professor Michael Davies, University College London Professor Paul Ruyssevelt, University College London
Peer reviewer(s)	Professor Sukumar Natarajan, University of Bath Chris Thorpe, Ricardo Energy & Environment

Acknowledgements	Dr Jonathon Taylor, Tampere University
Sign off	
Sign off name	Professor Paul Dodds
Sign off date	17/05/2023

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 four-year, £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 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 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).

Contents

Executive summary

This report aims to quantify the impact of climate change on the heating and cooling needs of the UK housing stock, with a specific focus on vulnerable segments of the population. It is the final output of the *"Projections of temperature change and impacts on UK housing",* a work package under the Climate Services for a Net Zero World (CS-N0W) Programme.

In summary, its three objectives were to:

1. Quantify the impact of a range of climate change projections on residential thermal comfort, heating and cooling loads across UK government regions for a range of dwelling archetypes and occupants, with an emphasis on urban areas.
2. Evaluate the implications of these changes for different groups, including older people, the fuel poor and other climate-vulnerable groups, taking into account the ability of these groups to adequately heat and cool their homes, adapt to, cope with and recover from excess heat and cold episodes, and the associated impacts on household fuel costs, energy use and carbon emissions, and health inequalities.
3. In close collaboration with key stakeholders, identify low-cost, low-carbon, 'win-win' measures that could be adopted in order to minimise adverse societal and environmental impacts of climate change-induced changes in the thermal performance of the UK housing stock.

A mixed methods approach was used. This included the statistical analysis of existing housing and population databases, modelling based on building physics simulation and machine learning techniques, and knowledge exchange activities with key stakeholders. The modelling component was underpinned by a review of heat and cold vulnerability; this identified population subgroups who are particularly vulnerable to detrimental health impacts following exposure to high and low ambient temperatures. These groups represent populations who may benefit most from reductions in space heating and cooling demand.

We acknowledge that there is significant diversity within and between population groups (e.g. ethnic minorities). Due to time constraints, we limited the analysis to a small number of groups. Future work could look at distributions of vulnerability for sub-categories within these groups.

Its ten key findings are:

1. **Four population subgroups are particularly vulnerable to high levels of heating and cooling demand due to underlying health, social, financial and/or built environment factors.** Vulnerable subgroups were identified as:
    - infants aged between 0-4 years old,
    - individuals aged 65 years or older,
    - those belonging to an ethnic minority, and
    - low-income individuals.

   Such subgroups are likely to be doubly burdened with high exposure to indoor heat. This is due to the location and type of buildings they typically occupy, combined with higher susceptibility to developing negative impacts following exposure due to potential underlying health conditions and the ability to adapt their surroundings.
2. **Whilst energy retrofit measures overall reduced space heating needs across the country, inequalities in heating needs may persist without a retrofit programme specifically targeting subgroups who are at greater risk of fuel poverty.** These differences were driven by certain subgroups being more likely to occupy detached properties and bungalows, which have higher space heating demand. We, therefore, suggest more stringent retrofit measures for these archetypes, especially amongst owner-occupied dwellings.
3. **Total annual heating energy needs by dwelling floor area (known as *Energy Use Intensity*, EUI) is higher in areas with a greater proportion of people aged above 65, and lower in areas with a greater proportion of under 5s, lower income individuals and ethnic minorities**. Such disparities for those aged above and below 65 years old were largest in London and across Scotland, identifying two key areas for the prioritisation of equitable domestic energy policy.
4. **The mean dwelling EUI across homes was the highest in Wales, followed by Northern Ireland. EUIs for Scotland and England were similar, thus supporting findings that the Welsh housing stock is older and less energy efficient, whilst Scottish homes are on average *more* energy efficient.** This is important considering the cooler, more northern climate of the Glasgow weather data used to model indoor conditions in Scottish dwellings, whilst the Cardiff weather data used to model the Welsh housing stock shared a similar latitude with London. It is likely, however, that the higher wind loads of the Cardiff weather file is likely to partly explain the observed differences.

5. **If no retrofit takes place by the 2030s, and under the assumptions made about housing characteristics and occupant behaviour, the majority of UK dwellings will fail current night time overheating criteria.** Dwellings with less attachment (bungalows, detached properties) are on average cooler, exceeding indoor overheating thresholds for a lower percent of annual night time hours. Flats and mid-terrace houses were warmer and spent more hours above the indoor overheating thresholds. Importantly, there was a large amount of variation in overheating across different flat archetypes, owing to the large variation across the different storey levels. It is, thus, recommended that overheating mitigation measures are implemented before the 2030s in the most overheating prone dwelling archetypes.
6. **The most effective strategy in terms of reducing overheating risk and associated cooling demand was external shutters.** However, we found that where the use of external shading may not be technically feasible, the use of internal blinds can also be effective for some dwelling archetypes, such as detached houses and bungalows. For example, across the English housing stock, the average annual cooling demand under RCP 8.5 in 2085 was 30% higher with internal blinds compared to external shutters, but for detached and bungalow properties, the difference was 13% and 8%, respectively.
7. **Under the specific assumptions made about the uptake of this measure, increasing the reflectivity of building external surfaces appeared to have little effect in reducing overheating.** There are a number of potential reasons for this, including the assumptions about the measure's uptake, the model's limited ability to account for temperature changes in the local outdoor environment following surface albedo modification and the effect of combining this measure with widespread wall and roof insulation. Adaptive window opening also made minimal difference when only adopted by a small proportion of the housing stock; in particular, ground floor flats and bungalows may experience increased risk of overheating, if cooling relies on optimised window opening compared to other dwelling types due to windows being kept closed due to security concerns.
8. **Although indoor overheating was widespread across the UK, the population weighted summertime bedroom temperature was significantly higher for ethnic minority and low income households in England and Wales, and areas with a higher proportion of low income households in Scotland.** As air conditioning may become more prevalent towards the latter 21st century, areas with a greater proportion of ethnic minorities, infants and low income households will generally experience higher cooling needs per floor area unit, which may not be reduced by the widespread use of external

shading. Inequalities in exposure to indoor heat and cooling demand were minimal for Northern Ireland.

9. **Dwellings located in areas with a high proportion of residents aged 65 and above overheated for a significant amount of time, although overall less than areas with *fewer* over 65s.** This remains concerning given the heightened vulnerability of older age groups to heat-related morbidity and mortality.
10. **Crucially, there is no "one-size-fits-all" solution to modifying the UK housing stock to protect against overheating and reduce inequalities in heating and cooling needs.** Due to the diverse building construction ages, typologies and household characteristics comprising the housing stock, a blanket, one-size-fits-all approach to modifying it to meet climate change adaptation and mitigation targets may be unsuitable.

We hope that the findings of this report and associated dataset will help the UK Government identify combinations of home retrofit measures that reduce space heating demand during the winter whilst minimising summertime overheating risk via passive strategies, under the current and future climate. This could inform the development of home energy and climate adaptation policies that account for the underlying differences in dwelling and population characteristics across the whole of the UK.

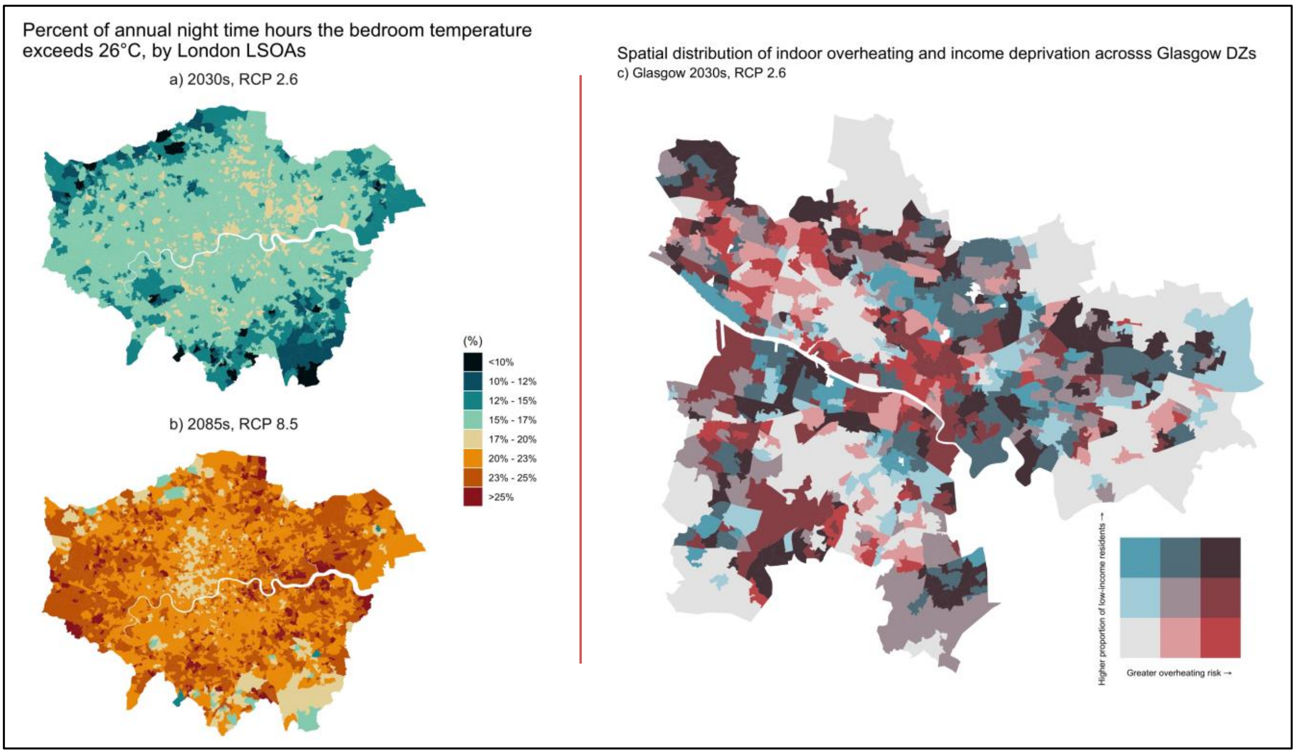


Figure 1. The mean percent of annual night time hours the nocturnal bedroom temperature exceeded 26°C, aggregated by London LSOAs, in the a) 2030s time horizon under RCP 2.6 and b) 2085s time horizon under RCP 2.6. c) Bivariate map showing the spatial distribution of indoor overheating risk in the 2030s time horizon under RCP 2.6 and current income deprivation across Scottish Data Zones for the city of Glasgow.

1. Introduction

The UK built environment is currently facing a number of challenges, including, the threat of increasing summertime temperatures due to climate change (Kendon et al., 2021) and the need to reduce the carbon emissions of the poorly performing housing stock in the context of national climate change mitigation efforts (BEIS, 2020). As the UK population spends up to 95% of their time indoors (Smith et al., 2016), much of our exposure to external temperatures will be modified by buildings. The thermal performance of UK homes is, therefore, central to ensuring households are able to keep their homes warm during winter, minimising summertime overheating risk and meeting greenhouse gas emission reduction targets. Both high and low temperatures are associated with adverse effects on population health (Gasparrini et al., 2022), but the burden of temperature-related mortality and morbidity is not shared equally across the population: Older individuals and those living with underlying co-morbidities, such as cardiovascular, respiratory and mental health conditions, are more vulnerable to heat- and cold-related health effects (Arbuthnott & Hajat, 2017; Lee et al., 2023).

British winters are expected to get warmer, wetter and windier, and summers hotter and drier as a result of global climate change (MetOffice, 2021). The occurrence of extreme heat events or heat waves is projected to increase (Lowe et al., 2018). This will have negative impacts for population health in the summer: A rise in excess mortality was associated with the 2003 (Johnson et al., 2005), 2006 (HPA, 2006), 2009 (Murray et al., 2010), 2011 (Green et al., 2012), 2019 (PHE, 2019) and 2020 heatwaves (PHE, 2020). The 2022 summer heatwave, where outdoor temperatures reached 40°C for the first time on record, was associated with 2,227 excess deaths in the two-week period between 10-25 July 2022 (ONS & UK HSA, 2022).

Alongside rising ambient temperatures is the UK's pledge to reduce carbon emissions to *Net Zero* by 2050, with an intermediate target of 68% reduction on 1990 levels by 2030 (BEIS, 2020). Buildings were responsible for approximately 17% of direct greenhouse gas emissions in the UK in 2019, and homes contributed to 77% of this share (CCC, 2020). The housing sector, thus, provides a likely avenue through which national carbon reduction can be partly achieved and progress towards said targets be attained. Given existing domestic buildings will account for approximately 75% of the 2050 UK housing stock, retrofitting existing structures is key to reducing energy demand in the domestic sector (IET, 2020; Schwartz et al., 2022). Despite two decades of energy retrofitting, much of the existing housing stock fails to meet targets: in 2019, nearly 19 million UK homes currently have an Energy Performance Certificate (EPC) rating of D or worse (HM Government, 2017), meaning a large-scale retrofitting programme is needed across much of the domestic sector.

Improving building energy efficiency not only reduces carbon emissions but, if appropriately implemented, can potentially improve health and lower operational costs for the occupants (Kerr et al., 2017), and reduce reliance on increasingly insecure fuel supplies in the UK. A recent report estimated that improving dwelling energy efficiency, along with the decarbonisation of household fuels, may result in a £6.8 billion boost to the UK economy via direct economic impacts, social benefits and job creation (Cambridge Econometrics, 2022). Estimated benefits were greater assuming high domestic energy prices, such as those seen throughout the ongoing energy crisis. However, it is estimated that up to 20% of the English housing stock is already experiencing indoor overheating (Lomas et al., 2021), which may be exacerbated by energy efficiency measures applied without sufficient cooling strategies; this could be due to increased building airtightness and internal solid wall insulation which may prevent heat from escaping (Makantasi & Mavrogianni, 2016; Taylor et al., 2023). This led to the release of Approved Document O of the Building Regulations in England in 2022, which aims to mitigate overheating in new residential dwellings (HM Government, 2021a). Whilst consideration of overheating risk at the design stage is an important step, measures to mitigate overheating must be primarily implemented to existing structures. The third UK *Climate Change Risk Assessment* (CCRA3) has encouraged better coordination of home decarbonisation policies and heat adaptation strategies for homes, as a means of minimising the risk to health and social care from extreme weather events (CCC, 2021). The *Cooling in the UK* report commissioned by the Department of Business, Energy and Industrial Strategy (BEIS) highlighted the potential cost savings of deploying cooling measures alongside a home retrofit programme to reduce costs and increase benefits to homeowner/tenants (BEIS, 2021). The report suggested that passive overheating measures, such as internal and external shading, improved ventilation practices and using surfaces with a high reflectivity, may reduce energy consumption for cooling demand by a greater amount compared with efficient active cooling systems, which may further increase building fuel costs and carbon emissions, but that the roll-out of such measures as part of wider decarbonisation goals needed more detailed consideration (BEIS, 2021).

The social housing stock has seen improvements in energy efficiency over the last ten years due to council-led retrofits, and uptake of energy efficient measures is highest in low income areas of England (Hamilton et al., 2014). However, parallel increases in outdoor temperatures have highlighted the vulnerability of social housing, and energy efficient homes more generally, to overheating (Mavrogianni et al., 2013; Ortiz et al., 2020; Porritt et al., 2013) especially those located in urban areas due to the Urban Heat Island (UHI) effect (Sanchez-Guevara et al., 2019).

Household cooling needs are not currently considered in UK definitions of fuel poverty (outlined in Inset 1) as air conditioning use is at present limited (Crawley et al., 2020), but future definitions may include the ability of a household to adequately cool their homes. A UK survey on health protection behaviour following the 2013 heatwave found high income earners were three times more likely to use an electric fan than those on lower incomes (Khare et al., 2015).

Low-income populations are overrepresented in urban areas and housing density is higher leading to smaller, more compact dwellings with limited opportunities for cross ventilation and heat transfer from neighbouring units. This results in a 'triple jeopardy' scenario where UHI intensity, population vulnerability and poor-quality housing overlap, creating high heat risk areas (Nickson et al., 2011; Taylor et al., 2015). A number of evidence reviews by the Zero Carbon Hub (ZCH) found heat waves, demographic changes, urbanisation and new construction practices are increasing the risk of overheating, which is principally experienced in urban areas with overlapping older populations, multi-unit and densely compact housing (ZCH, 2015a, 2015b, 2016).

UK Fuel Poverty Definitions

England: If a household is living in a property with an EPC rating of band D or below and spending the amount required to heat their home would leave their residual income below the official poverty line.

Wales: If a household is spending more 10% of their income to maintain a satisfactory indoor temperature.

Scotland: If a household is spending 10% or more of their after housing cost equivalent net income on fuel *and* their remaining income is at least 90% of the UK Minimum Income Standard (MIS) after childcare deductions and including any disability or care benefits received.

Northern Ireland: If a household is spending

other occupied rooms.

Inset 1. Fuel poverty definitions for England, Wales, Scotland and Northern Ireland (Hinson & Bolton, 2022).

In the context of the *'Climate Services for a Net Zero Resilient World'* (CS-N0W) programme, the UK Government commissioned this study to gain a better understanding of climate change impacts on energy costs and thermal conditions within UK homes for vulnerable households. We employ a mixed methods approach, including the statistical analysis of existing housing and population databases, building performance simulation, and knowledge exchange activities with key stakeholders. Taking into account the major challenges for the UK housing stock posed by climate change, this report aims to address the following overarching research question:

- *What is the impact of climate change on the heating and cooling needs of the UK housing stock, in particular for vulnerable segments of the population?*

The research question outlined above was addressed through the following objectives:

1. Quantify the impact of a range of UK Climate Change Projections (UKCP) on residential thermal comfort, heating and cooling loads across UK government regions for a range of dwelling archetypes and occupants, with an emphasis on urban areas.
2. Evaluate the implications of these changes for different groups, including older people, the fuel poor and other climate-vulnerable groups, taking into account the ability of these groups to adequately heat and cool their homes, adapt to, cope with and recover from excess heat and cold episodes, and the associated impacts on household fuel costs, energy use and carbon emissions, and health inequalities.
3. In close collaboration with key stakeholders, identify low-cost, low-carbon, 'win-win' measures that could be adopted in order to minimise adverse societal and environmental impacts of climate change-induced changes in the thermal performance of the UK housing stock.

To achieve these three objectives, a building stock performance model was used that identified the physical building characteristics (such as building size, shape, degree of attachment, standard of energy efficiency, etc.) leading to different heating and cooling demand levels. In addition, these outputs will feed into a tool for local authorities and local enterprise partnerships that will assist them in understanding climate change implications for local climate adaptation and decarbonisation plans (to be generated in the context of another CS-N0W Work Package).

2. Methods

2.1 Building-physics based housing model

To assess the energy and thermal performance of the UK housing stock, we used an existing housing stock model developed at the UCL Institute for Environmental Design and Engineering (IEDE), as part of the National Institute for Health Research Health Protection Research Unit (HPRU) in Environmental Change and Health, funded by the National Institute for Health and Care Research (NIHR). A meta-modelling approach is adopted, based on machine learning techniques and a large number of *EnergyPlus* simulations for indoor temperature and building energy use.

EnergyPlus is a building physics-based, whole-building energy simulation software which dynamically models building performance, taking into account the outdoor climate and terrain; building characteristics such as geometry, fabric, airtightness, floorspace; and occupant behaviour (e.g. window opening frequency and internal gains) as inputs (US DOE, 2020). EnergyPlus has previously been used to model indoor temperatures (Mavrogianni et al., 2017; Oikonomou et al., 2012), building energy use (Beagon et al., 2020) and indoor exposure to air pollution (Shrubsole et al., 2016; Taylor et al., 2014) for dwellings representative of the London and wider English housing stock. The existing meta-model has been used to assess the spatial variation of indoor air pollution for 11.5 million English and Welsh homes (Taylor et al., 2019) and project the impact of housing on temperature-related mortality in London (Taylor et al., 2021).

Housing stock modelling inputs were primarily derived from the Energy Performance Certificate (EPC) register. A dwelling enters the register whenever it is constructed, sold or let, thus newer, more energy efficient dwellings are overrepresented in the EPC register. Data for domestic properties is available from 2007 up until December 2021.

Using the meta-model, dwellings were modelled based on eight archetypes broadly representative of the English housing stock, representing approximately 75% of English homes (Taylor et al., 2016). A detailed explanation of how EPC data is cleaned and converted to inputs for the meta-model is provided in Taylor et al. (2019), and briefly in the Appendix A, including floor plans for each of the eight archetypes. Where EPC data for a building is largely missing or obvious errors are identified, the entry for this building is omitted. This leads to an EPC entry for 64.3% of the existing English (*n* = 15,847,767), 58% of the Welsh (*n* = 834,605), 52.4% of the Scottish (*n* = 1,404,758) and 44% of the Northern Irish (*n* = 358,282) housing stocks. The coverage of EPCs across UK local authorities is shown in Figure 2. The local authority with the highest percentage of homes with an EPC was Nottingham, at 78.6%, and the lowest percentage was Anglesey in Wales, at 7.1%.

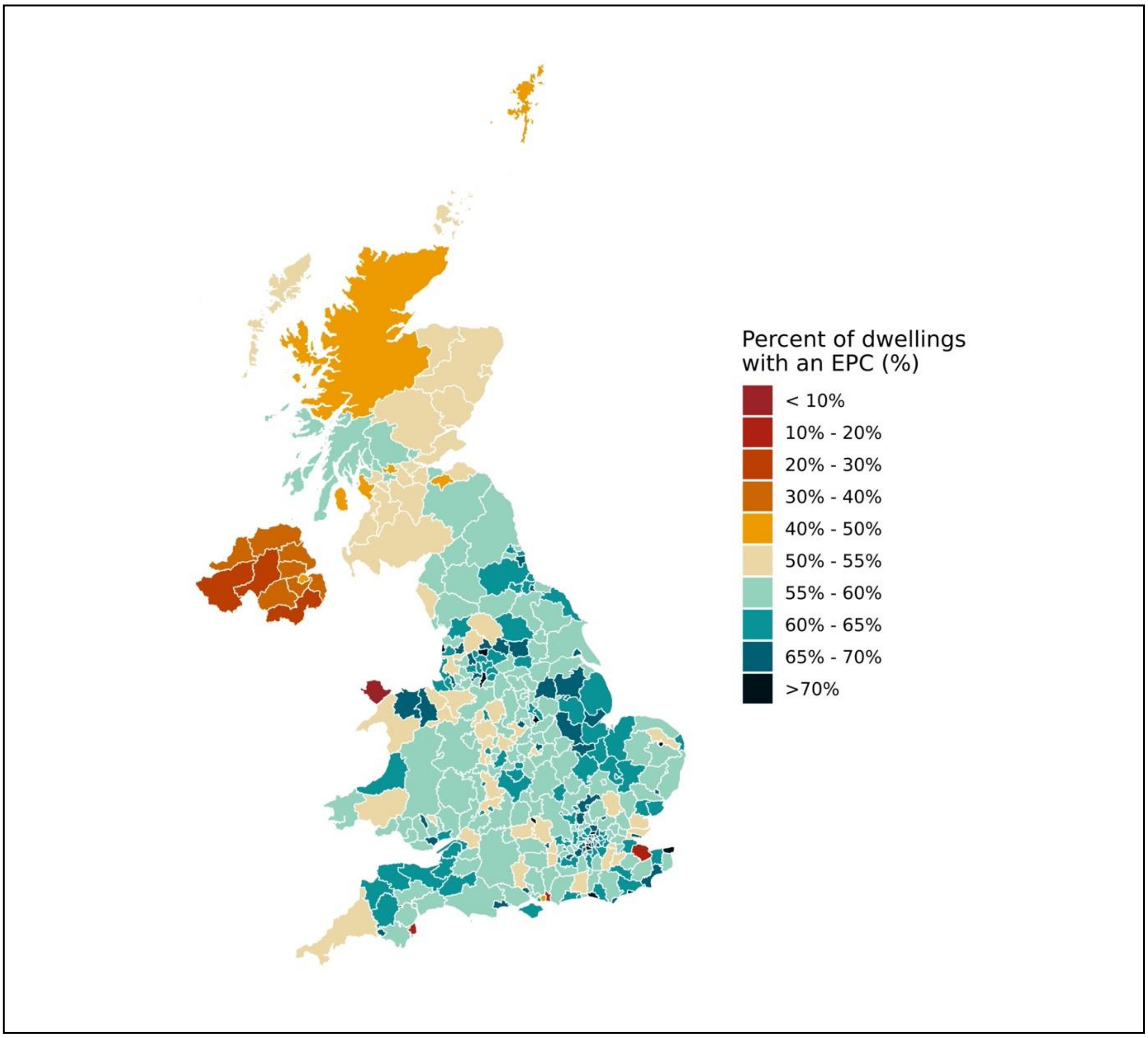


Figure 2. The percentage of dwellings on the EPC register, by UK local authorities (DCLG, 2022).

2.2 Climate data

The outdoor climate was modelled using weather files previously developed for BEIS in the context of the 2021 *Cooling in the UK* report (BEIS, 2021a). Future weather files using 2018 UK Climate Projections (UKCP18) were used to model the projected outdoor conditions in the years 2030, 2050 and 2085 under Relative Concentration Pathway (RCP) 2.6. EPC dwellings located in England were modelled using an outdoor weather file for London; those located in Wales were modelled using an outdoor weather file for Cardiff; Scottish dwellings were modelled using a Glasgow weather file and Northern Irish dwellings modelled using a Belfast weather file. Additionally, outdoor conditions in England in 2085 were modelled using an RCP 8.5 weather file to assess a scenario in which global greenhouse gas emissions continue to rise with little abatement.

A summary of the corresponding projected temperature changes for each RCP scenario is outlined below in Table 1, adapted from the Intergovernmental Panel on Climate Change (IPCC) Synthesis Report (IPCC, 2014). All scenarios were modelled using a Design Summer Year (DSY) weather file. The DSY is a single continuous year, representing a 'warm' year selected from a 30-year period. At the time of this study, UKCP18 weather files were not yet available for UK countries outside of London, Cardiff, Belfast and Glasgow, in a format suitable for building simulation, though earlier UKCP09 scenarios are available for 42 locations across the UK from the EPSRC-funded University of Exeter PROMETHEUS research project (Eames et al., 2011)[1]. Later UKCP09 weather files at high spatial resolution (5km) have additionally been developed which partially overcome the limitations of earlier UKCP09 files (Liu et al., 2020).

Table 1. The projected change in global mean surface temperature of each Relative Concentration Pathway (RCP) scenario, for the mid and late 21st century relative to the 1985-2005 period. The table is adapted from the Intergovernmental Panel on Climate Change (IPCC) Synthesis Report (IPCC, 2014), with the two RCP scenarios modelled in this report shown in ***bold italic***.

Scenario	2046-2065		2081-2100	
	Global mean surface temperature change (°C)	Likely range (°C)	Global mean surface temperature change (°C)	Likely range (°C)
RCP 2.6	***1.0***	***0.4 to 1.6***	***1.0***	***0.3 to 1.7***
RCP 4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
RCP 6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
RCP 8.5	***2.0***	***1.4 to 2.6***	***3.7***	***2.6 to 4.8***

2.3 Retrofit scenarios

We assessed the effect of five different scenarios on the annual heating, cooling demand and indoor temperature exposure for different population groups. Scenarios were developed following consultation with DESNZ, the Ministry of Housing, Communities & Local Government (MHCLG) and other stakeholders, to identify combinations of energy retrofit and overheating mitigation measures that simultaneously reduce energy demand and limit overheating in the UK domestic stock. Following stakeholder consultation, the following building retrofit and operation scenarios were modelled:

[1] A sensitivity analysis was carried out between UKCP18 and UKCP09 weather files for the work package interim report, finding that UKCP09 weather files underestimated the outdoor temperature compared to the later UKCP18 weather files.

1 – **Baseline housing stock conditions** derived using data from the Energy Performance Register (EPC). No passive overheating measures or active cooling uptake were assessed.

2a – Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the Climate Change Committee (CCC), along with ***external passive shading***. Air conditioning uptake increases at each time horizon according to area-measures of household income.

2b – Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the CCC, along with ***internal passive shading***. Air conditioning uptake increases at each time horizon according to area-measures of household income.

3 – Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the CCC, along with ***modifications to external surface reflectivity, known as surface albedo.*** For this intervention, homes located in urbanised areas of each of the four UK nations are targeted. Air conditioning uptake increases at each time horizon according to area-measures of household income.

4 – Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the CCC, along with ***behavioural adaptations by occupants.*** For this intervention, the indoor temperature threshold at which windows opened varied, taking into consideration of occupant security concerns. Air conditioning uptake increases at each time horizon according to area-measures of household income.

The uptake of these technologies and behaviours varied according to the time period examined, with values based on the best available evidence, detailed below and summarised in Table 3.

2.3.1 Energy retrofit

To assess the impact of household energy efficiency measures on heating energy demand, values for the installation of retrofit measures across the stock in 2030, 2050 and 2085 were taken from the CCC's Balanced Pathway (CCC, 2022). According to this pathway, there should be around 6.5 million installations of loft insulation, 1.9 million installations of cavity wall insulation and 2.4 million installations of solid wall insulation across the housing stock between 2022-2030. Between 2030-2048, a further 4.3 million installations of loft insulation, 1.1 million installations of cavity wall insulation and 900,000 installations of solid wall insulation are required to meet Net Zero by 2050. We assume that these measures are distributed randomly across the EPC dataset from which the housing data is taken. This results in 70% of the existing EPC stock retrofitted with at least one of the measures by 2030 and 100% of the EPC stock retrofitted by 2050. In the 2085 time horizon, energy efficiency installations are assumed to remain at the 2050 level. Building fabric target values for each element were taken from Part L of the Building Regulations in England and Wales for existing buildings (HM Government, 2021b), shown in Table 2, and applied only when the baseline U-value was above that recommended in Part L[2].

Table 2. U-value building fabric targets for external cavity and solid walls, and loft insulation taken the English and Welsh building regulations (HM, Government, 2021b).

Feature		Building regulations for existing dwellings: U-value ($W/m^2/K$)	Source
External wall	Solid	0.30	(HM Government, 2021b)
	Cavity	0.55	
Roof		0.16	

2.3.2 Shading devices

External window shutters have been found to be a more effective intervention in building thermal simulation studies that compared a range of passive overheating strategies (Mavrogianni et al., 2014; Porritt et al., 2013). External shutters prevent solar radiation warming the internal dwelling space, as well as the outdoor air between the shutter and the window, which can then be transferred to the room (ZCH, 2016). It is recommended that shading is combined with other interventions, such as external wall insulation, to significantly reduce overheating (Porritt et al., 2013). We assess the impact of applying external shutters alongside homes that are retrofitted on indoor temperatures and summertime overheating. Shutters were assumed to be closed from 9 am – 6 pm during summer months (May – September) to quantify their maximum impact. Shutters were added in homes that were modelled with an energy retrofit package for each of the three time horizons of 2030, 2050 and 2085, as the third UK Climate Change Risk Assessment (CCRA3) has encouraged better coordination of home decarbonisation policies and heat adaptation strategies for homes.

[2] A lower U-value is associated with higher levels of heat loss through the building fabric.

However, issues may arise implementing external shutters to existing buildings due to heritage and spatial and/or design restraints, as the majority of UK homes have externally opening windows. Internal blinds have been recommended as a low cost solution for existing buildings (ZCH, 2016). We, therefore, additionally assess how internal blinds compare to external shutters in terms of overheating mitigation. Internal blinds were implemented in homes which had received energy efficiency measures in 2030, 2050 and 2080 and assumed to be closed from May until September throughout the day from 8 am – 8 pm.

2.3.3 Surface albedo modification

Modifying the reflectivity of building surfaces by reducing solar absorption via high albedo materials has been identified as an effective way to mitigate overheating in urban areas (Gago et al., 2013; Gupta & Gregg, 2012; Santamouris & Fiorito, 2021; Yang et al., 2015). To assess the impact of this measure on the indoor temperature and energy use, we reduce the solar absorption coefficient of external roofs and walls from a baseline of 0.8 to 0.1 in Scenario 3, representing the painting of external surfaces with a low absorption paint. Dwellings located in urbanised areas are prioritised for this scenario. We estimate the effect of surface albedo modification on indoor temperature and cooling energy use for London, Cardiff, Glasgow and Belfast in 2030; additionally, in the 2050 scenario the West Midlands, Swansea, Edinburgh and County Armagh were assumed to modify the surface albedo of their buildings and in 2085 dwellings located in Manchester, Rhondda Cynon Taff, Fyfe and Causeway and Glens were additionally assessed. All areas represent the three most built-up areas of each country in terms of the available EPC data. A number have a notable UHI effect (Krüger et al., 2013; Levermore et al., 2015; Tomlinson et al., 2012; Watkins et al., 2002) which has, in some cases, been associated with an increased mortality burden during heatwaves (Heaviside et al., 2016; Taylor et al., 2015). This results in 15%, 21% and 26% of the EPC stock receiving modifications to the building surface for 2030, 2050 and 2085, respectively.

2.3.4 Window operation

Window-opening has been shown to be an effective way to reduce indoor overheating, when outdoor temperatures are lower than indoor, and behavioural adaptations may be a low-cost option for short-term reductions in indoor overheating. A lack of operable windows during heatwaves has been attributed to an increased mortality risk of between 29-65% in a modelling study of dwellings located in the West Midlands (Taylor et al., 2018). Monitoring data from 26 low-energy Scottish homes attributed much of the variation in indoor overheating between dwellings with a very similar design to occupant window opening (Morgan et al., 2015).

Within the model, window opening was modelled as a function of indoor and outdoor temperature, where windows were opened during summer when the indoor temperature exceeded 22°C and if the indoor temperature exceeded the outdoor temperature. The indoor temperature threshold of 22°C was taken from CIBSE guidelines (CIBSE, 2015). Whilst there a number of reasons people open windows, indoor temperature is consistently found to be one of the main drivers (Fabi et al., 2012; Yao & Zhao, 2017). To assess the effect of increased window opening on indoor temperatures, the indoor temperature threshold at which windows were opened was reduced to 18°C in homes that adopted this behaviour. This represents a scenario where windows are almost continuously open. This was distributed randomly across the housing stock to see how this behavioural adaptation effects indoor temperatures in different dwelling types with varying orientations and layouts, but only for homes where the bedroom was on the second-storey and above. Ground-floor flats and bungalows were assumed to not adopt increased window opening due to security concerns. The adoption of lower window opening thresholds was assumed to increase as the ambient temperature increased, with 25%, 50% and 75% of dwellings adopting it in 2030, 2050 and 2085, respectively. Additionally, a counterfactual window-opening scenario was assessed where the indoor temperature threshold was set to 35°C in a subset of homes (10%) where bedrooms are located on the ground floor, to represent a scenario where windows are continuously closed. The three window opening thresholds of 18°C, 22°C and 35°C have previously been used by Taylor et al. (2018) to quantify the role of window operation on heat-related mortality.

2.3.5 Air conditioning uptake

Despite a lack of UK data on uptake of air conditioning in homes, prevalence is estimated to be less than 3% (BEIS, 2017). However, a recent study of participants living in London showed the purchase of a home air conditioning unit was being contemplated (Murtagh et al., 2022) and uptake is expected to rise up to around 30% by 2050 (Crawley et al., 2020). Based on international evidence, uptake is likely to be more common in affluent homes (O'Neill et al., 2005; Thomson et al., 2019).

We, therefore, modelled the adoption of home air conditioning using a socioeconomic uptake scenario, where adoption increased in descending order of area-measures of household income. The most recent small-area estimates of household income for England and Wales are available from 2018 (ONS, 2020). Small-area estimates of household income were not available for Scotland and Northern Ireland. Data on area income deprivation from the 2020 *Scottish Index of Multiple*

Deprivation (SIMD, 2020) and 2017 Northern Irish *Multiple Deprivation Measure* (NISRA, 2018) was, therefore, used to estimate air conditioning uptake for Scottish Data Zones and Northern Irish Super Output Areas (SOAs), respectively. Homes in areas with a higher median household income (or lower levels of income deprivation) adopted air conditioning earlier, and those located in less affluent areas (with more income deprivation) adopted air conditioning later as ambient temperatures continued to increase with climate change. Values for the deployment of air conditioning units across the stock were taken from Crawley et al. for 2030 and 2050, 1.6% and 30%, respectively. For the 2085 scenario, air conditioning adoption was assumed to continue at a rate of 1.4% per year, resulting in 79% of the stock adopting air conditioning by 2085. The 55-year uptake trajectory (from 1.6% in 2030 to 79% in 2085) is comparable to that of the US, where fewer than 2% of homes had air conditioning in 1955 (Biddle, 2008) versus 88% in 2020 (EIA, 2020). The propagation of air conditioning across the housing stock at the three time horizons is shown in Figure 3.

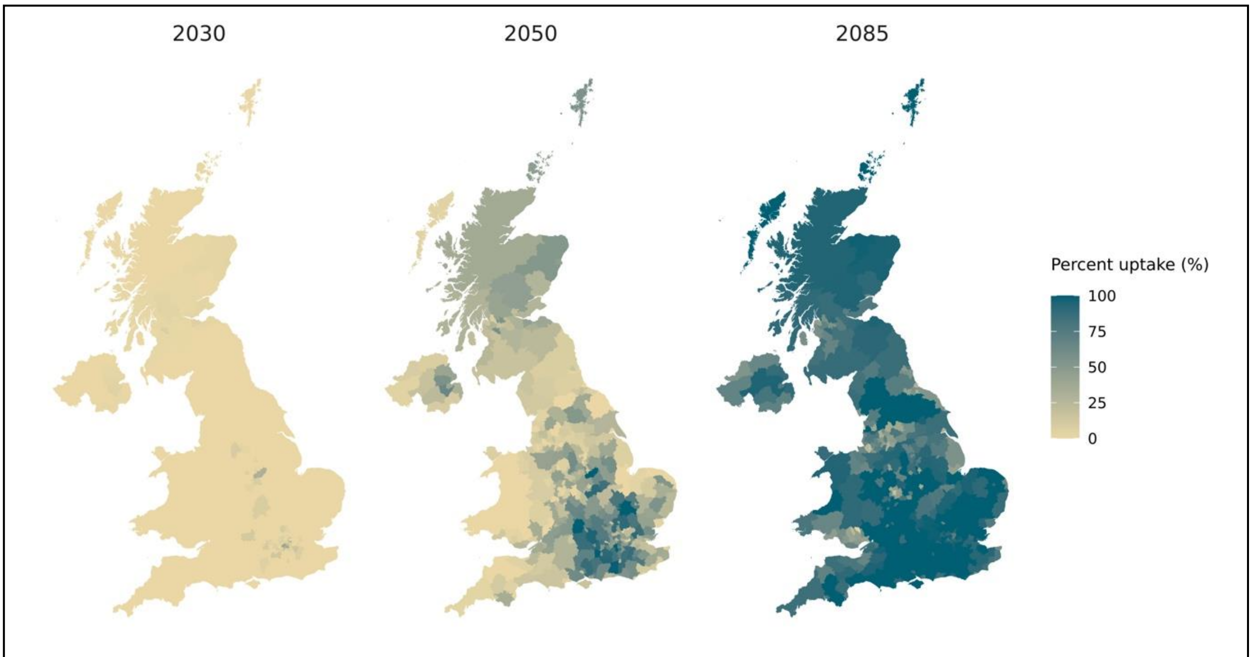


Figure 3. The percentage of households with an air conditioning unit, by UK local authorities, at the three time horizons. Values for the percent deployment across the housing stock at each time horizon are taken from Crawley et al. (2020) for 2030 and 2050 and estimated to continue at the same rate (1.4% per year) in 2085.

Table 3. Socio-technical retrofit uptake scenarios under RCP 2.6 and 8.5.

Scenario	Intervention	Deployment scenario	**Percent deployment**		
			2030[a]	2050[a]	2085[ab]
1 – Baseline	No intervention	Counterfactual scenario where no building or behavioural interventions are implemented across the stock.	-	-	-
2a – Energy retrofit and external passive shading	Building interventions	Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the Climate Change Committee (CCC)	71%	100%[c]	100%
	Shading overheating mitigation	External shutters are implemented alongside home retrofit for *all* dwellings which received energy efficiency measures	71%	100%	100%
	Air conditioning uptake	Homes residing in neighbourhoods with the higher levels of area household income first install air conditioning units	1.6%	30%	79%
2b – Energy retrofit and internal passive shading	Building interventions	Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the CCC	71%	100%	100%
	Shading overheating mitigation	Internal blinds are used in *all* retrofitted buildings due to the infeasibility of external shutters	71%	100%	100%
	Air conditioning uptake	Homes residing in neighbourhoods with the higher levels of area household income first install air conditioning units	1.6%	30%	79%
3 – Energy retrofit and external surface	Building interventions	Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the CCC	71%	100%	100%
	Overheating mitigation	Low feasibility of external shutter implementation results in surface albedo modification in possible UHI areas, selecting the three most urbanised areas in each country	15%	21%	27%

Scenario	Intervention	Deployment scenario	Percent deployment		
			2030[a]	2050[a]	2085[ab]
reflectivity modification	Air conditioning uptake	Homes residing in neighbourhoods with the higher levels of area household income first install air conditioning units	1.6%	30%	79%
4 – Energy retrofit and improved window opening	Building interventions	Building Regulations-standard solid, cavity and loft insulation are installed across the housing stock, based on projections by the CCC	1.6%	30%	79%
	Overheating mitigation	Occupants residing in buildings with second storey and above bedrooms adopt improved window opening behaviour in response to rising temperatures and minimal remediation strategies. 10% of dwellings with bedrooms on the ground floor (bungalows and ground-floor flats) are assumed to not open windows at all.	71%	100%	100%
	Air conditioning uptake	Homes residing in neighbourhoods with the higher levels of area household income first install air conditioning units	35% (25% increase window opening) and 10% keep windows closed at all times)	60% (50% increase window opening) and 10% keep windows closed at all times)	85% (75% increase window opening) and 10% keep windows closed at all times)

[a] Representative concentration pathway (RCP) 2.6.

[b] RCP 8.5: This was applied to the English housing stock to assess the *worst-case* scenario, where global emissions continue to rise with little abatement.

[c] Up to 17.1 million homes are required to be retrofitted with solid/cavity wall and loft insulation in order to meet Net Zero by 2050.

2.4 Outputs

2.4.1 Energy use

To calculate the potential energy savings from a home retrofit, annual heating energy use was summed for all rooms with an electric heater sized for the individual building zones according to CIBSE guidelines (CISBE, 2003) and assumed to operate at 80% efficiency. The heating system was operated from September 30th to March 31st between 7-8 am and 5-10 pm each day. The thermostat setting for each dwelling was randomly sampled from a distribution defined by reported thermostat set-points in centrally-heating dwellings. Assumptions were based on the 2021 Energy Follow-Up Survey (EFUS) (BEIS, 2021b) in a nationally representative sample of 957 households, where the mean thermostat temperature setting was recorded as 20.4°C. The distribution is outlined below in Figure 4.

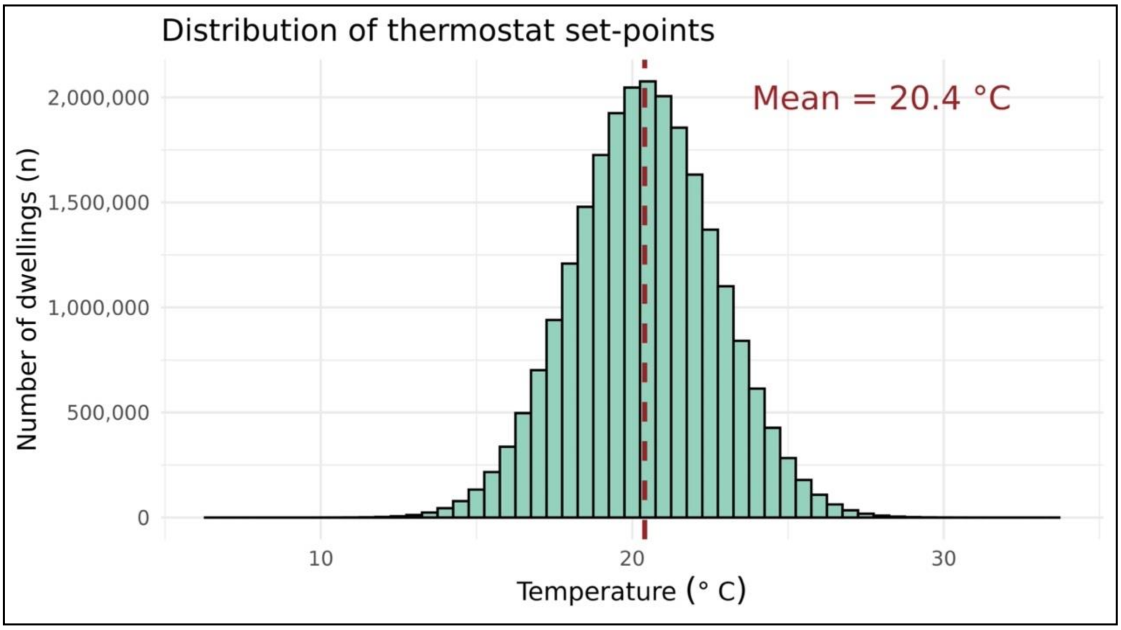


Figure 4. The distribution of thermostat setpoints used as input to determine annual heating energy use.

Cooling demand was estimated using an electric cooler sized for each room, where the schedule ran from May 1st to September 31st and operated during the daytime when the indoor temperature exceeded 26°C in homes that adopted air conditioning (see details on uptake scenarios in Table 3). There is limited to no empirical evidence on domestic air conditioning uptake and usage in the UK. The indoor temperature for air conditioning operation was, therefore, taken from published global studies (Meier et al., 2019; Willand et al., 2016; Wright et al., 2020). Previous analysis of future air conditioning use in the UK have emphasised the need to learn from the best international practice where air conditioning is already widely in use (McLachlan et al., 2016).

Dwelling susceptibility to low indoor temperatures in winter was assessed using heating Energy Use Intensities (EUI), calculated by dividing the total annual heating energy consumption by the dwelling floor area. All dwellings were assumed to be actively heated in winter using a central heating system and the thermostat setting for each household was sampled from the same distribution (Figure 4). The heating energy use required to maintain the thermostat setpoint temperature will, therefore, better capture a household's vulnerability to cold indoor temperatures during winter, especially given the recent unit increase in domestic energy prices in the UK (Bolton & Stewart, 2023). Likewise, as buildings become actively cooled towards the latter 21st century, we assess *cooling-related* energy use intensities for different population groups to see if they bear a disproportionate energy burden during summer, and therefore may be susceptible to summer fuel poverty.

2.4.2 Indoor temperature

Indoor temperature was assessed using a number of temperature-related metrics. Exposure to indoor temperature in summer was assessed using nocturnal bedroom temperature, as studies on heat-related mortality suggest warm nights are most strongly associated with risk of cause-specific mortality by the degradation of sleep quality (Díaz et al., 2002; He et al., 2022; Royé et al., 2021). The average night time temperature during summer time (June – August) and the mean, two-day maximum indoor temperature was calculated in bedrooms when the outdoor temperature was between 20-22°C, 22-24°C and 24-26°C degrees. These outdoor temperature thresholds were applied to the simulations for 2030, 2050 and 2085 time horizons, respectively. The 20-22°C threshold was selected for all simulations using a 2030 weather file as during the recent summer heatwave of 2022, external temperature throughout the night did not fall below 20°C for several consecutive days (Kendon et al., 2021). Additionally, the percent of annual night time hours (10 pm - 7 am) above 26°C in the bedroom was also assessed and calculated as a percentage of total annual hours, taken from the second overheating criterion of the CIBSE *Technical Memorandum 59* (CIBSE TM59, 2017). A recent assessment of overheating in existing homes by Arup demonstrated that the majority of representative dwelling archetypes in the UK failed the CIBSE bedroom criterion under current climatic conditions (Arup, 2022). Therefore, the percent of annual night time hours exceeding additional indoor temperature thresholds of 27°C, and 28°C was also assessed. These thresholds may be applicable for people of different thermal sensitivities as an alternative to the largely unattainable 26°C threshold under the UK's future climate (Arup, 2022; Cui et al., 2022).

2.5 Vulnerability metrics

Population exposure to indoor climate and risk of fuel poverty was assessed using a number of vulnerability metrics. A review of population vulnerability to ambient temperature was carried out, included in the Appendix B, identifying four subgroups of the population who may bear a disproportionate risk from temperature-induced health impacts. These were identified as (i) infants aged 4 years old and under; (ii) individuals aged 65 years old and above; (iii) lower income individuals and (iv) ethnic minorities. A detailed rationale for the inclusion of these population subgroups is provided in Appendix B. As the UK Census does not collect information on income, data from the Department of Working Pensions (DWP) providing the number of individuals in receipt of Universal Credit per English and Welsh Lower Super Output Areas (LSOAs) and Scottish Data Zones was used as a proxy of low income. Universal credit is a means-tested social security payment for adults who are unemployed or on a low-income. The DWP dataset was not available for Northern Irish Output Areas. We, therefore, used the proportion of individuals with a personal income that is less than 60% of the national median income in Northern Ireland across Northern Irish SOAs (NISRA, 2018). Population estimates of age were taken from the 2021 UK Census for English and Welsh LSOAs (ONS, 2021) and the National Records of Scotland for 2021 for Scottish Data Zones (NRS, 2022). For Northern Ireland, population age estimates from the Census were not available for small areas. We, therefore, use banded population estimates for Northern Irish SOAs from the Northern Ireland Statistics and Research Agency (NISRA) (NISRA, 2020). As population estimates were banded (for example, 0 – 15, 16 – 45, 45 – 65 and 65 and above), it was not possible to get estimates for infants aged 0 – 4 years old as was done for English, Welsh and Scottish OAs. We therefore assess vulnerability for all those in the 0 – 15 years old age band. A summary of the vulnerability metrics used and additional data sources to parameterise the model is outlined in Table 4.

To assess if these subgroups are subject to disproportionately high and low indoor temperatures, the mean indoor temperature and percent of annual night time hours the bedroom temperature exceeded a given threshold was calculated for each output area. Each output area was then linked to the latest available population estimates, which provides the number of individuals in each subgroup and a population weighted mean was calculated using Equation 1:

$$1)\ \tilde{x} = \frac{\sum x_i \times W_i}{\sum W_i}$$

Where $\bar{x}$ is the population-weighted mean indoor temperature or overheating rate (%), x represents a mean indoor temperature for each LSOA, i, and W is the weight associated with each indoor temperature, in this case the frequency of each of the four population subgroups per LSOA.

To assess disparities in Energy Use Intensity (EUI) between different population groups, we calculate the average EUI for the 20% of output areas with the largest population of each subgroup outlined in Table 4 and compare this to the average EUI in the 20% of output areas with the smallest population of each subgroup. For example, in England, low-income individuals represent on average 17% of the population in the 20% of LSOAs with the highest proportion of this subgroup, compared with an average of 2.5% of the population in the 20% of LSOAs with the smallest proportion of this subgroup. This metric has previously been used to assess social equity in household urban energy use interventions in the US (Tong et al., 2021).

The socioeconomic population data is primarily used to assess inequalities for shorter-term projections (for example, in the 2030 time horizon) as the spatial distribution of different population groups across the UK groups will likely change throughout the 21st century, but some analyses at later time horizons are provided in Appendix C for reference.

Table 4. Summary of datasets used to parameterise the housing stock model, define the building intervention uptake scenarios and assess inequalities in energy use and exposure to indoor summertime temperatures.

Model component	**Data**	**Definition**	**Source(s)**
Housing stock meta-model	Dwelling Energy Performance Certificate (EPC)	Buildings database describing the quality of building features and fabric efficiency	(DCLG, 2022; Energy Saving Trust, 2023)[a]
Building intervention scenarios	Income-derived air conditioning	• *England and Wales*: Net annual household income after housing cost, by Middle layer super output areas (MSOAs) • *Scotland*: Income deprivation rank, by Scottish Data Zones	(NISRA, 2018; ONS, 2020; SIMD, 2020)

Model component	Data	Definition	Source(s)
	uptake scenario	• *Northern Ireland*: Income deprivation rank, by Northern Irish Super Output Areas (SOAs)	
Vulnerability analysis	Individuals aged 65+	• *England and Wales: The frequency of the population aged 65 years and over, by LSOA* • *Scotland: The frequency of the population aged 65 years and over, by Scottish Data Zones* • *Northern Ireland: The frequency of the population aged 65 years and over, by Northern Irish SOAs*	(NRS, 2022; NISRA, 2020; ONS, 2021)
	Children / infants	• *England and Wales: The frequency of the population aged 0 – 4 years old, by LSOA* • *Scotland: The frequency of the population aged 0 – 4 years old, by Scottish Data Zones* • *Northern Ireland: The frequency of the population under 16 years old, by Northern Irish SOAs*	(NRS, 2022; NISRA, 2020; ONS, 2021)
	Ethnic minority[b]	England and Wales: The frequency of the population belonging to a racial or ethnic group outside of the majority white British population of the UK, by LSOA	(ONS, 2022)
	Low-income	• *England, Wales and Scotland: The frequency of individuals in receipt of Universal Credit per LSOAs.* • *Northern Ireland: The frequency of individuals earning an income which is more than 60% of the Northern Irish median income*	(DWP, 2022; NISRA, 2018)

[a]EPC data for Northern Irish Dwellings is not publicly available and was acquired from Northern Ireland's Department of Finance.

[b]Small-area estimates of population ethnicity data were not available for Scottish and Northern Irish output areas.

3. Results

3.1 England

3.1.1 Energy consumption for heating and cooling

The annual heating energy use across the English housing stock under each emission and retrofit scenario is shown in Table 5. Heating energy use is projected to decline throughout the 21st century as the ambient temperature increased, though differences were minimal under the same emission scenario (RCP 2.6). Retrofitting the stock led to a further decline in heating energy use for all emission scenarios, which were confirmed to be statistically significant using a two-sample, paired t-test (Pasek, 2022).

Table 5. Mean annual heating energy use in the baseline scenario and following energy efficiency measures, for the English housing stock at time horizons of 2030, 2050 and 2085 under 1.5ºC and 4.0ºC warming.

	Year	2030	2050	2085	
	RCP emission scenario	**2.6**	**2.6**	**2.6**	**8.5**
Annual heating energy use (kWh)	Baseline (mean + 95%CI)	13,107 (13,099 – 13,115)	12,826 (12,818 – 12,833)	12,619 (12,611 – 12,626)	10,453 (10,442-10,455)
	Retrofit (mean + 95%CI)	10,706 (10,699 – 10,713)	7,634 (7,627 – 7,640)	4,318 (4,311 – 4,324)	3,085 (3,079 – 3,089)
T-test between pre- and post-retrofitted stock	*p*-value	<0.00	<0.00	<0.00	<0.00
	Mean of differences (kWh)	2,471	5,513	8,330	7,397

The distribution of annual heating energy use by dwelling and wall type under 2030 RCP 2.6 emission scenario is shown in Figure 5. Annual heating energy use was higher for solid-walled properties and those with less attachment to other dwellings, such as detached and semi-detached dwellings, which is in agreement with existing studies (Liddiard et al., 2021).

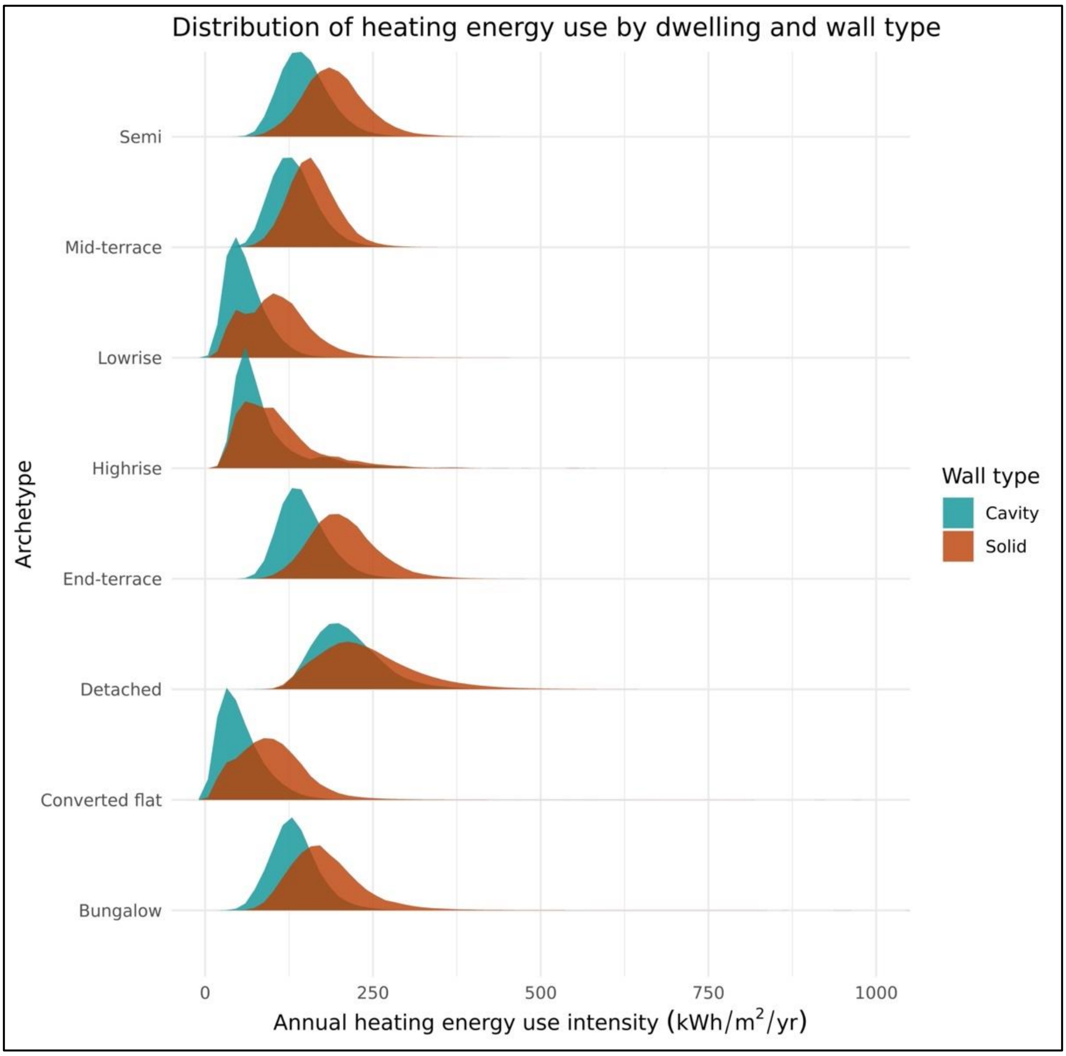


Figure 5. The distribution of heating energy use, by dwelling and wall type, under the RCP 2.6 emission scenario in 2030 for English dwellings.

Table 6 shows the percent decrease in heating energy use by dwelling archetype following the energy efficiency measures for all four emission scenarios. All archetypes saw a decrease in heating energy use following the energy retrofit under each of the four emission scenarios.

In general, properties which are on average older, such as terrace houses (ONS, 2022a), saw a smaller percent decrease in heating energy use. This speaks to concerns that a *blanket*-approach to modifying the stock may be unsuitable due to the diverse building ages and typologies comprise the housing stock (Duan & Pelsmakers, 2016). The majority of terrace homes in the UK were built before 1919, suggesting they would benefit from a higher retrofit standard as their baseline thermal efficiency is on average lower than other archetypes.

Table 6. Percent decrease in heating energy use following energy efficiency measures for the English housing stock, at time horizons of 2030, 2050 and 2085 under RCP 2.6 and 8.5.

Dwelling type	Mean percent decrease in heating energy use following retrofit (%)			
	2030 RCP 2.6	**2050 RCP 2.6**	**2085 RCP 2.6**	**2085 RCP 8.5**
Bungalow	18.4	43.9	69.7	74.8
Converted flat	31.1	54.5	71.1	73.9
Detached	14.1	42.7	67.4	72.2
End-terrace	19.2	37.7	65.9	69.7
Highrise	22.1	43.8	55.3	58.9
Low-rise	28.1	50.6	69.4	72.0
Mid-terrace	19.3	36.4	61.0	64.8
Semi	19.4	40.9	64.3	70.2

There were ~ 240,000 English dwellings that adopted air conditioning in 2030 under RCP 2.6, ~5 million in 2050 under RCP 2.6 and ~12 million in 2085 under RCP 2.6 and 8.5 emission scenarios. An analysis of cooling demand across each of the four retrofit scenarios for each year and emission is shown in Figure 6. Results suggest that cooling demand was offset the most by the use of external shutters in Scenario 2a, followed by internal blinds in Scenario 2b. Though external shutters generally outperformed internal blinds, internal blinds were similarly effective for some archetypes, such as detached properties. For example, across the English housing stock, average cooling demand under RCP 8.5 in 2085 was 30% higher in Scenario 2b compared with Scenario 2a, but for detached and bungalow properties, the difference was 13% and 8%, respectively.

The effectiveness of adaptive occupant behaviour varied by dwelling type. For free standing dwellings with the ability to cross-ventilate, such as semi-detached and detached buildings, optimised window opening appears to reduce cooling demand in the two 2085 emission scenarios, RCP 2.6 and 8.5, when the uptake of this behaviour is greater across the housing stock (75%). Optimised window opening is less effective in flats, due to their reduced ability to cross ventilate and a proportion of ground floor flats having kept windows closed in Scenario 4 due to security concerns.

There is a considerably large increase in cooling demand for bungalows in Scenario 4. This is because a larger proportion of this dwelling type were assumed to keep windows closed, again due to security concerns stemming from having a bedroom on the ground floor. Surface albedo modification appears to be least effective in homes which are able to optimise window opening behaviour: For dwellings which were assumed to have bedrooms on the second floor or above (semi-detached, mid-terraces, end-terraces and detached properties), surface albedo modification appears to be the least effective building intervention at the later time horizons (2050s, 2085s) when building interventions are more widespread across the housing stock, with reasons for this discussed below.

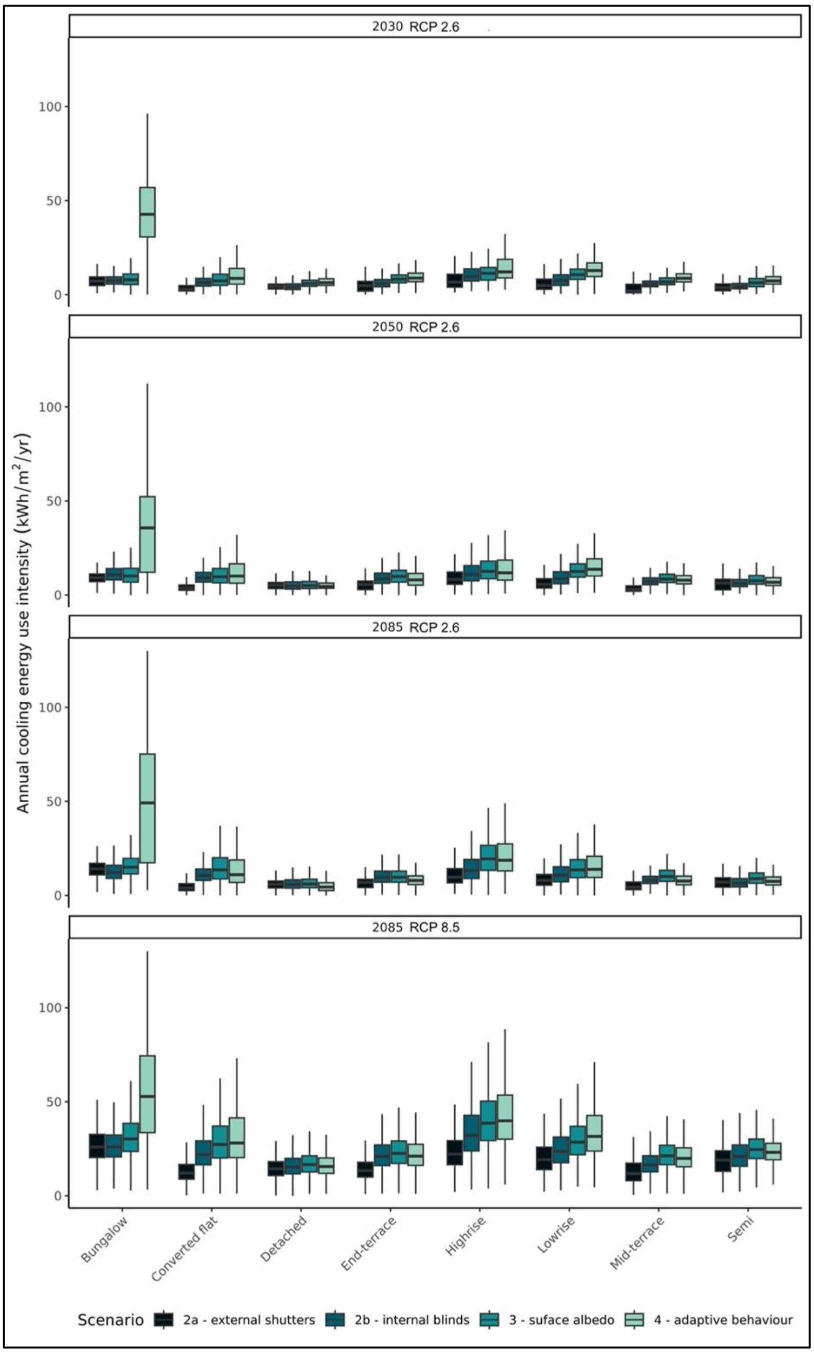


Figure 6. The distribution of cooling energy use intensities by English dwelling type, across the four building intervention scenarios for each time horizon and emission scenario: in 2030 under RCP 2.6 (top), 2050 under RCP 2.6 (mid-top) and 2085 RCP 2.6 (mid-bottom) and 8.5 emission scenarios (bottom figure).

3.1.1.1 Energy consumption by population group

To assess how heating energy use was distributed across different population subgroups, we calculate the annual mean Energy Use Intensity (EUI) in kWh/m^2/yr for English LSOAs. Results were linked to the area-measures of vulnerability outlined in Table 4 and aggregated by region. Figure 7 shows that EUIs are higher in areas with a greater proportion of over 65s and lower in areas with a greater proportion of lower-income individuals under the 2030s RCP 2.6 emission scenario. Differences in EUI disparities for those aged above and below 65 years old were largest in London, identifying a key area for the prioritisation of equitable domestic energy policy. A recent Age UK report found fuel poverty rates in London were higher amongst over 50s than other areas of England (Age UK, 2022). For ethnic minorities, the calculated EUI was greater in LSOAs with a lower ethnic diversity for all regions, except the East and West Midlands. The result suggest EUIs are *lower* in areas with a greater proportion of infants and lower income individuals across all English regions. The LSOA-average annual EUIs were highest in the East Midlands, and lowest in London, at 147 kWh/m^2/yr and 121 kWh/m^2/yr, respectively.

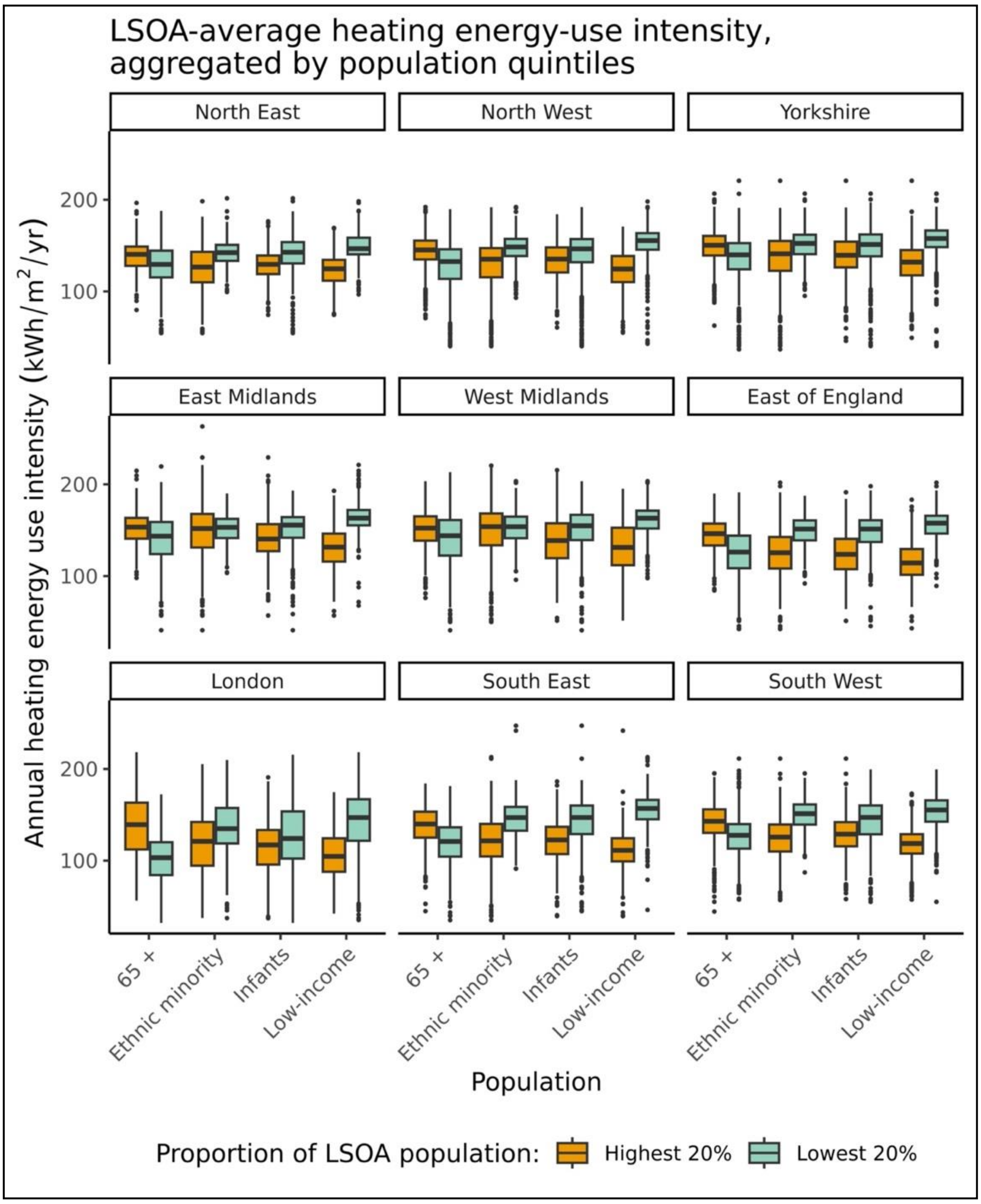


Figure 7. Mean heating energy use intensities aggregated by English LSOAs under 2030 RCP 2.6 emission scenario, aggregated by quantile of population vulnerability, showing the 20% of LSOAs with the lowest proportion of each vulnerable population (green) and the 20% with the highest (orange).

To assess if the energy efficiency measures installed in Scenarios 2-4 improved disparate EUIs under 2030 RCP 2.6 scenario, we compared EUIs for LSOAs with highest and lowest quintile of population proportions for each of the vulnerable subgroups outlined in Table 4, in the baseline versus retrofit scenario, shown in Figure 8. The results suggest whilst the retrofit measures reduced EUIs for all LSOA population quintiles, disparities persist without a retrofit programme specifically targeting subgroups who are at greater risk of fuel poverty.

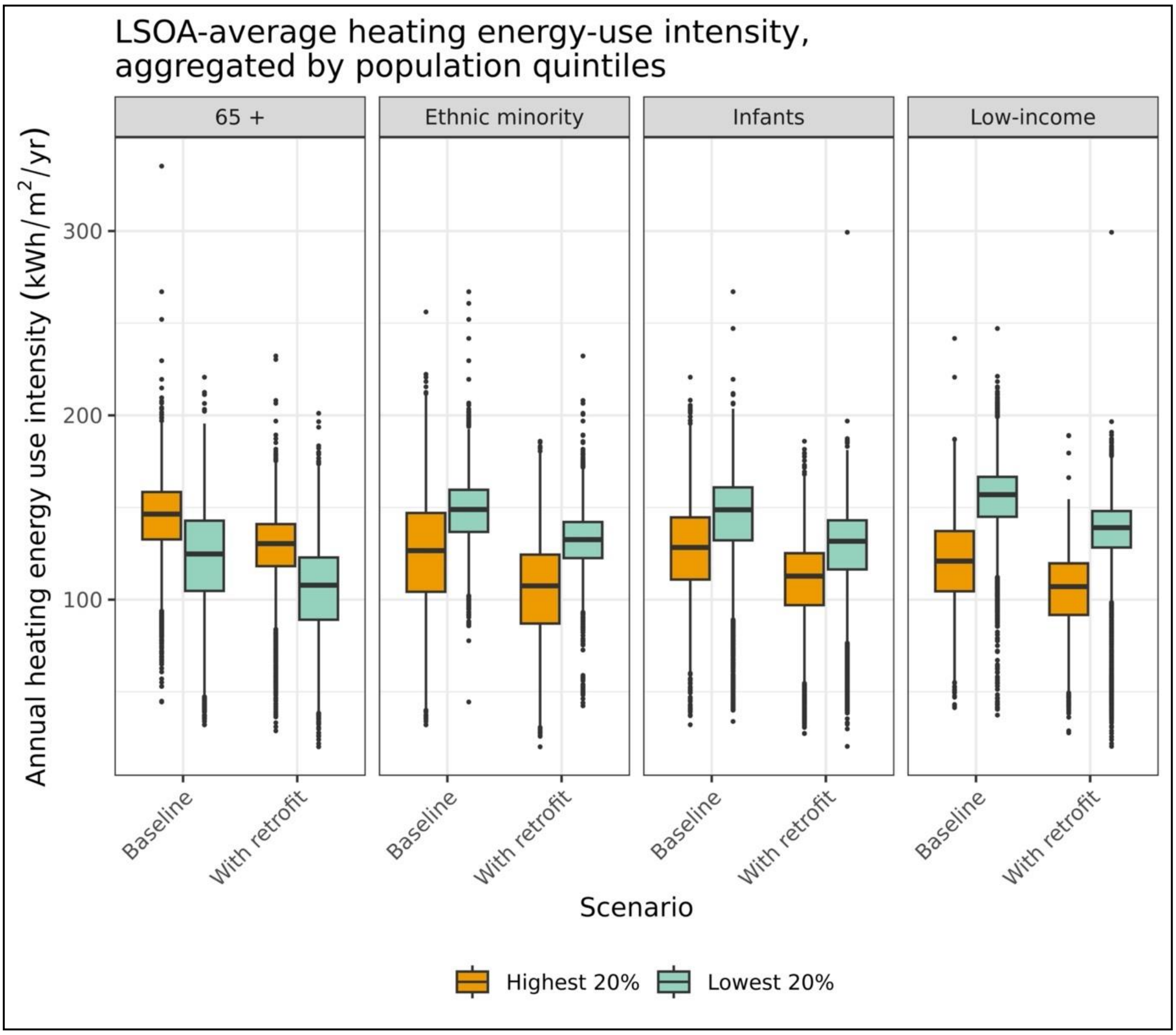


Figure 8. LSOA-average heating energy-use intensities (EUI) for each population subgroup under baseline English housing stock conditions and with retrofit measures under the 2030 RCP emission scenario.

Given the higher propagation of air conditioning across the stock in 2050 under the RCP 2.6 emission scenario compared to 2030, we model EUIs for domestic *cooling* by population subgroup in 2050, shown in Figure 9, though acknowledge the spatial distribution of each subgroup is likely to have changed by 2050. The figure shows that LSOAs which presently have a greater proportion of minorities, infants and low-income individuals generally have higher domestic EUIs for cooling in 2050, apart from in Scenario 2a (external shading). The use of internal blinds in Scenario 2b is most effective at reducing EUIs for cooling in areas with a high proportion of over 65s. This may be due to the higher effectiveness of this overheating mitigation measure in detached dwellings and bungalows (Figure 6), which are more commonly found in neighbourhoods with a high proportion of this population subgroup. Results for cooling EUIs in 2085 under the RCP 8.5 emission scenario are included in Appendix C and largely mirrored the results shown in Figure 9, but overall EUIs were higher due to the greater cooling demand under this emission scenario.

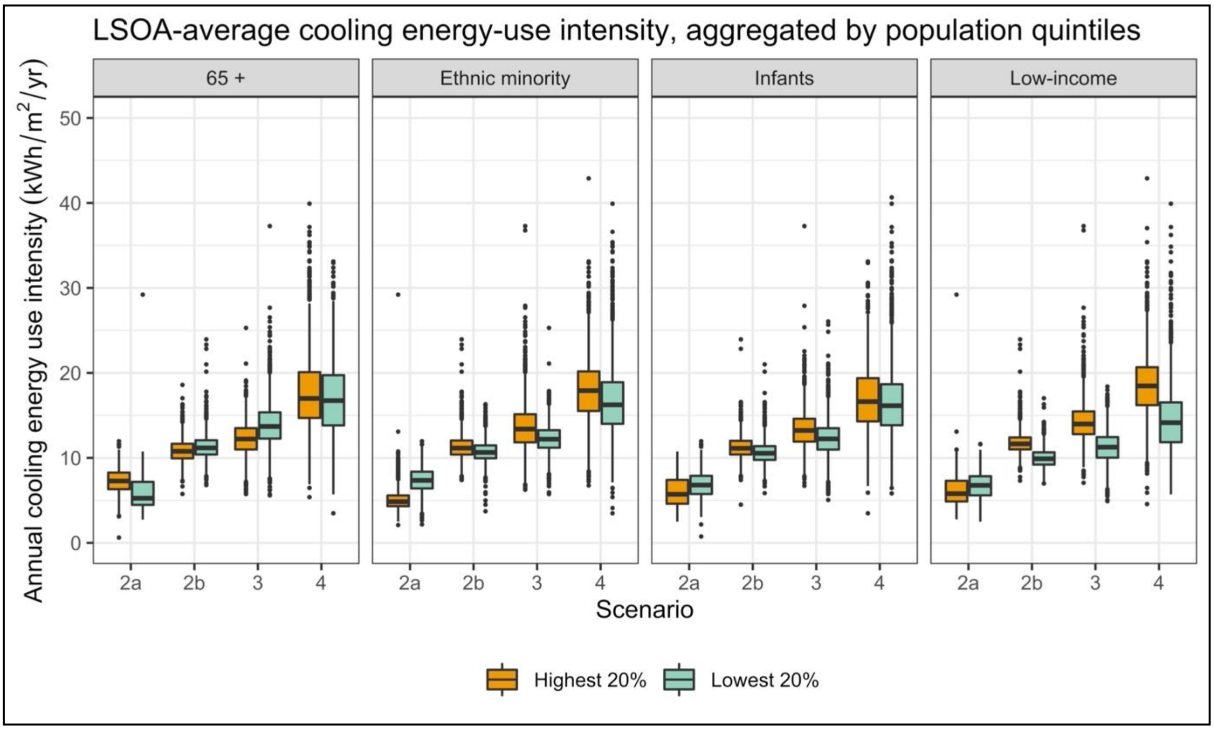


Figure 9. LSOA average cooling energy-use intensities (EUIs) for English LSOAs, aggregated by population quintiles in scenarios 2a - 4, in the 2050s time horizon under RCP 2.5 emission scenario.

3.1.2 Summertime indoor temperatures

An analysis of indoor overheating by dwelling type for all emission scenarios is shown in Figure 10. The figure shows the percent of nocturnal bedroom hours (10pm – 7am) the three indoor temperature thresholds were exceeded by. Across the housing stock, with no building interventions, all dwellings failed CIBSE TM59 bedroom criteria, with the bedroom temperature exceeding 26°C for 14.3%, 15,4%, 16.1% and 21.8% of annual night time hours under 2030 RCP 2.6, 2050 RCP 2.6, 2085 RCP 2.6 and 2085 RCP 8.5 emission scenarios, respectively. The figure suggests dwellings with less attachment (bungalows, detached properties) are on average cooler, exceeding the indoor threshold for a lower percent of annual night time hours. Flats and terraced homes were warmer and spent more hours above the indoor threshold. Notably, overheating levels vary significantly across the storey levels of the different flat archetypes (shown via the error bars). For example, ground floor high rise flats spent on average 7.1% of annual night time hours above the 26°C temperature threshold in 2030 RCP 2.5 emission scenario, compared with 17% for top-floor high rise flats.

We additionally map the mean percent of annual night time hours the bedroom temperature exceeded 26°C across Greater London LSOAs in the 2030 and 2085 time horizon under RCP 2.6 and 8.5 emission scenario, respectively, in Figure 11. Greater London was selected as the use of the London outdoor weather file more accurately represents the outdoor conditions in this sample of dwellings. Results suggest that inner London LSOAs experience greater indoor overheating in the 2030 time horizon under RCP 2.6 emission scenario, especially in the east. By the 2085 time horizon under the RCP 8.5 emission scenario, inner, eastern and outer West London experience the highest indoor overheating.

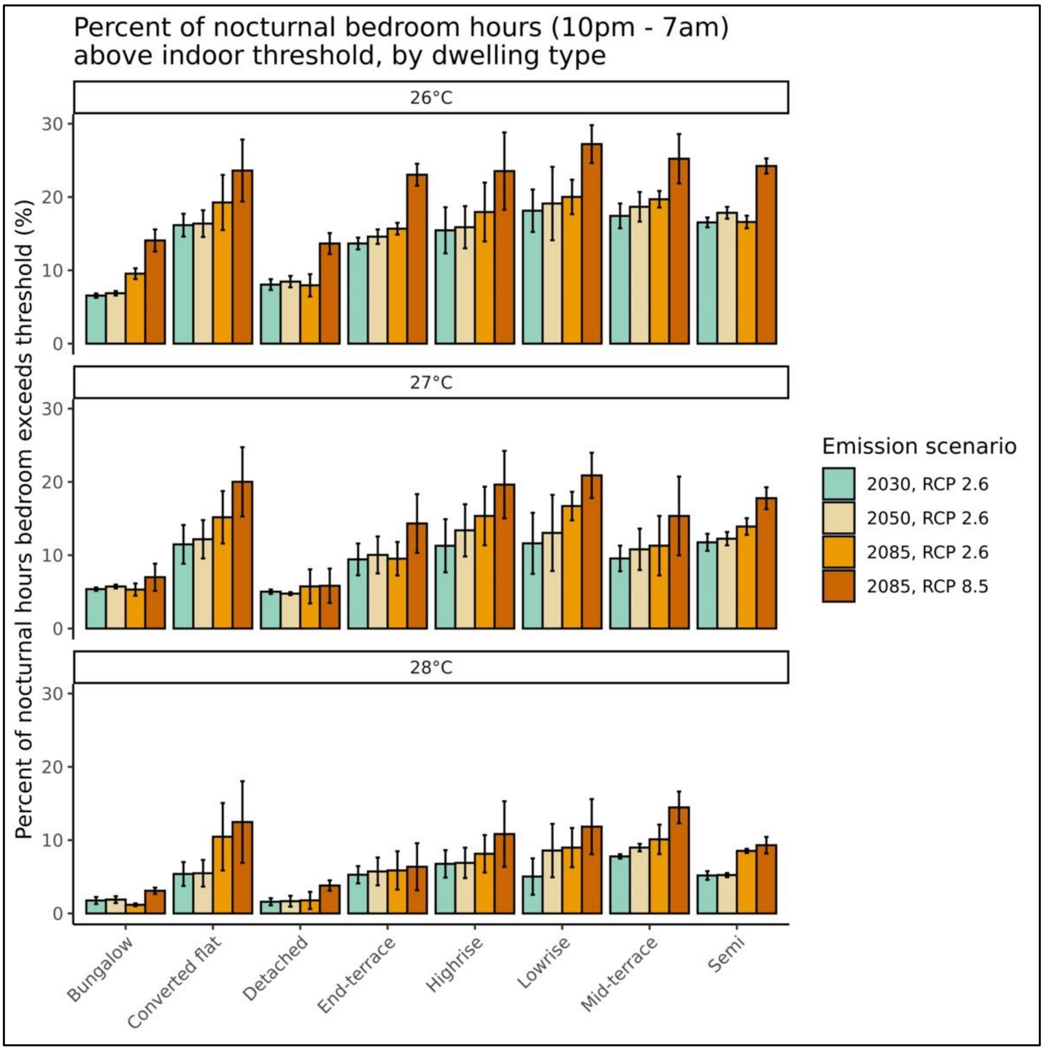


Figure 10. The percent of nocturnal (10pm - 7am) the bedroom temperature exceeded 26C, 27C and 28C, by dwelling type for the English stock at time horizons of 2030s, 2050s, 2085s RCP 2.6 emission scenario and 2085 RCP 8.5 emission scenario.

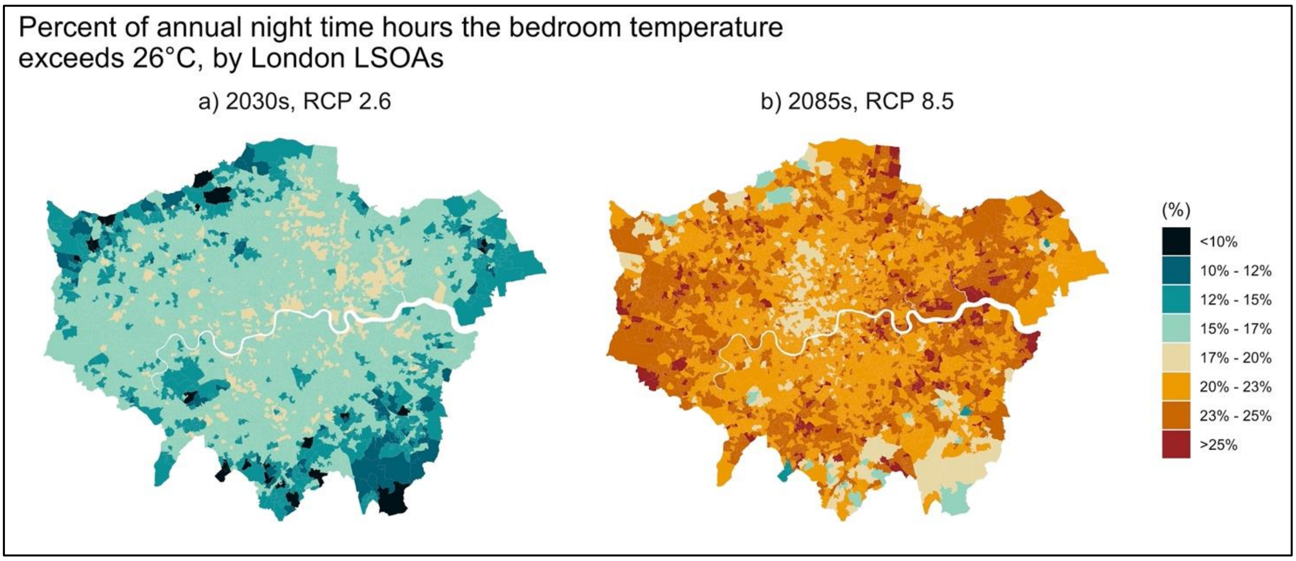


Figure 11. The mean percent of annual night time hours the nocturnal bedroom temperature exceeded 26C, aggregated by London LSOAs, in the a) 2030s time horizon under RCP 2.6, b) 2085s time horizon under RCP 8.5 emission scenario.

An analysis of the effect of each intervention on summertime overheating in the 1.5°C warming 2030s scenarios, by dwelling type, is shown in Figure 12A. The figure shows that shading devices, both external and internal, are most effective at reducing the percent of bedroom overheating, across all dwelling types. Adaptive window opening made minimal difference, which is consistent with other modelling studies (Taylor et al., 2018) and may again be due to its limited projected uptake across the housing stock in 2030 (25% of all dwellings with a bedroom on the second storey or above). However, for the 10% of homes with bedrooms on the ground floor where windows were assumed to stay closed, this led to a significant rise in the percent of annual night time hours above 26°C (Figure 12B).

Interestingly, surface albedo modification appeared to have little effect, possibly due to its small uptake across the stock in the 2030s RCP 2.6 emission scenario. This is contrary to existing findings in international studies (Carnielo et al., 2013; Mansouri et al., 2017). There may be a number of reasons behind this:

- The uptake of surface albedo modifications across the stock was limited in 2030, and primarily targeted at urban areas, where flats are more common and dwellings are generally smaller with limited opportunities for cross ventilation. The baseline temperature in these dwellings will, therefore, be higher than the baseline temperature in dwellings outside of urban areas.
- We combine the changes in surface albedo with widespread wall and roof insulation, in line with the Government's planned heating decarbonisation goals (BEIS, 2020). As insulation will limit heat

transfer through the building envelope, this will reduce the effectiveness of albedo modifications on indoor temperature.

- The EnergyPlus simulations from which the meta-model is derived do not account for changes in the *outdoor* temperature that can occur when the solar absorptance of buildings in reduced, which can be significant (Macintyre & Heaviside, 2019).

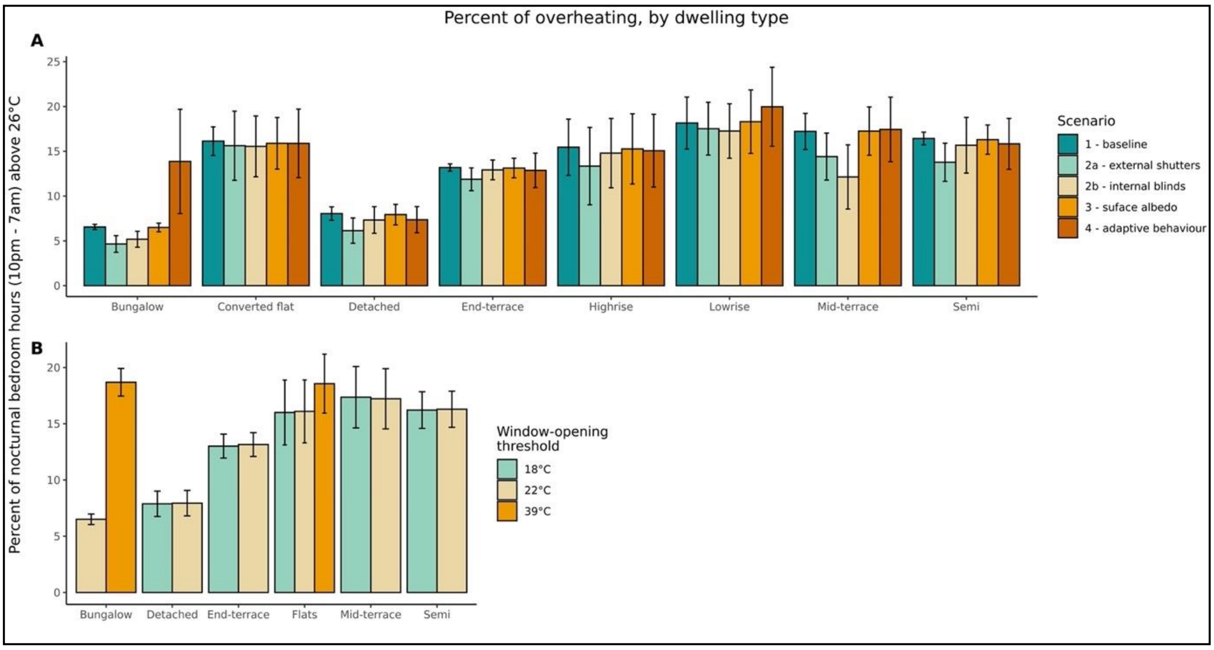


Figure 12. The percent of annual night time hours the bedroom temperature exceeded 26°C, by dwelling type, across all building intervention scenarios, in the 2030 time horizon under RCP 2.6 emission scenario. Figure 9B. The percent of annual night time hours the bedroom exceeded 26°C in Scenario 4, by dwelling type and with variable window-opening thresholds, in the 2030 time horizon under RCP 2.6 emission scenario.

As a proof of concept, we reduce the solar absorption coefficient in all dwellings across the English housing stock under baseline conditions in 2030 RCP 2.6 scenario. It is acknowledged that surface albedo modifications across the whole building stock are unrealistic. The results are shown in Figure 13. We find that reducing the solar absorption coefficient leads to lower levels of overheating, particularly in detached dwellings and bungalows which may receive outdoor heat transfer through all sides of the building façade. For flats and smaller dwellings with fewer outdoor façades, this intervention has limited effectiveness. This may be due to the model not accounting for changes in the outdoor temperature, which can have large impacts (Macintyre & Heaviside, 2019), as previously mentioned.

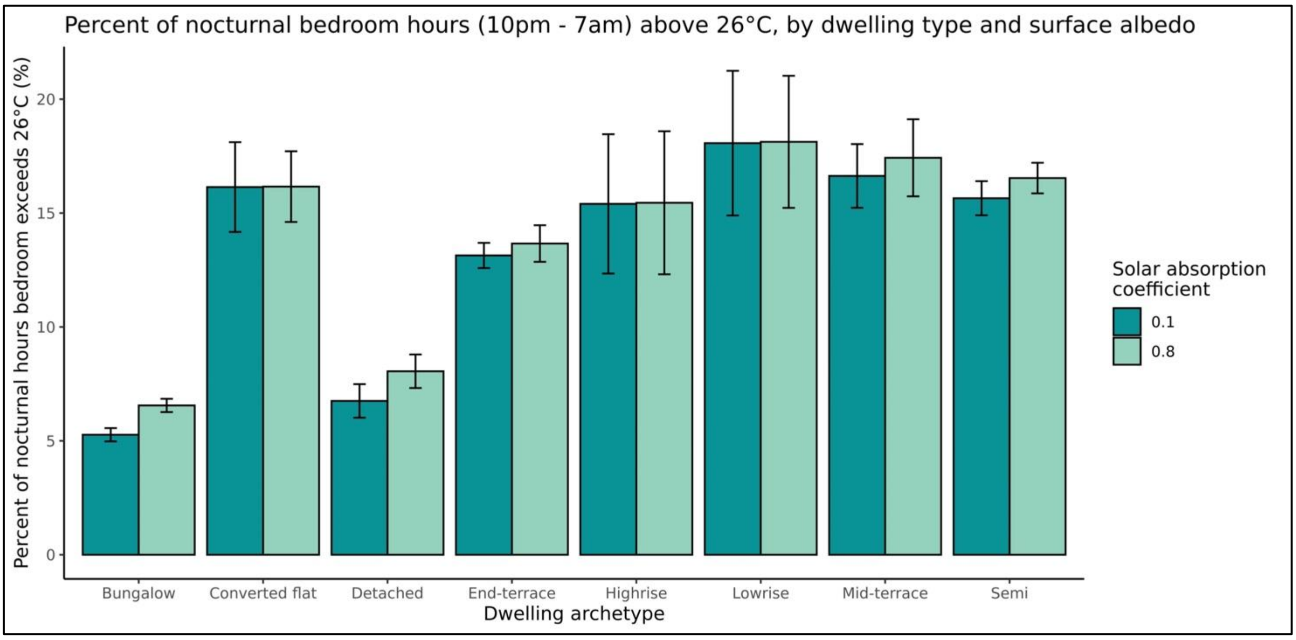


Figure 13. The percent of annual night time hours the bedroom temperature exceeded 26°C, by English dwelling types with different levels of solar absorption, in the 2030 time horizon under RCP 2.6 emission scenario.

Figure 14 shows an analysis of dwelling summertime overheating under 4.0°C warming in 2085 for each of the building intervention scenarios. The figure supports the findings from Figure 12A that internal and external shading are most effective at reducing overheating. Likewise with Figure 12B, keeping windows closed in dwellings with bedrooms on the ground floor causes significantly higher indoor overheating. Apartment from bungalows in Scenario 4, all dwellings saw decreases in the percent of nocturnal hours above 26°C, partly owing to the high uptake of air conditioning across the stock by 2085 (79%).

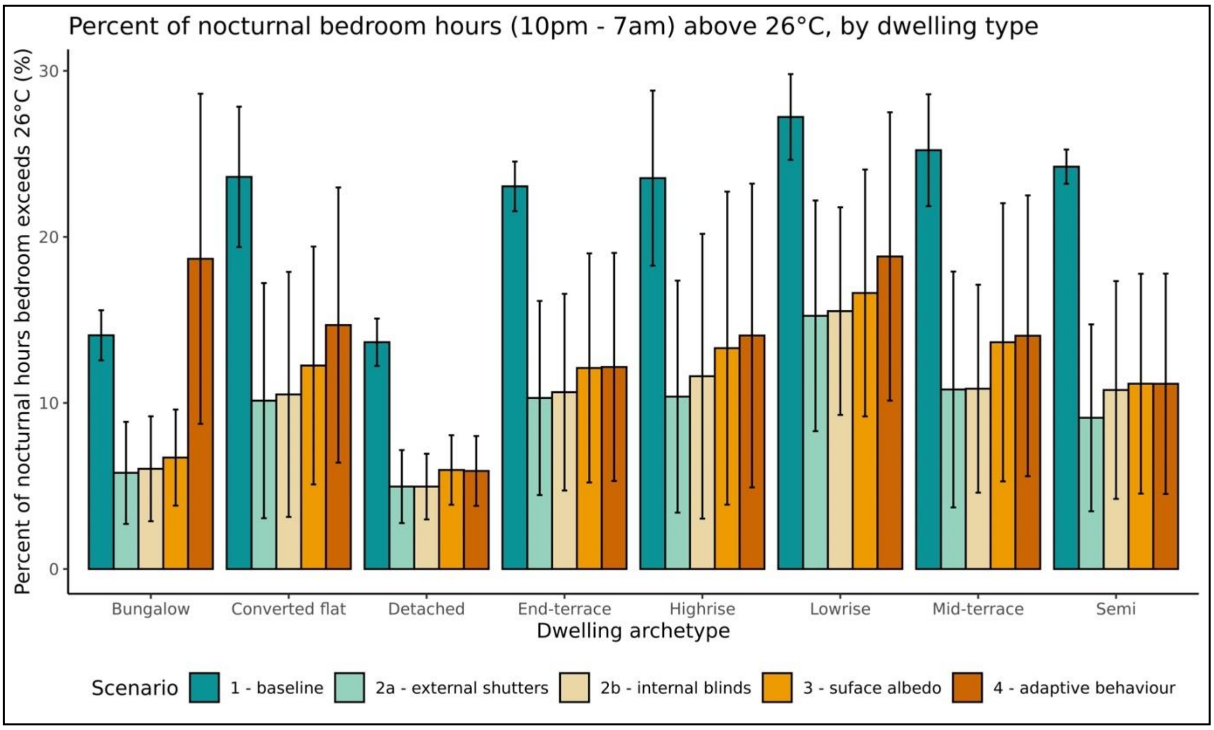


Figure 14. The percent of annual night time hours the bedroom temperature exceeded 26°C, by dwelling type, across all scenarios for the English housing stock, in the 2085 time horizon under RCP 8.5 emission scenario.

3.1.2.1 Overheating by population group

To assess population exposure to high summertime temperatures, the percent of nocturnal bedroom hours above the three thresholds is shown in Figure 15 under RCP 2.6 emission scenario in 2030 for each of the vulnerable population groups identified from the review. Results were aggregated by LSOA and a population-weighted mean percent of annual bedrooms hours above each threshold was calculated. Figure 15 shows the percent of annual night time hours the bedroom temperature exceeded 26°C, 27°C and 28°C across English LSOAs. The figure shows dwellings in areas with greater ethnic diversity, lower income individuals and infants (to a lesser extent) overall may spend a greater amount of annual night time hours above the three temperature thresholds. Differences were greatest for ethnic minorities versus non-ethnic minorities. Whilst dwellings located in areas with a greater number of those under 65 years old exceeded the bedroom temperature *less* than those located in areas with fewer over 65s, areas with a greater proportion of older individuals still experience high indoor temperatures during summer for a significant amount of time. This is concerning given the heightened vulnerability of this age group to high summertime temperatures (Arbuthnott & Hajat, 2017).

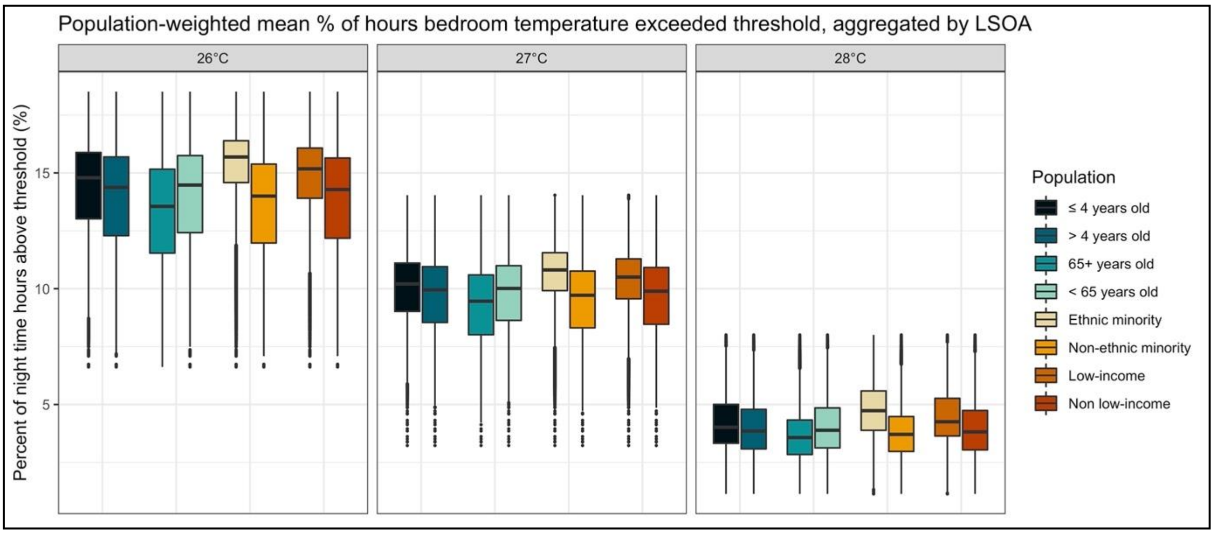


Figure 15. The percent of annual night time hours the bedroom temperature exceeded indoor threshold of 26°C, 27°C and 28°C, aggregated by English LSOAs and weighted for the different population groups in 2030 time horizon under RCP 2.6 emission scenario.

Additionally, a population weighted mean indoor temperature was calculated for each population subgroup under RCP 2.6 in 2030. The average nocturnal bedroom temperature (10pm – 7am) and the mean indoor temperature when the outdoor temperature is between 20 – 22°C was assessed and is shown in Figure 16. Whilst distributions have significant overlap for all population subgroups, the population weighted summertime bedroom temperature was significantly higher for areas with a higher proportion of ethnic minority and low-income groups versus non-ethnic minority and non-low income groups, respectively, in agreement with the findings shown in Figure 15.

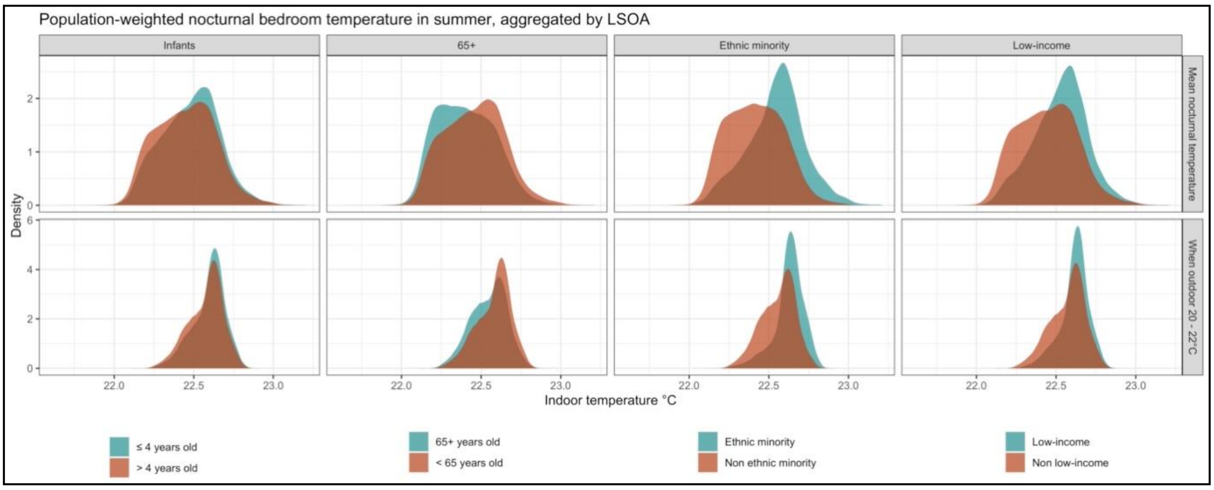


Figure 16. The distribution of population-weighted mean indoor temperatures in summertime across English LSOAs, in 2030s time horizon under RCP 2.6 emission scenario.

Figure 17 shows how each building intervention in Scenarios 2 – 4 affects the population-weighted mean nocturnal bedroom temperature for different subgroups. The figure shows that the use of external shutters in Scenario 2a reduces the divergence seen in the temperature distribution between vulnerable and non-vulnerable subgroups in Figure 16, suggesting it is most effective at reducing disparate exposures to high indoor temperatures during summer under 2030 RCP 2.6 emission scenario.

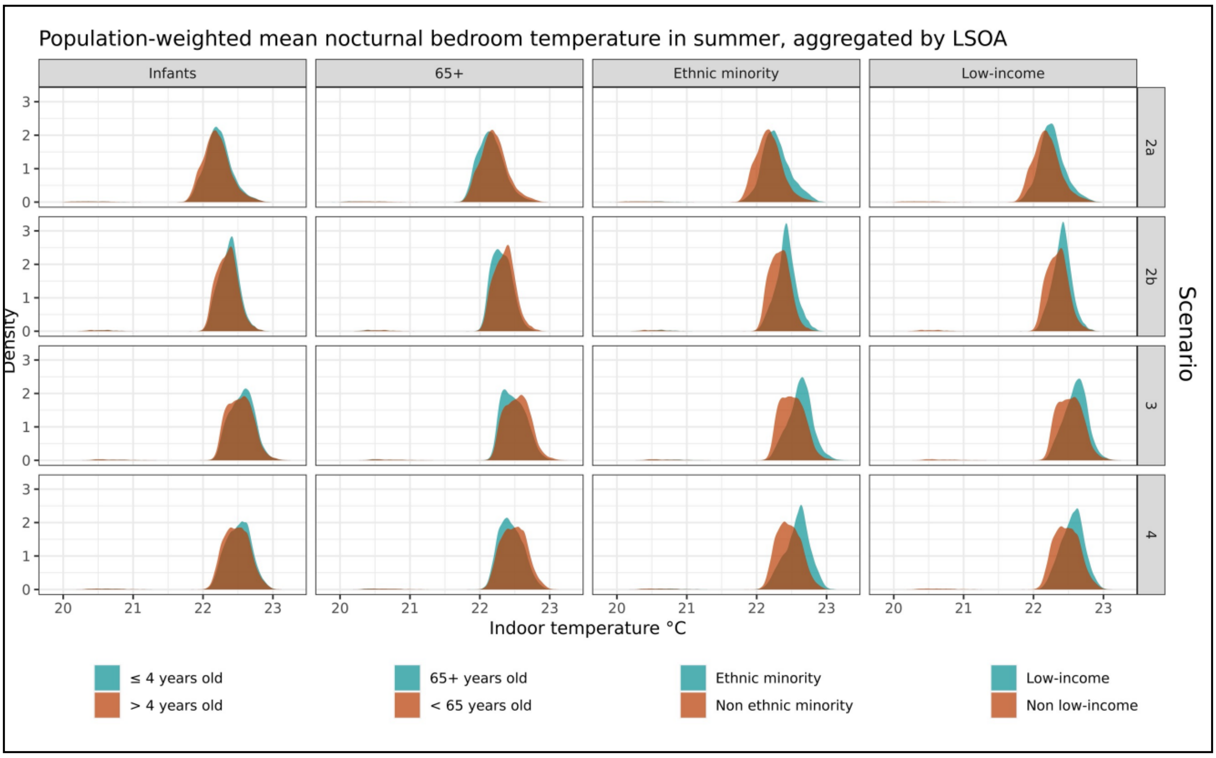


Figure 17. The population-weighted mean nocturnal bedroom temperature in summer for different population groups, across the four building intervention scenarios for English LSOAs, in 2030s time horizon under RCP 2.6.

3.2 Wales

3.2.1 Energy consumption for heating and cooling

The annual heating energy use across the Welsh housing stock under each emission and retrofit scenario is shown in Table 7. Alike with the English stock, heating energy use marginally declined throughout the 21st century under the same RCP 2.6 emission scenario. Domestic heating energy use was higher in Wales compared with England, supporting findings that the Welsh housing stock is the oldest and most inefficient in the UK (Piddington et al., 2020). Retrofitting the stock led to a larger decline in heating energy use for all time slices, which were confirmed to be statistically significant using a two-sample, paired t-test (Pasek, 2022).

Table 7. Annual heating energy use in the baseline scenario and following energy efficiency measures across the Welsh housing stock, at time horizons of 2030, 2050 and 2085 under RCP 2.6 emission scenarios.

	Year	2030	2050	2085
	Emission scenario	2.6	2.6	2.6
Annual heating energy use (kWh)	Baseline (mean + 95%CI)	16,979 (16,953 – 17,005)	16,691 (16,665–16,717)	16,480 (16,454 – 16,505)
	Retrofit (mean + 95%CI)	14,046 (14,023 – 14,069)	10,103 (10,084 – 10,122)	6,330 (6,316 – 6,345)
T-test between pre- and post-retrofitted stock	*p*-value	<0.00	<0.00	<0.00
	Mean of differences (kWh)	2,935	6,954	10,154

The distribution of heating energy use intensities by dwelling and wall type under RCP 2.6 in 2030 is shown in Figure 18. Alike with the English stock, larger, solid-walled properties have a higher EUI, representing a priority area for dwelling retrofit programmes. The small number of high rise dwellings in the Welsh EPC stock (*n*=133) resulted in a multi-modal distribution of heating energy use for this archetype.

Table 8 shows the mean percentage decrease in heating energy demand following the retrofit by the different dwelling types. All archetypes saw a decrease in heating energy use following the energy retrofit under each of the three year/emission scenarios. Reductions increased as uptake of retrofit measures increased between 2030-2050, in line with national decarbonisation retrofit programme.

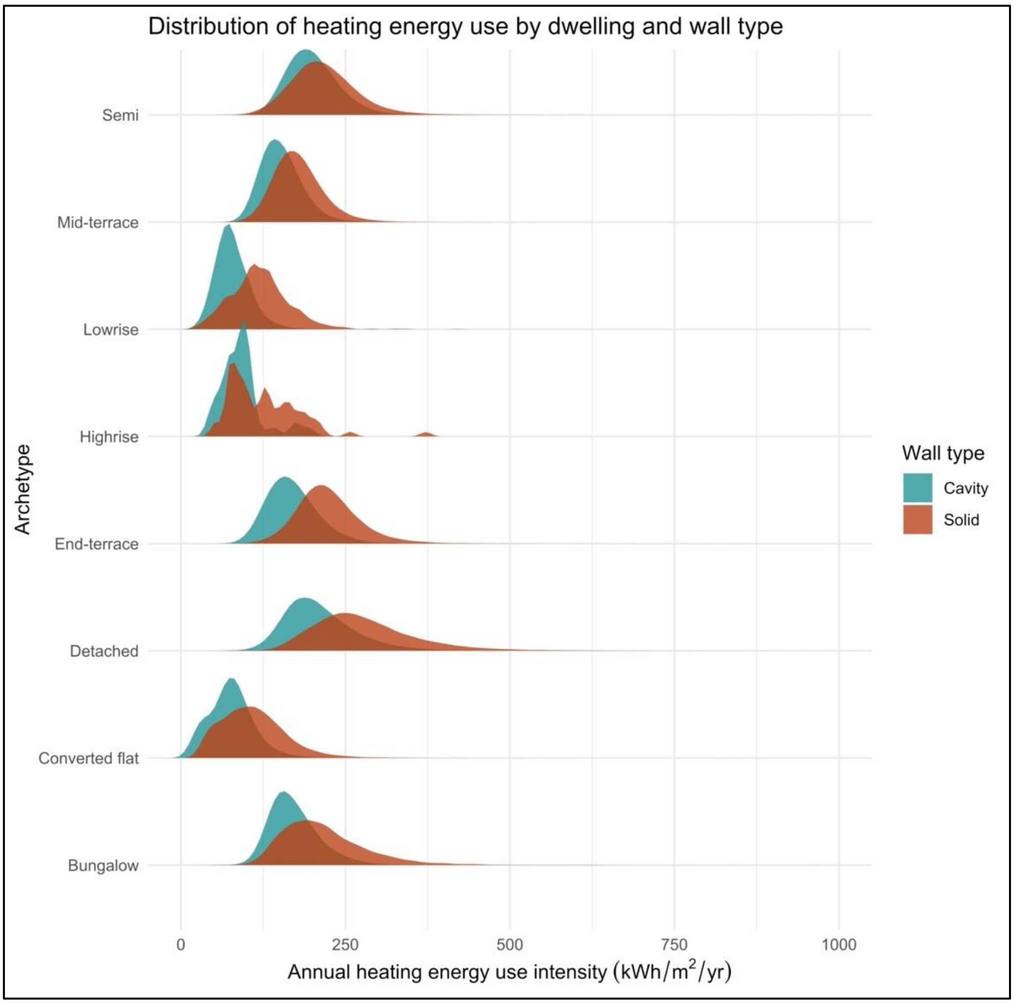


Figure 18. The distribution of heating energy use intensities (kWh/m^2/yr) by dwelling and wall type for the baseline Welsh housing stock, in the 2030 time horizon under RCP 2.6 emission scenario.

Table 8. Percent decrease in heating energy use following energy efficiency measures across the Welsh housing stock, at time horizons of 2030, 2050 and 2085 under RCP 2.6.

Dwelling type	Mean percent decrease in heating energy use following retrofit (%)		
	2030 RCP 2.6	2050 RCP 2.6	2085 RCP 2.6
Bungalow	13.9	39.2	64.0
Converted flat	21.6	42.4	64.0
Detached	16.9	46.4	65.7
End-terrace	19.9	37.1	60.0

Dwelling type	Mean percent decrease in heating energy use following retrofit (%)		
	2030 RCP 2.6	2050 RCP 2.6	2085 RCP 2.6
Highrise	14.8	38.9	48.0
Low-rise	21.8	44.9	68.3
Mid-terrace	18.6	32.8	56.5
Semi	16.3	36.4	59.4

There were ~13,000 dwellings assumed to have adopted air conditioning in 2030 under RCP 2.6, ~280,00 in 2050 under RCP 2.6 and 650,000 in 2085 under RCP 2.6 emission scenario across the Welsh housing stock. Figure 19 shows annual cooling energy use by dwelling type across the four building intervention scenarios. Alike with the English housing stock, the figure suggests shading devices reduce cooling demand the most. External shutters were most effective, although as shown in Figure 6 with the English stock, internal blinds may be similarly effective for free-standing dwellings such as detached properties and bungalows. Keeping windows closed in Scenario 4 caused cooling demand to rise in bungalows, though to a lesser extent than that seen across the English stock (Fig 5) due to the cooler outdoor climate of the Cardiff weather file versus London. Optimised window opening in properties with bedrooms on the second floor or above is generally more effective at offsetting cooling demand in the later scenarios when the uptake of this behavioural modification is more prevalent across the stock.

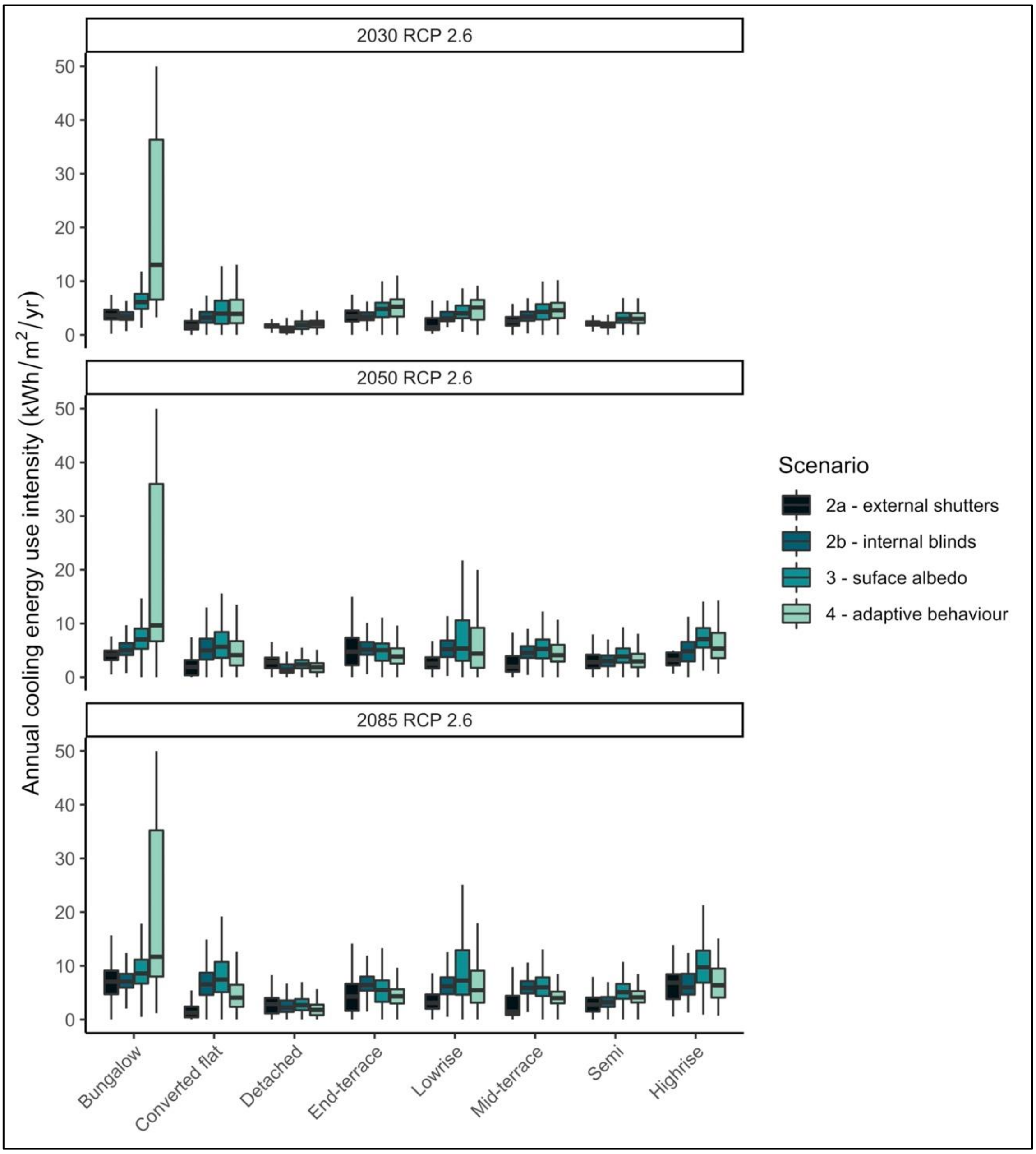


Figure 19. The distribution of cooling demand by dwelling type for the Welsh housing stock, across the four building intervention scenarios for each time horizon and emission scenario: in 2030s (top), 2050s (mid) and 2085s (bottom figure) under RCP 2.6 emission scenarios.

3.2.1.1 Energy consumption by population group

To assess how heating energy use was distributed across different population subgroups, the annual mean energy use intensity (EUI) in kWh/m^2/yr was calculated for Welsh LSOAs and linked to the area-measures of vulnerability outlined in Table 4. Figure 20 shows that EUIs are higher in areas with a greater proportion of over 65s and lower in areas with a greater proportion of under 5s, lower income individuals and ethnic minorities under the 2030s RCP 2.6 emission scenario. The mean dwelling EUI across Welsh homes was 179.6 kWh/m^2/yr, higher than that of English homes, again supporting findings that the Welsh housing stock is older and less efficient (Piddington et al., 2020).

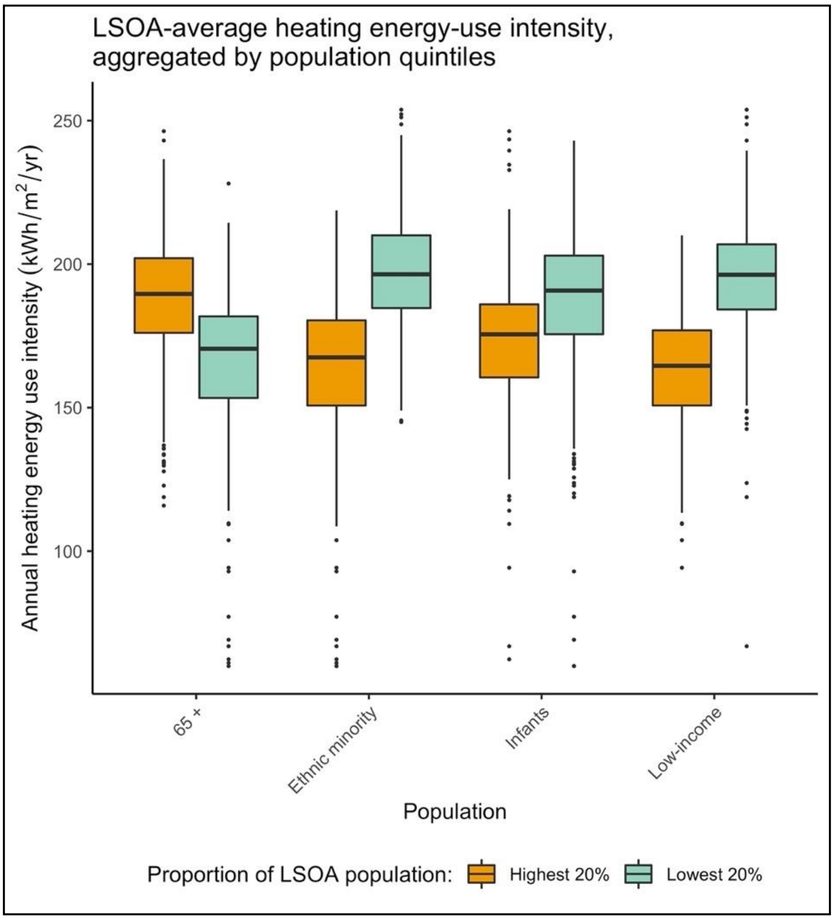


Figure 20. Mean heating energy use intensities aggregated by Welsh LSOAs under RCP 2.6 emission scenario in 2030, aggregated by quantile of population vulnerability, showing the 20% of LSOAs with the lowest proportion of the each vulnerable population (green) and the 20% with the highest (orange).

Likewise with the English housing stock, given the higher adoption of air conditioning in Welsh homes in 2050 compared to 2030, we model EUIs for domestic *cooling* by population subgroup under 2050 2.6 emission scenario, shown in Figure 21. The results vary to that of the English stock as, LSOAs with a greater proportion of minorities, infants and low-income individuals generally have higher domestic EUIs for cooling which are not always reduced by the widespread use of external shading. Keeping the windows closed in homes with a bedroom on the ground floor in Scenario 4 caused cooling EUIs to increase significantly, which exacerbated inequalities for those aged 65+ and lower-income individuals due to these population groups being more likely to occupy flats and bungalows (DCLG., 2016; Ferguson et al., 2021). Cooling EUIs were overall lower across the Welsh housing stock due to the cooler outdoor climate from the Cardiff versus London weather file.

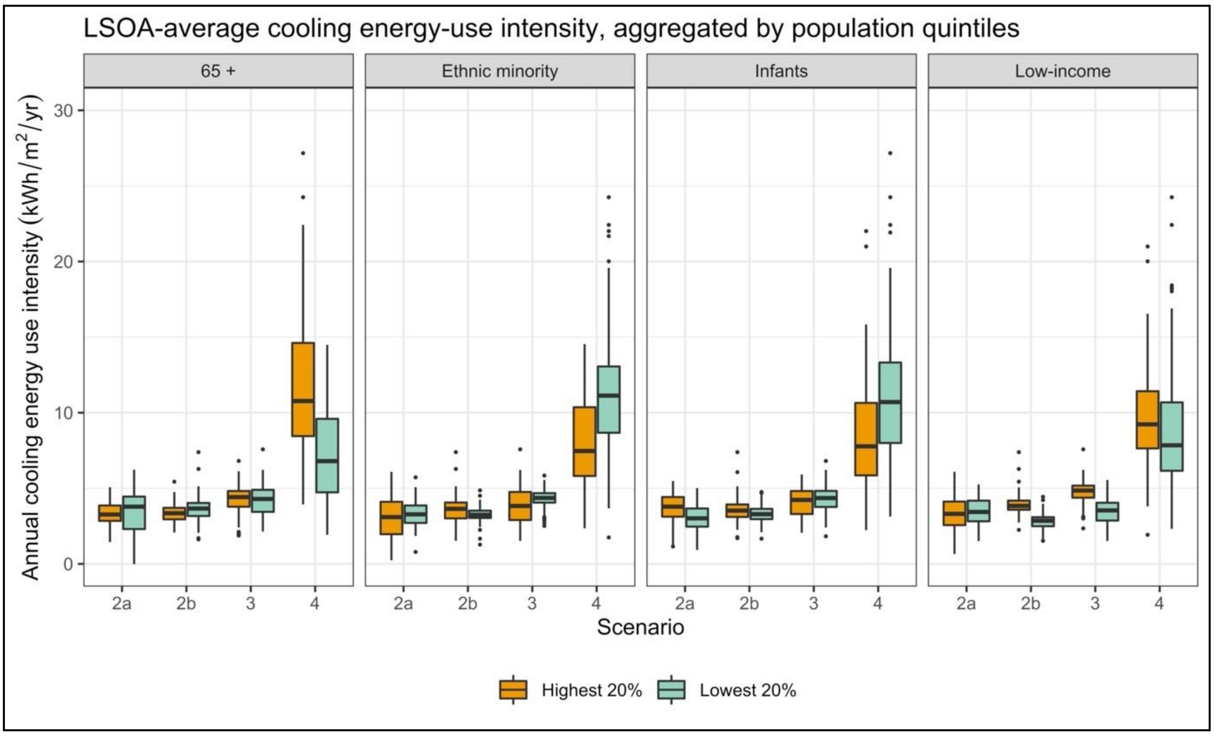


Figure 21. Welsh-LSOA average cooling energy-use intensities (EUIs) by population quintiles in scenarios 2a - 4, in the 2050s time horizon under RCP 2.6.

3.2.2 Summertime indoor temperatures

An analysis of indoor overheating by dwelling type under all year/emission scenarios is shown in Figure 22. Results suggest the percent of nocturnal bedroom hours (10pm – 7am) the three indoor temperature thresholds were exceeded by dwelling type. Across the housing stock, with no building interventions, all dwellings failed CIBSE TM59 bedroom criteria, with the bedroom temperature exceeding 26°C for an average of 12.2%, 13.0%, and 13.7% of annual night time hours under 2030, 2050 and 2085 RCP 2.6 emission scenarios, respectively. Differences are generally small due to the same emissions scenario across the three time horizons (RCP 2.6). The figure suggests dwellings with less attachment (bungalows, detached properties) are on average cooler, exceeding the indoor threshold for a lower percent of annual night time hours. Flats and terraced homes were warmer and spent more hours above the indoor threshold. Though there was a large amount of variation in overheating across the different flat archetypes (shown via the error bars), owing to the large variation across the different storey levels.

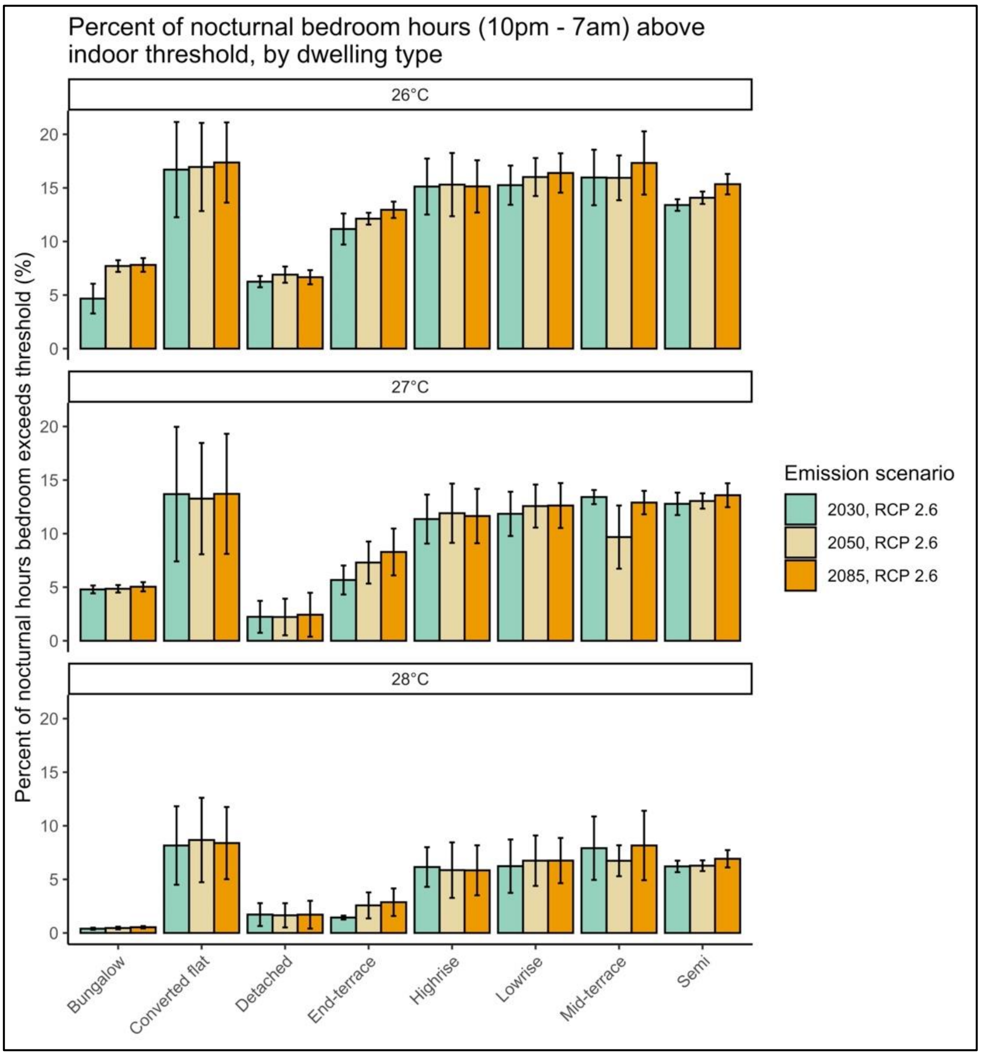


Figure 22. The percent of nocturnal (10pm - 7am) the bedroom temperature exceeded 26°C by dwelling type in Wales at time horizons of 2030s, 2050s and 2085s under RPC 2.6 emission scenario.

Figure 23 shows the effect of each intervention on summertime overheating under RCP 2.6 emission scenario in 2030, by dwelling type. The figure shows that shading devices, both external and internal, are most effective at reducing the percent of bedroom overheating, across all dwelling types. Results for the effect of each intervention under RCP 2.6 in 2050 and 2085 are available in Appendix C.

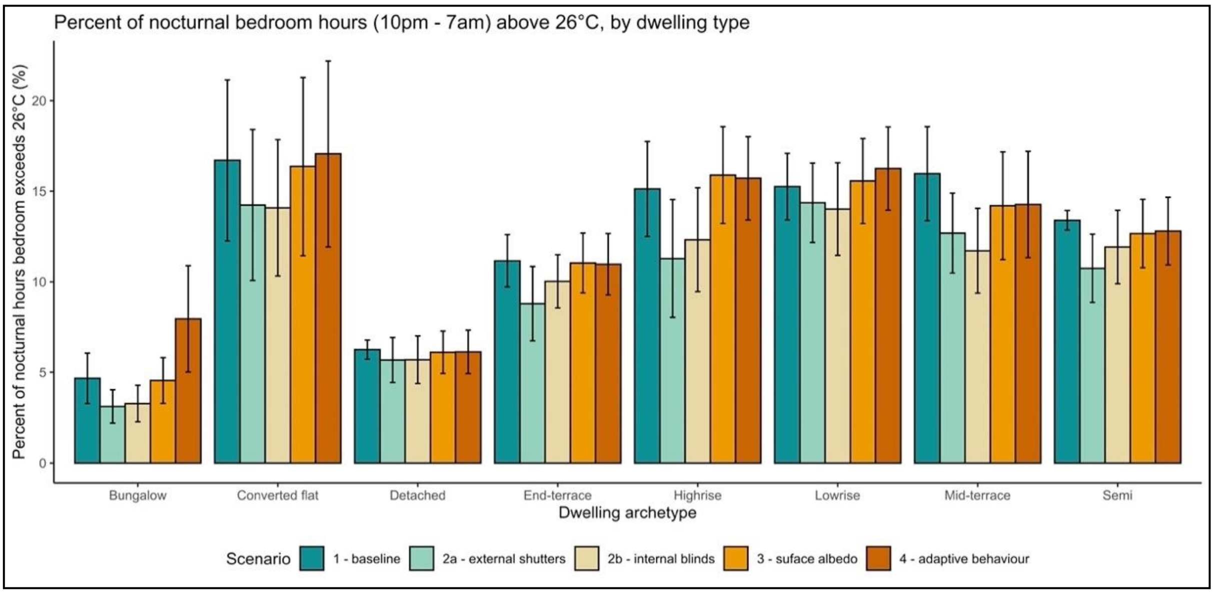


Figure 23. The percent of annual night time hours the bedroom temperature exceeded 26°C, by dwelling type, across all building intervention scenarios, under RCP 2.6 in 2030 for Welsh dwellings.

3.2.2.1 Overheating by population group

To assess population exposure to high summertime temperatures, the percent of nocturnal bedroom hours above the three thresholds is shown in Figure 24 under RCP 2.6 in 2030 for each of the vulnerable population groups identified from the review. Figure 24 shows the percent of annual night time hours the bedroom temperature exceeded 26°C, 27°C and 28°C across Welsh LSOAs, weighted for each subgroup. Likewise with the English stock, the figure shows dwellings in areas with a higher proportion of ethnic minorities, lower income individuals and infants (to a lesser extent) overall may spend a greater amount of annual night time hours above the three temperature thresholds.

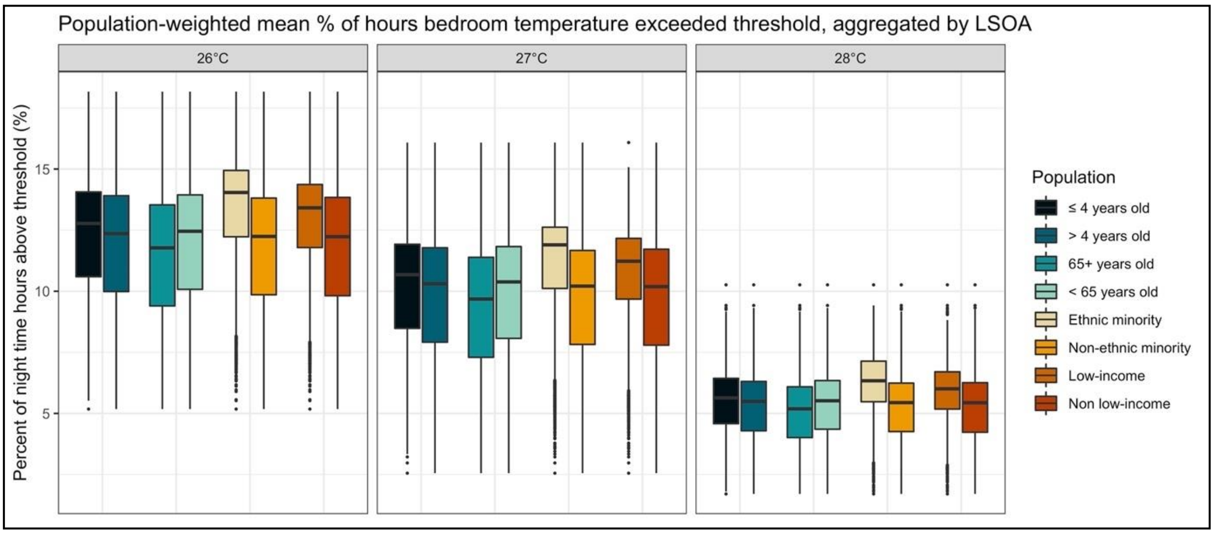


Figure 24. The percent of annual night time hours the bedroom temperature exceeded the indoor threshold of 26C, 27C and 28C, weighted for the different population groups across Welsh LSOAs in 2030s time horizon under RCP 2.6 emission scenario.

3.3 Northern Ireland

3.3.1 Energy consumption for heating and cooling

The annual mean heating energy use of Northern Irish dwellings pre- and post-retrofit is shown in Table 9 for each of the three time horizons. Alike with the English and Welsh results, heating energy use marginally declined in the baseline stock condition throughout the 21st century under the same RCP 2.6 emission scenario. The mean annual heating energy use in 2030 Northern Ireland was only 384 kWh higher than the annual mean for Welsh dwellings under the same conditions, despite the more northern climate of the Belfast versus Cardiff weather file, again likely supporting findings that Welsh homes are the oldest and poorest performing of the UK housing stock (Piddington et al., 2020). Retrofitting the Northern Irish housing stock led to declines in heating energy use for all time slices, which were confirmed to be statistically significant using a two-sample, paired t-test (Pasek, 2022).

Table 9. Annual heating energy use in the baseline scenario and following energy efficiency measures across the Northern Irish stock, at time horizons of 2030, 2050 and 2085 under RCP 2.6.

	Year	**2030**	**2050**	**2085**
	Emission scenario	**RCP 2.6**	**RCP 2.6**	**RCP 2.6**
Annual heating energy use (kWh)	Baseline (mean + 95%CI)	17,636 (17,597 – 17,675)	17,463 (17,424–17,502)	17,128 (17,089 – 17,166)
	Retrofit (mean + 95%CI)	16,182 (16,145 – 16,219)	12,585 (12,551 – 12,618)	7,835 (7,809 – 7,860)
T-test between pre- and post-retrofitted stock	*p*-value	<0.00	<0.00	<0.00
	Mean of differences (kWh)	1,453	4,878	9,293

The distribution of heating energy use intensities by dwelling and wall type under RCP 2.6 in 2030 is shown in Figure 25. Alike with results for England and Wales, homes with less attachment to other dwellings, such as detached properties and bungalows have higher annual heating energy use, especially those with solid walls. This is an important finding given that Northern Ireland has a much higher proportion of bungalows than the other three countries of the UK (Piddington et al., 2020), presenting a priority archetype for energy efficiency measures in Northern Ireland. Likewise, Table 10 shows the percent reduction in heating energy use following energy efficiency measures where bungalows saw the smallest reductions at each of the three time horizons, again suggesting this archetype should be prioritised under Northern Irish domestic Net Zero policies.

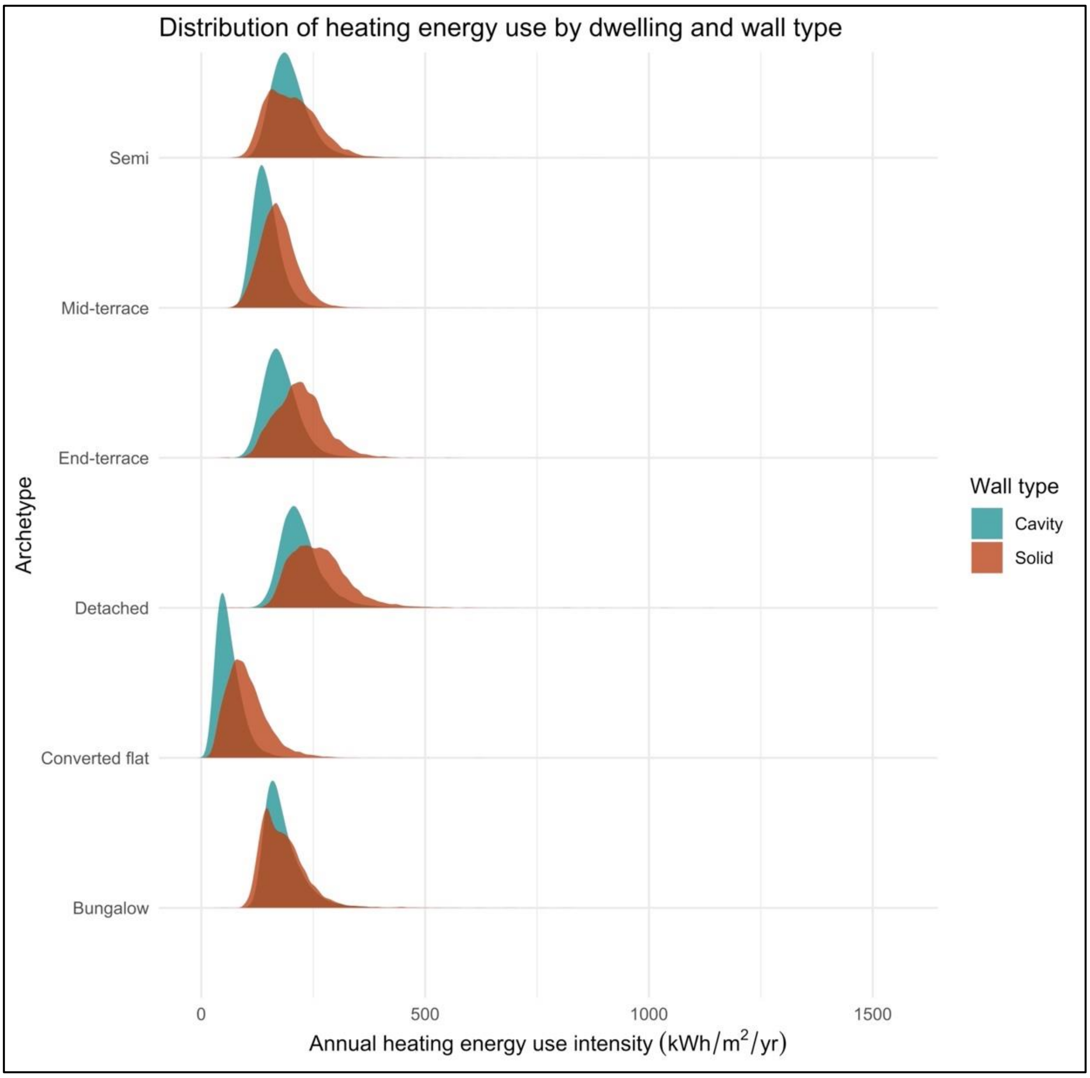


Figure 25. The distribution of heating energy use intensities (kWh/m²/yr) by dwelling and wall type for the baseline Northern Irish housing stock, in the 2030s time horizon under RCP 2.6.

Table 10. Percent decrease in heating energy use by dwelling type for Northern Irish dwellings, following energy efficiency measures, at time horizons of 2030, 2050 and 2085 under RCP 2.6.

Dwelling type	Mean percent decrease in heating energy use following retrofit (%)		
	2030 RCP 2.6	2050 RCP 2.6	2085 RCP 2.6
Bungalow	5.8	21.4	48.6
Converted flat	10.1	30.9	56.9
Detached	8.1	31.8	55.8

Dwelling type	Mean percent decrease in heating energy use following retrofit (%)		
	2030 RCP 2.6	2050 RCP 2.6	2085 RCP 2.6
End-terrace	8.9	24.6	55.3
Mid-terrace	10.5	26.2	55.5
Semi	8.3	31.4	55.8

There were ~6,000 dwellings that were assumed to have adopted air conditioning in 2030, ~100,000 in 2050 and 280,00 in 2085 under the RCP 2.6 emission scenario across the Northern Irish housing stock. Figure 26 shows annual cooling energy use by dwelling type across the four building intervention scenarios. The figure suggests shading devices reduce cooling demand the most. External shutters were most effective, although as shown in Figure 6 with the English stock, internal blinds may be equally effective for free-standing dwellings such as detached properties and bungalows. Keeping windows closed in Scenario 4 caused cooling demand to rise in bungalows, though to a lesser extent than that seen across the English stock (Figure 6) due to the cooler outdoor climate of the Belfast weather file versus London. Optimised window opening in properties with bedrooms on the second floor or above is generally more effective at offsetting cooling demand in the later scenarios when the adoption of this behavioural modification is more prevalent across the stock.

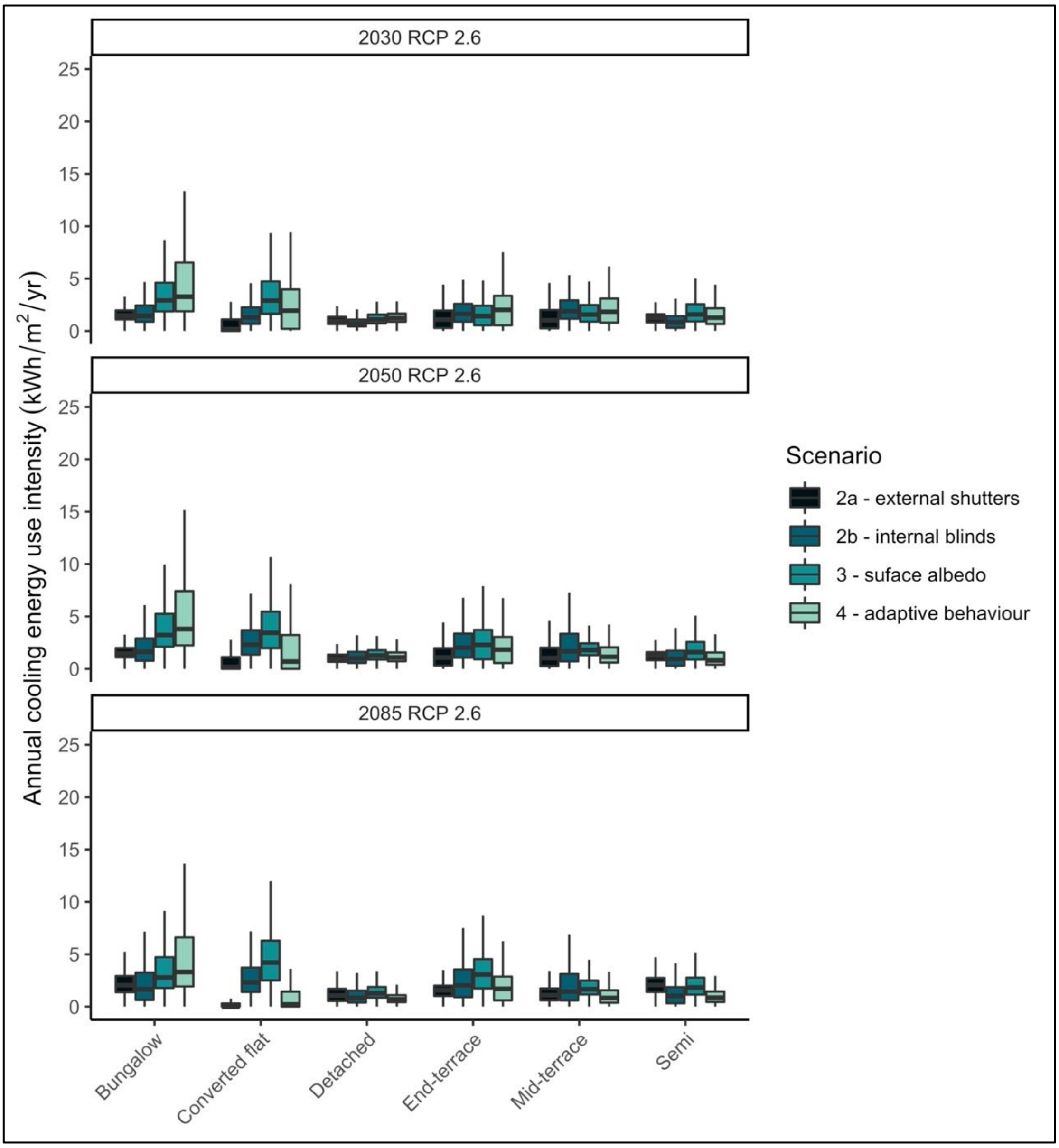


Figure 26. The distribution of cooling demand by dwelling type, across the four building intervention scenarios for each time horizon and emission scenario: in 2030s (top), 2050s (mid) and 2085s (bottom figure) under RCP 2.6 emission scenario, for the Northern Irish housing stock.

3.3.1.1 Energy consumption by population group

Figure 27 shows the distribution of annual heating energy use across Northern Irish SOAs, aggregated by population vulnerability. The figure suggests inequalities in heating energy use are less pronounced in Northern Ireland, despite the country having higher overall fuel poverty rates than England and Wales (Hinson & Bolton, 2022). Output areas with a high proportion of children have marginally higher heating EUIs than areas with a smaller childhood population across

Northern Ireland, which contrasts the findings in England and Wales, though this may reflect the slightly different metric used (proportion of <5 year olds in England and Wales compared with proportion of <16 year olds in Northern Ireland) due to the lack of data availability in Northern Ireland. This may place additional financial pressure on families with children, especially as Northern Irish homes are largely reliant on oil as their primary fuel source, which is more expensive (Piddington et al., 2020).

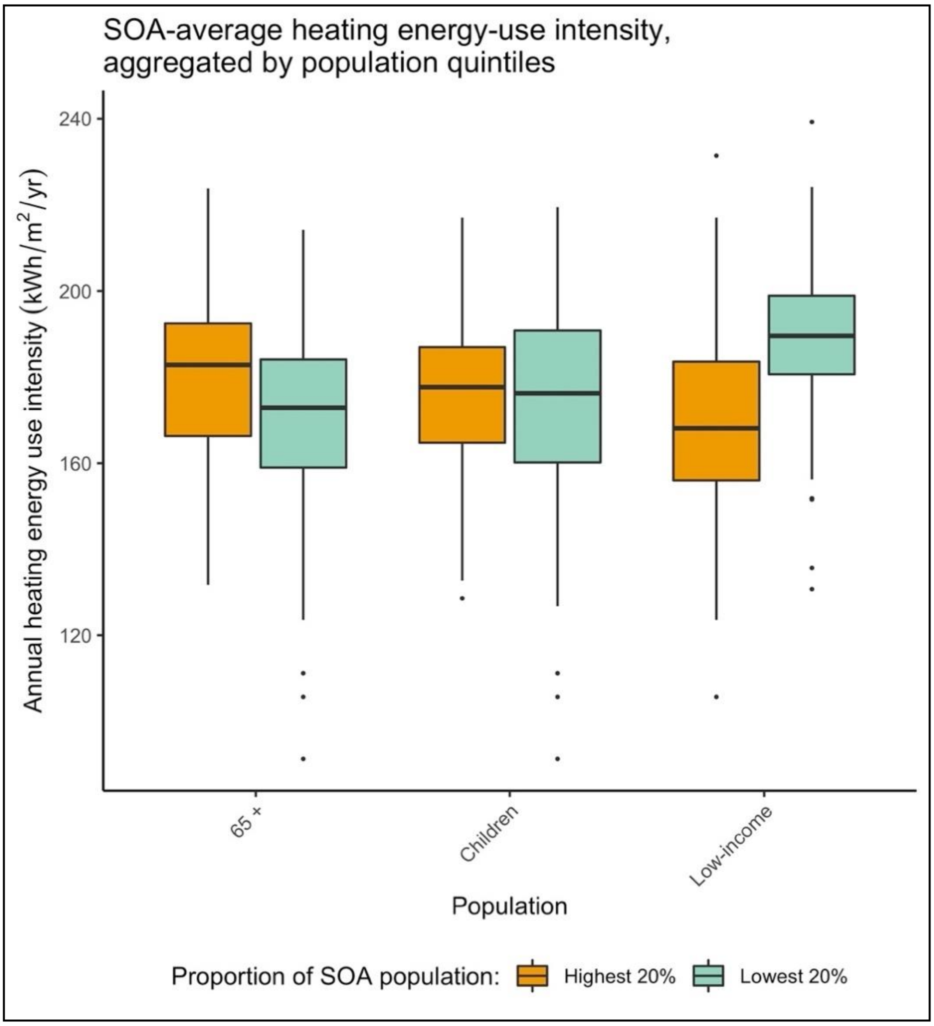


Figure 27. Mean heating energy use intensities aggregated by Northern Irish SOAs in 2030s under RCP 2.6, aggregated by quantile of population vulnerability, showing the 20% of SOAs with the lowest proportion of the each vulnerable population (green) and the 20% with the highest (orange).

Domestic cooling EUIs were modelled under 2050 RCP the 2.6 emission scenario, due to the higher uptake of air conditioning at this time horizons. Figure 28 suggests that keeping the windows closed in Scenario 4 causes EUIs to increase in output areas with a high proportion of those aged 65+ and low-income individuals, likely because of these population groups more likely to live in bungalows and flats (DCLG., 2016; Ferguson et al., 2021). Cooling EUIs were overall much lower for Northern Irish dwellings than in England and Wales due to the cooler climate of the Belfast weather file.

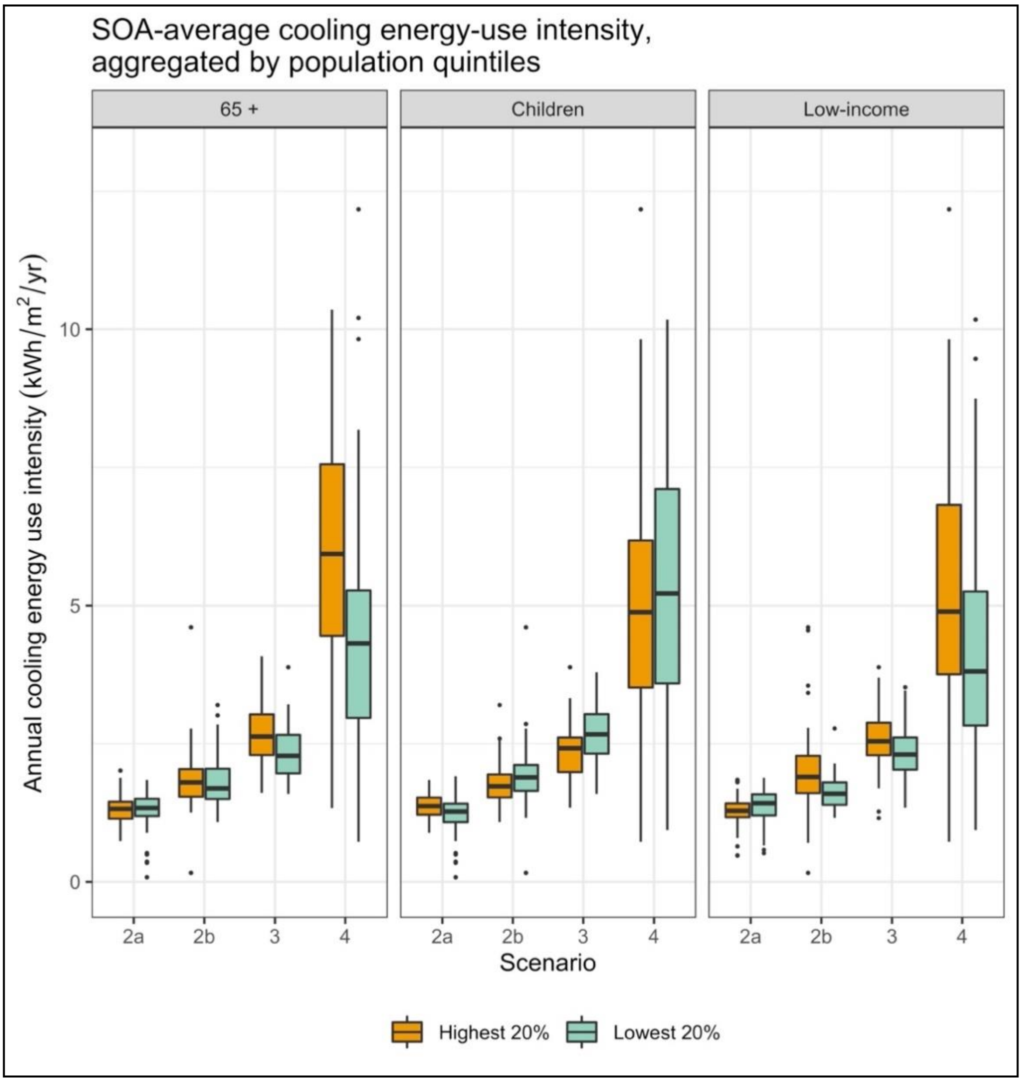


Figure 28. SOA average cooling energy-use intensities (EUIs) by population quintiles in Scenarios 2a - 4, in 2050s under RCP 2.6.

3.3.2 Summertime indoor temperatures

Figure 29 shows the shows the percent of nocturnal bedroom hours (10pm – 7am) the three indoor temperature thresholds were exceeded by dwelling type. Across the housing stock, with no building interventions, the bedroom temperature exceeded 26°C for an average of 9.4%, 9.6%, and 9.9% of annual night time hours under 2030, 2050 and 2085 RCP 2.6, respectively. Differences are generally small due to the same emission scenario across the three time horizons (RCP 2.6).

Flats and terraces buildings generally overheat more than buildings with less attachment to others, supporting the findings from England and Wales.

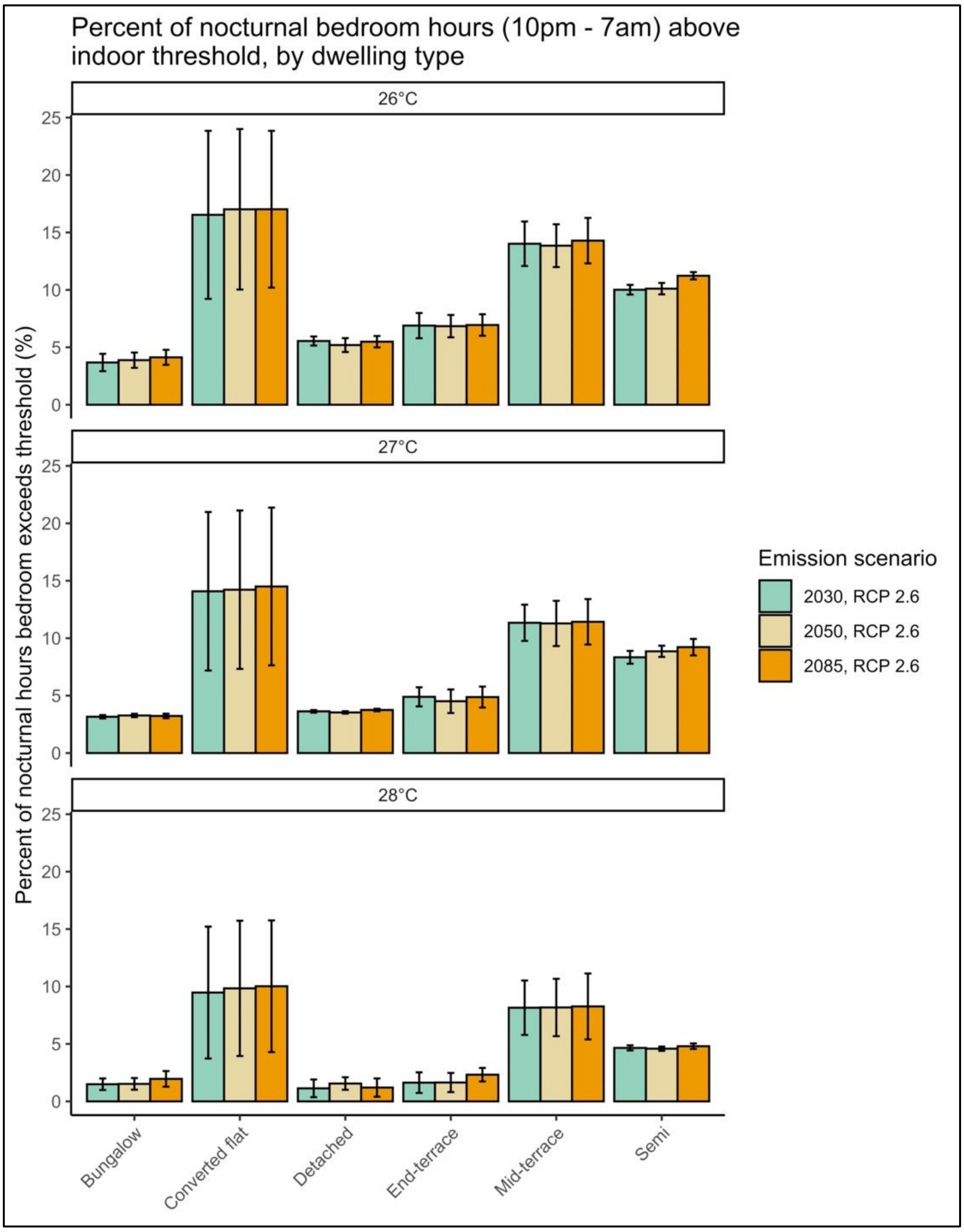


Figure 29. The percent of nocturnal (10pm - 7am) the bedroom temperature exceeded 26C, 27C and 28C by dwelling type for the baseline Northern Irish stock at time horizons of 2030s, 2050s and 2085s under RCP 2.6.

Figure 30 shows the effect of each intervention on summertime overheating under RCP 2.6 emission scenario in 2030, by dwelling type. The figure shows that shading devices, both external and internal, are most effective at reducing the percent of bedroom overheating, across all dwelling types. Results for the effect of each intervention at additional time horizons are available in Appendix C.

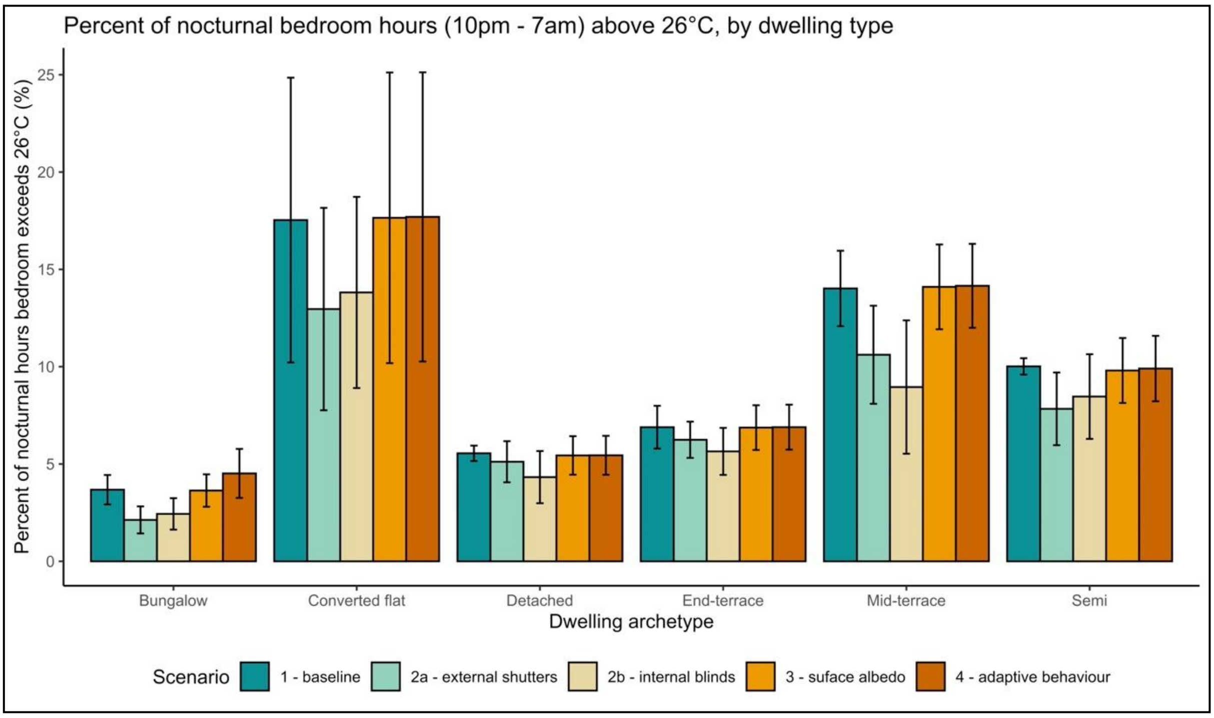


Figure 30. The percent of annual night time hours the bedroom temperature exceeded 26C, by dwelling type, across all scenarios for Northern Irish stock, at 2030s time horizon under RCP 2.6.

3.3.2.1 Overheating by population group

To assess if vulnerable subgroups bear a disproportionate risk from indoor overheating under future climate, Figure 31 shows the percent of annual night time hours the bedroom temperature exceed 26°C for different population groups in 2030 under RCP 2.6. The results show minimal differences in the percent of overheating experienced by each group. Northern Ireland has less income inequality than other areas of the UK (Tinson et al., 2016) and lower housing demand, meaning those with fewer resources, such as low income households and families, may be less likely to be priced out of larger, higher quality housing that is more resilient to summertime overheating.

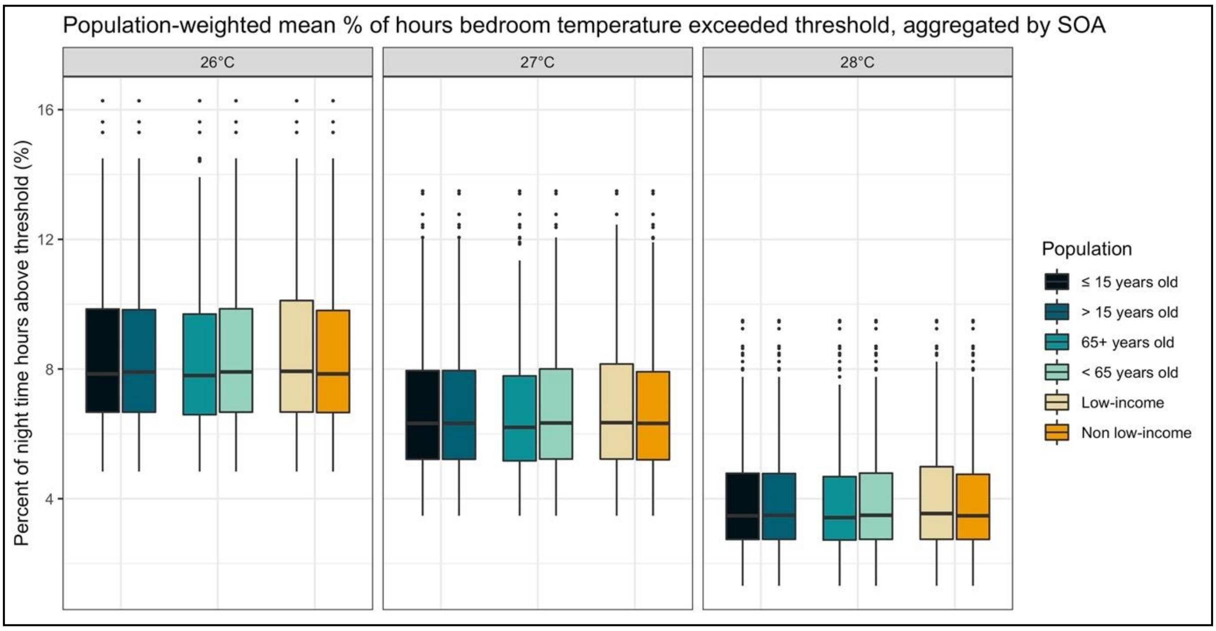


Figure 31. The percent of annual night time hours the bedroom temperature exceeded indoor threshold of 26C, 27C and 28C, weighted for the different population groups across Northern Irish SOAs, at the 2030s time horizon under RCP 2.6.

3.4 **Scotland**

3.4.1 Energy consumption for heating and cooling

The mean annual heating energy use across the Scottish housing stock pre- and post-retrofit is shown in Table 11 under 2030, 2050 and 2085 RCP 2.6. Alike with the results for England, Wales and Northern Ireland, heating energy use declines minimally throughout the 21st century under the same 1.5°C warming emission scenario. Reductions in heating energy use are greater as uptake of the retrofit measures increase in line with national decarbonisation targets. Under the baseline stock conditions in 2030, the annual mean heating energy use was higher than England but lower than Wales and Northern Ireland. Scottish dwellings are generally considered more energy efficient than those in other areas of the UK. The mean of 14,154 kWh in annual heating energy for Scottish housing stock 2030 under RCP 2.6 compared to 13,107 kWh in England is likely a result of the colder, more northern climate of the Glasgow weather file compared to the London weather file used for the English stock.

Table 11. Annual heating energy use in the baseline scenario and following energy efficiency measures for the Scottish housing stock, at time horizons of 2030, 2050 and 2085 under RCP 2.6.

	Year	2030	2050	2085
	Emission scenario	**RCP 2.6**	**RCP 2.6**	**RCP 2.6**
Annual heating energy use (kWh)	Baseline (mean + 95%CI)	14,154 (14,132 – 14,175)	13,996 (13,975–14,017)	13,784 (13,764 – 13,805)
	Retrofit (mean + 95%CI)	12,955 (12,935 – 12,976)	9,597 (9,580–9,614)	6,006 (5,993 – 6,020)
T-test between pre- and post-retrofitted stock	*p*-value	<0.00	<0.00	<0.00
	Mean of differences (kWh)	1,198	4,402	7,793

Figure 32 shows the distribution of heating energy use intensities by dwelling and wall type under 2030 under RCP 2.6. The distributions for all dwelling types show greater overlap than the results for England, Wales and Northern Ireland. Additionally, differences in energy use between solid and cavity walls were less pronounced across the Scottish housing stock, though demand was still higher for solid-walled properties.

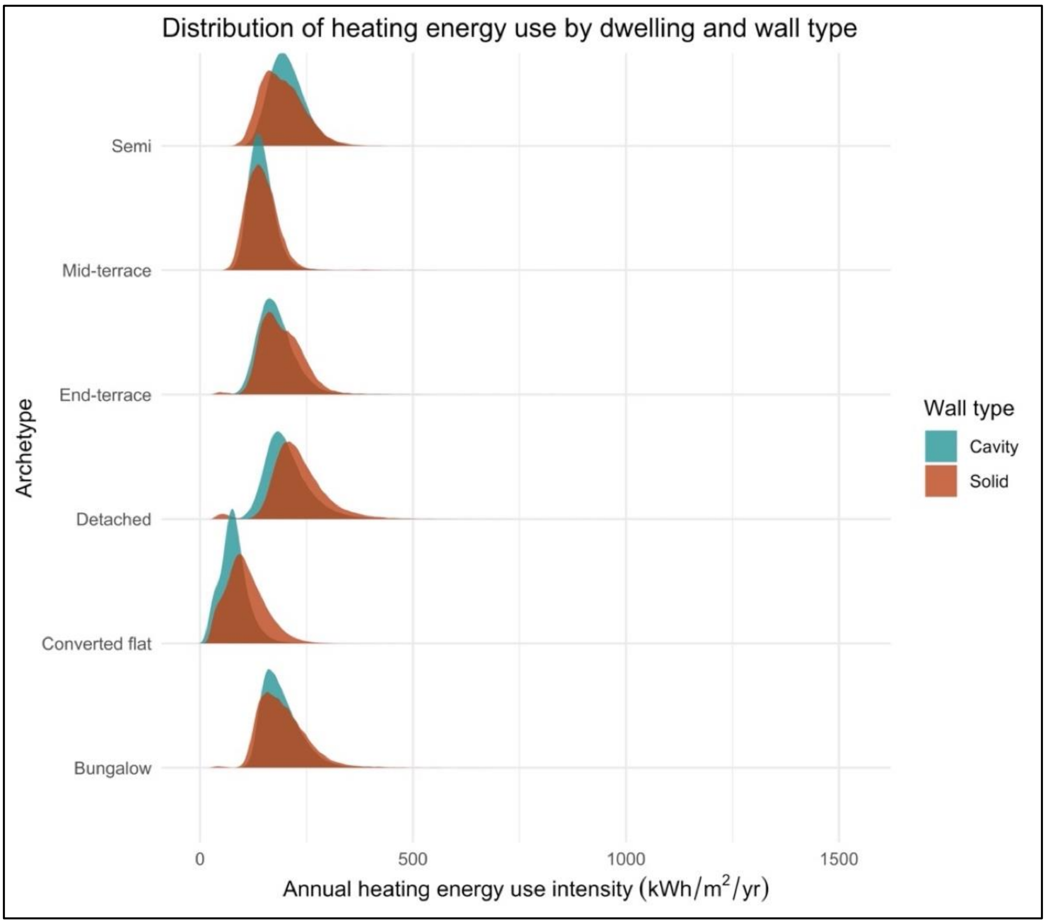


Figure 32. The distribution of heating energy use intensity (kWh/m^2/yr) by dwelling and wall type for the baseline Scottish housing stock, under RCP 2.6 for the 2030s time horizon.

Table 12 shows the percent decrease in heating energy use following energy efficiency measures for each of the three time horizons.

Table 12. Percent decrease in heating energy use by dwelling type in the Scottish housing stock, following energy efficiency measures, at time horizons of 2030, 2050 and 2085 under RCP 2.6.

Dwelling type	Mean percent decrease in heating energy use following retrofit (%)		
	2030 RCP 2.6	2050 RCP 2.6	2085 RCP 2.6
Bungalow	7.6	31.9	56.9
Converted flat	10.7	25.7	52.5
Detached	7.6	42.0	60.2

Dwelling type	Mean percent decrease in heating energy use following retrofit (%)		
	2030 RCP 2.6	2050 RCP 2.6	2085 RCP 2.6
End-terrace	8.3	21.5	55.0
Mid-terrace	9.0	22.1	55.3
Semi	8.1	28.5	54.9

There were ~22,000 dwellings that adopted air conditioning in 2030, ~420,000 in 2050 and ~1.1 million in 2085 under RCP 2.6 across the Scottish housing stock. Figure 33 shows annual cooling energy use intensities by dwelling type across the four building intervention scenarios. Results generally agree with the findings for other UK countries, that external shading may be most effective at offsetting cooling demand, followed by internal blinds. Internal blinds may be especially effective in detached homes. Dwellings where windows were kept closed in Scenario 4 saw a greater increase in cooling demand.

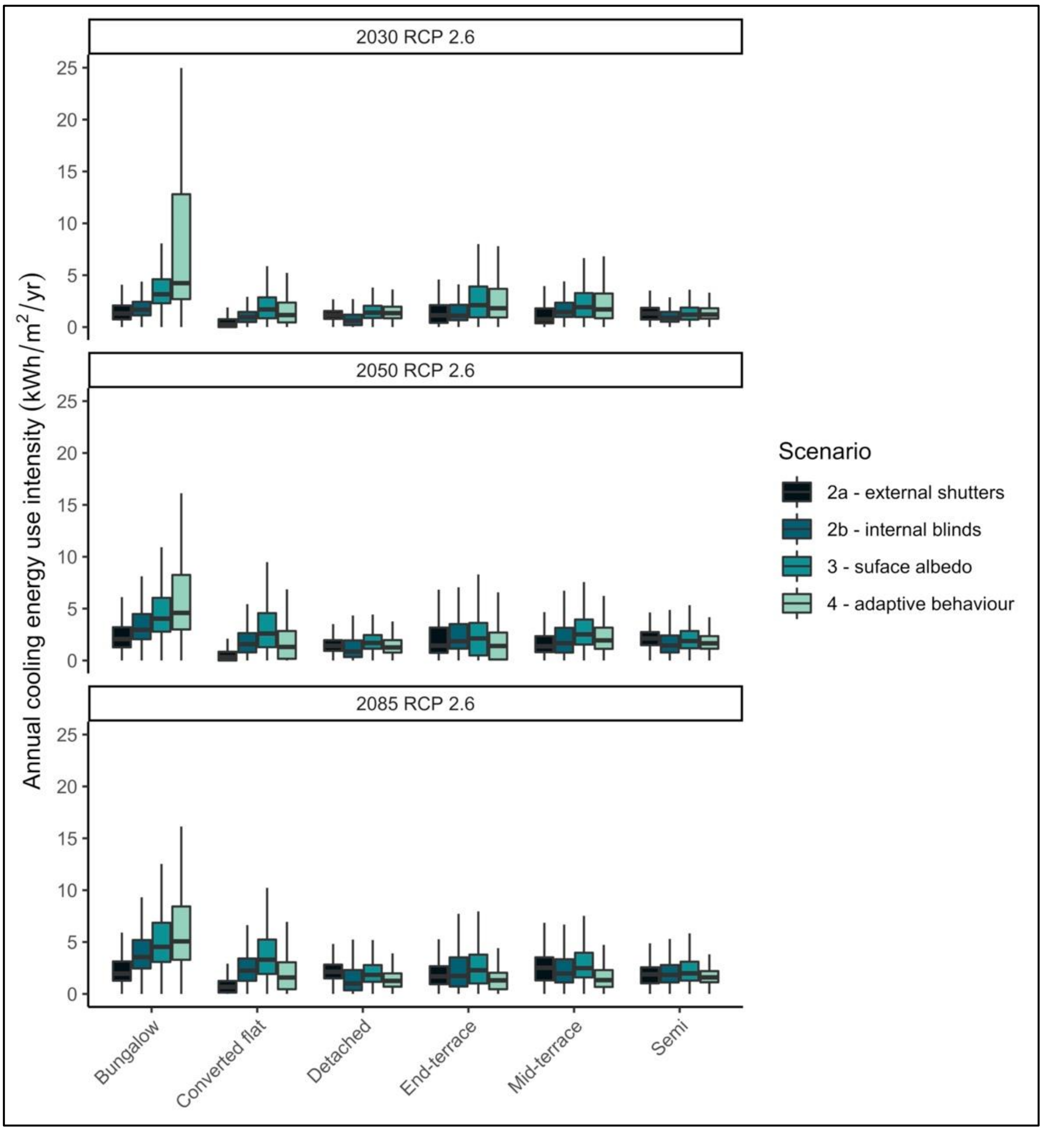


Figure 33. The distribution of cooling demand in the Scottish housing stock by dwelling type, across the four building intervention scenarios for each time horizon and emission scenario: in 2030s (top), 2050s (mid) and 2085s (bottom figure) under RCP 2.6.

3.4.1.1 Energy consumption by population group

The mean annual heating EUIs under RCP 2.6 in 2030 were calculated for each Scottish data zone and aggregated by population quintiles to assess if areas with a high proportion of each vulnerable subgroup have a higher energy burden during winter, shown in Figure 34. The results suggest dwelling energy efficiency is considerably lower in areas with a higher proportion of those aged 65 and above, but higher in areas with a larger low income population, likely due to the higher energy efficiency of social housing (Hamilton et al., 2014; Shrubsole et al., 2016).

Differences in heating EUIs for between dwellings located in areas with a high versus low proportion of infants age 4 and below were minimal.

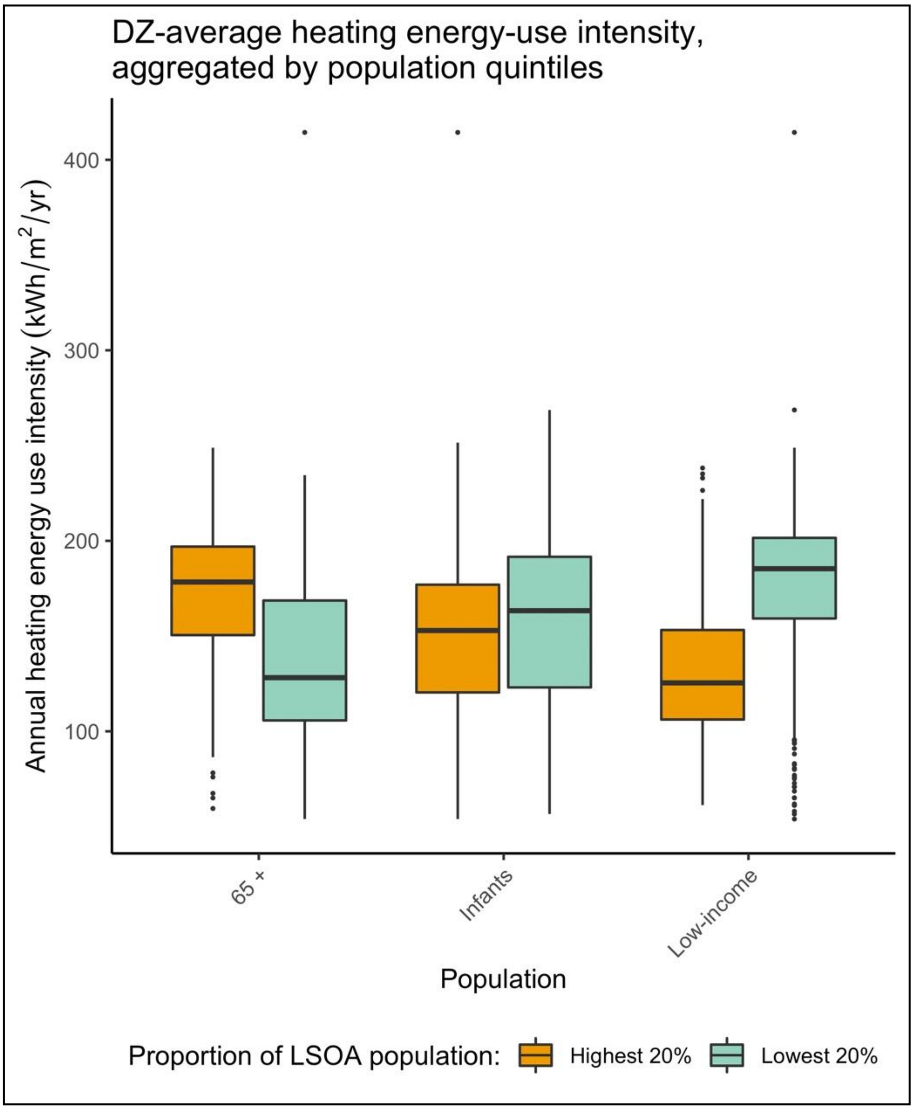


Figure 34. Mean heating energy use intensities aggregated by Scottish data zones (DZ) in 2030s under RCP 2.6, aggregated by quantile of population vulnerability, showing the 20% of DZs with the lowest proportion of the each vulnerable population (green) and the 20% with the highest (orange).

We again assess inequalities in domestic cooling EUIs in 2050 under RCP 2.6 cooling due to the higher uptake of air conditioning across the stock (30%). Results are shown in Figure 35, suggesting that buildings located in areas with a high proportion of those aged 65 and over and low-income individuals may have higher cooling demand, especially in Scenario 4 in dwellings where windows were kept closed.

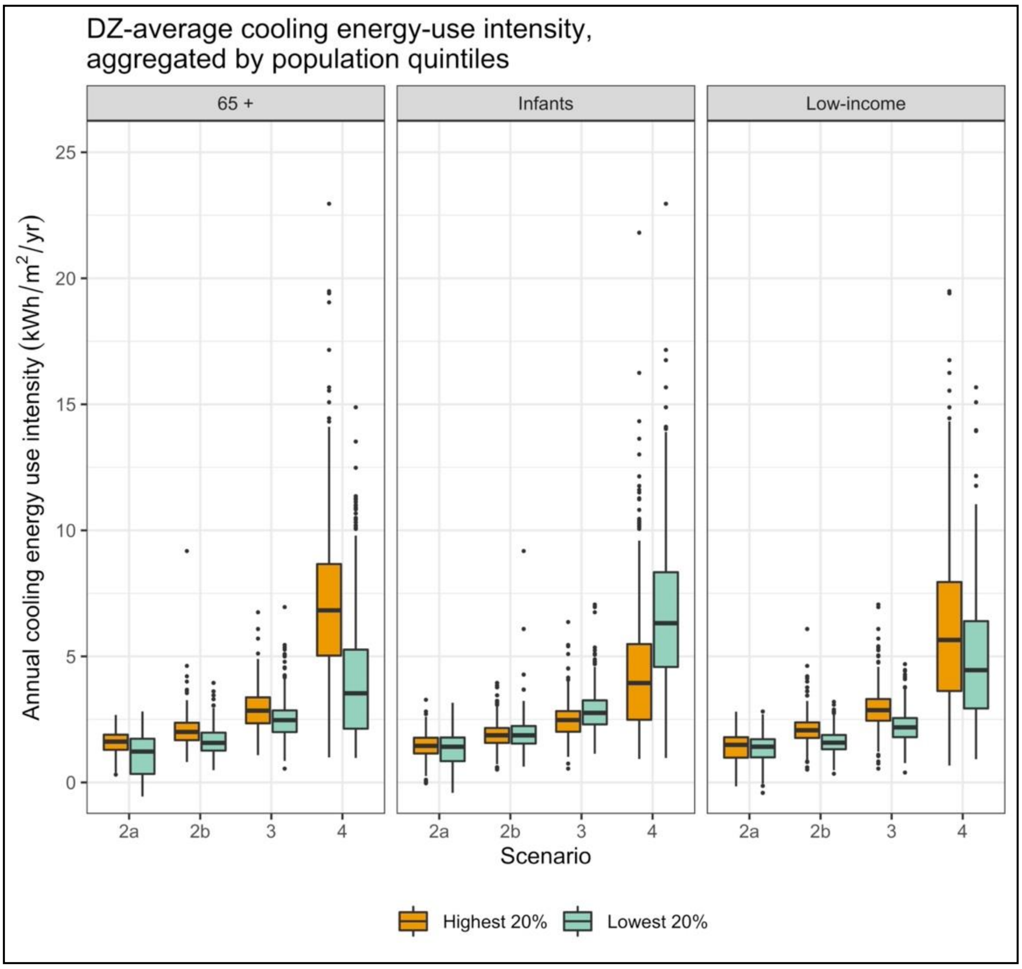


Figure 35. Average cooling energy-use intensities (EUIs) across Scottish DZs, aggregated by population quintiles in building intervention Scenarios 2a - 4, in 2050s under RCP 2.6.

3.4.2 Summertime indoor temperatures

Figure 36 shows the percent of annual hours the nocturnal bedroom temperature exceed 26◦C, 27◦C and 28◦C under RCP 2.6 in 2030, 2050 and 2085. Across the Scottish housing stock, with no building interventions, the bedroom temperature exceeded 26◦C for an average of 10.9%, 11,0%, and 11.1% of annual night time hours under 2030 1.5◦C warming, 2050 1.5◦C warming and 2085 1.5◦C warming, respectively. Flats and mid-terraces experience the most overheating, aligning with the results for other UK countries. There is significant variation across converted flats owing to the differences in overheating across the different storey levels.

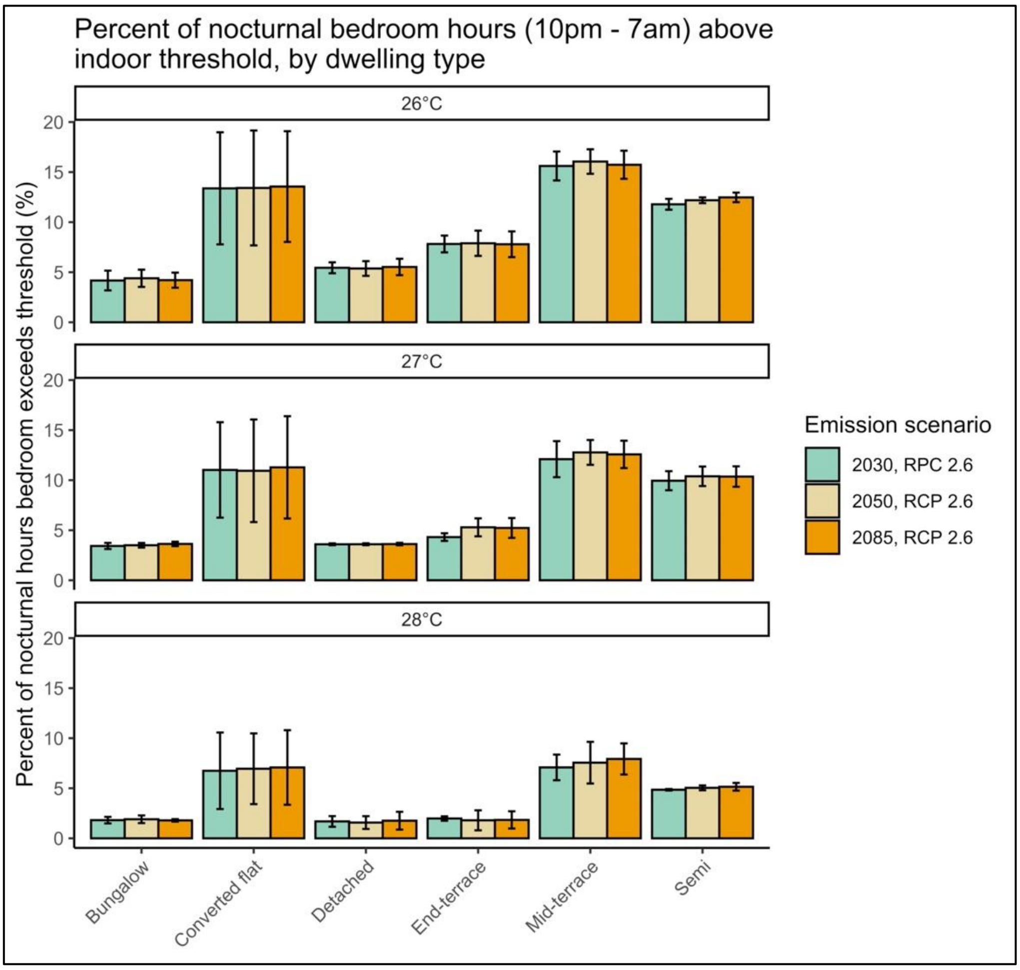


Figure 36. The percent of nocturnal (10pm - 7am) hours the bedroom temperature exceeded 26C, 27C and 28C by dwelling type across the baseline Scottish housing stock, at time horizons of 2030s, 2050s and 2085s under RCP 2.6.

An assessment of indoor overheating under the four different building intervention scenarios is compared with the baseline, shown in Figure 37. Shading devices, including external shutters and internal blinds, are most effective and minimising bedroom overheating. Adaptive occupant behaviour and surface albedo modification appear to make minimal difference on the baseline scenario, though this may be explained due to the limited uptake of these adaptions across the housing in 2030. Results for additional time horizons are included in Appendix C.

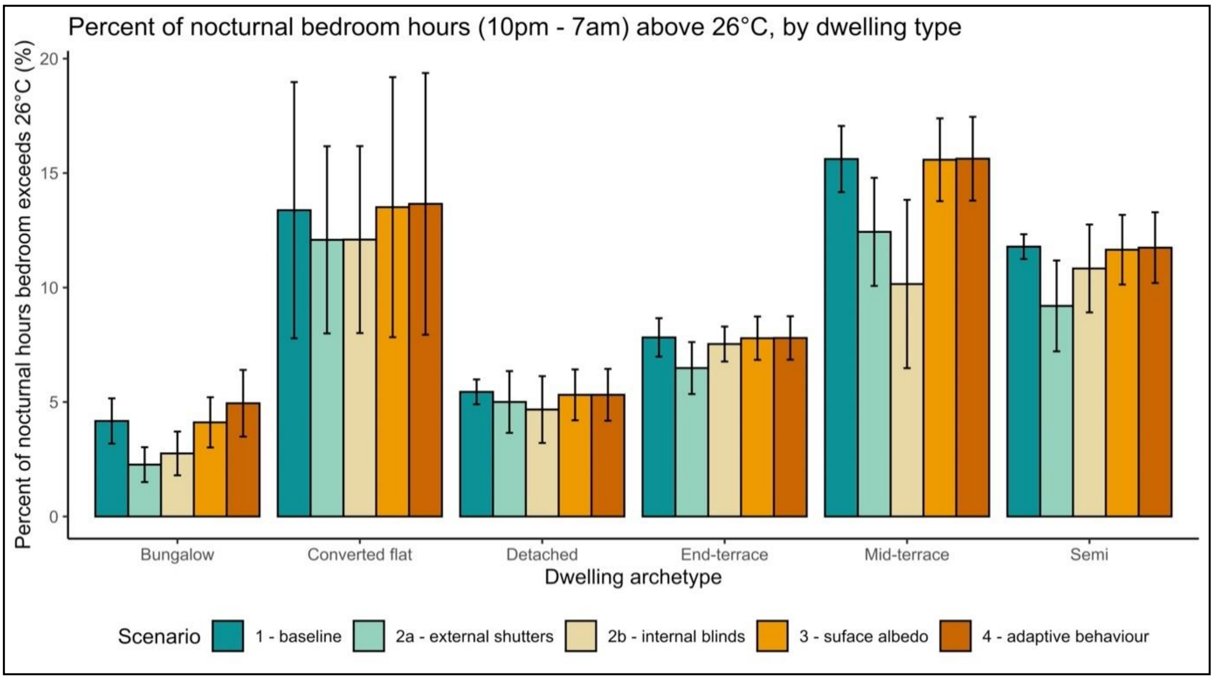


Figure 37. The percent of annual night time hours the bedroom temperature exceeded 26C, by dwelling type, across all building intervention scenarios, in the 2030s time horizon under RCP 2.6 scenario, for Scottish dwellings.

3.4.2.1 Overheating by population group

We assess inequalities in heat exposure by calculating the mean percent of hours the bedroom temperature exceeded 26◦C, 27◦C and 28◦C for Scottish DZs and linking results to area measures of population characteristics. Results are shown in Figure 38, suggesting that all population groups experience a similar degree of indoor overheating, with differences only noticeably higher for low income individuals. This is likely driven by low income individuals being more likely to live in flats (Taylor et al., 2014), which have a higher risk of overheating (Figure 37).

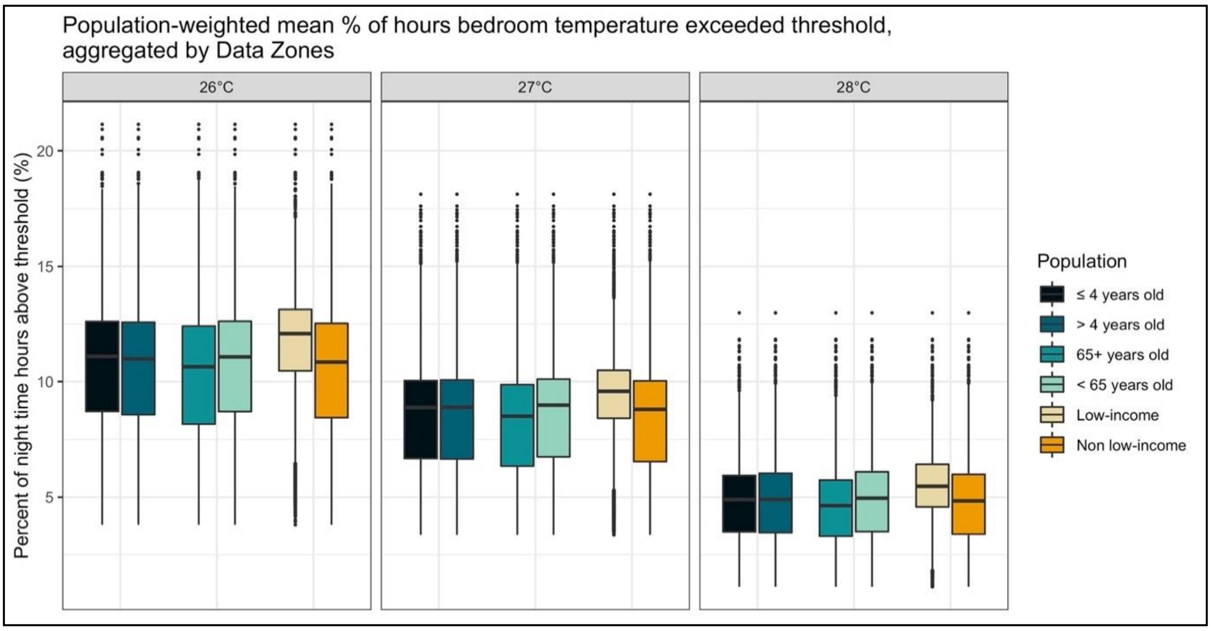


Figure 38. The percent of annual night time hours the bedroom temperature exceeded indoor threshold of 26C, 27C and 28C, across Scottish DZs weighted for the different population groups in the 2030s time horizon under RCP 2.6.

Additionally, we map indoor overheating risk in the 2030 time horizon under RCP 2.6 and co-located low income populations across Glasgow DZs on a bivariate map, as Figure 38 suggests this population group may have increased exposure to indoor heat under the baseline housing stock conditions. The results show small areas of Glasgow doubly burdened with income deprivation and high indoor summertime temperatures in 2030s under RCP 2.6. Glasgow has a longstanding history of stark health inequalities between the most- and least-deprived areas of the city (Reid, 2011) and a notable UHI effect (Krüger et al., 2013). A recent analysis showed heat-related health impacts were higher in more deprived parts of Glasgow (Wan et al., 2022). Figure 39 highlights key areas for the spatial prioritisation of domestic overheating mitigation measures in Glasgow.

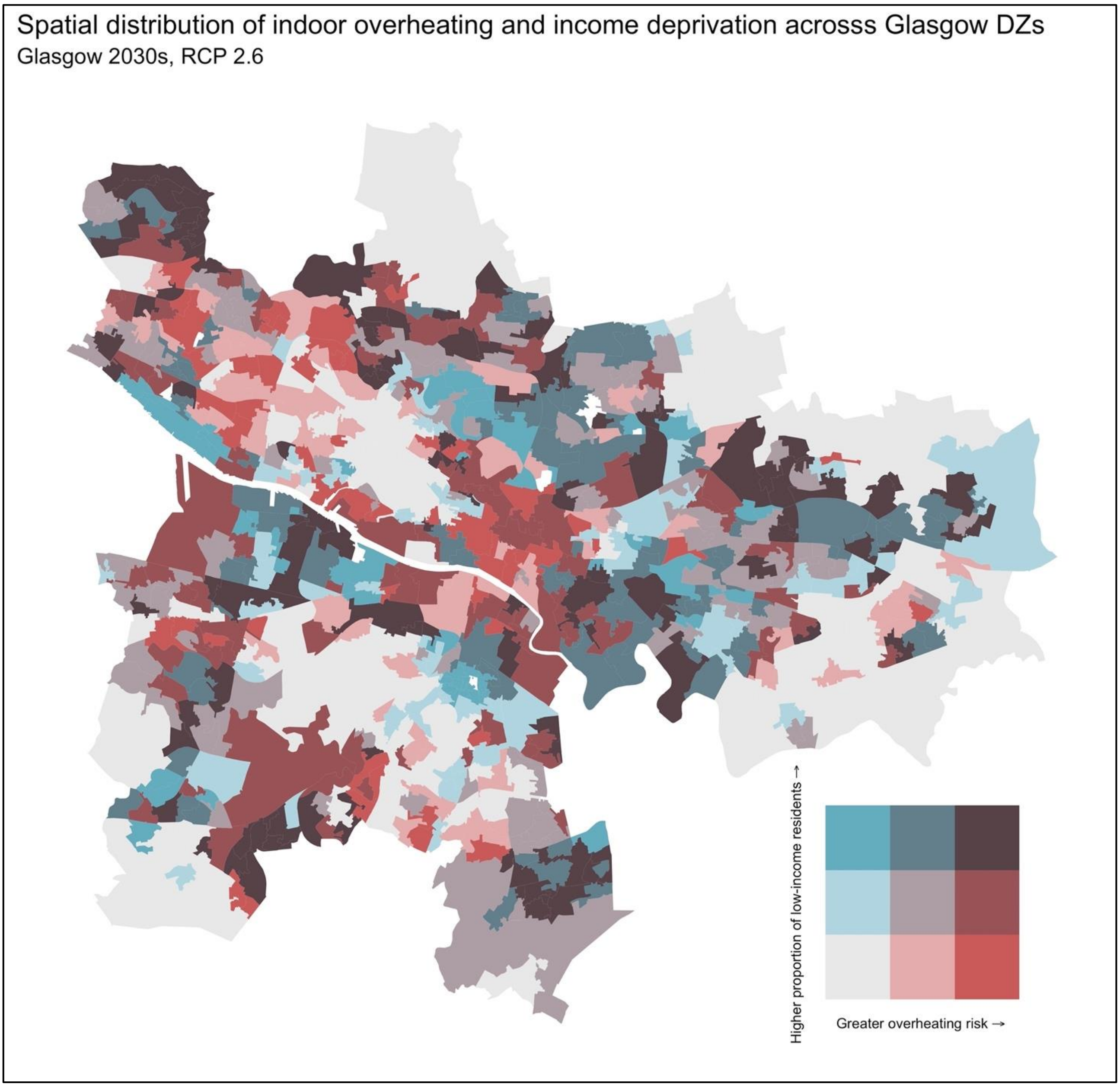


Figure 39. The spatial distribution of indoor overheating risk in the 2030s time horizon under RCP 2.6 and current income deprivation across Scottish Data Zones for the city of Glasgow.

4. Conclusions

4.1 Summary of findings

This work has quantified the impact of a range of UK Climate Change Projections (UKCP) on the residential thermal comfort, heating and cooling loads across UK regions for a range of dwelling archetypes and occupants. With reference to the specific objectives outlined in the Executive Summary, to;

1. *Quantify the impact of a range of climate change projections on residential thermal comfort, heating and cooling loads across UK government regions for a range of dwelling archetypes and occupants, and with further emphasis on urban areas.*

Under the input assumptions made in this modelling work, we find that the majority of existing UK dwellings would fail the CIBSE overheating criteria currently applied for new build with no modifications to the building stock. Indoor overheating was pronounced in mid-terrace properties and flats. Semi-detached dwellings may also be at increased risk, in some cases more so than end-terrace properties. These findings are in line with other modelling and empirical studies which have found flats and terraces are at greater risk of summertime overheating (Lomas et al., 2021; Taylor et al., 2015) and semi-detached buildings may also be susceptible (Gupta & Gregg, 2013; Taylor et al., 2014). Likewise, without any modifications to the housing stock, domestic energy use for space heating will decline as the ambient temperature increases with climate change, but the decrease will be limited if global warming remains under RCP 2.6. Even under the RCP 8.5 scenario in the 2085 time horizon used for English dwellings, the average annual mean heating energy use across the housing stock was still considerably high, meaning a domestic retrofit programme will be necessary to meet national carbon reduction targets irrespective of global progress on limiting climate change.

The model does not assess the indoor overheating risk and energy use of newly built dwellings. New measures introduced to help cities recover from the Covid-19 pandemic and address the urban housing shortage will aim to deliver 300,000 new homes per year across England’s 20 largest cities (MHCLG, 2020). To meet this demand in urban areas where land is already scarce, higher density developments must be built. New-build homes are likely to be smaller and a number of additional homes will be gained by converting houses to flats (MHCLG, 2021), which the work here has shown are more likely to overheat. This should be considered during the planning and delivery of new housing across the UK, especially in England where housing developments are already dense and ambient temperatures are higher.

2. *Evaluate the implications of these changes for different groups, including older people, the fuel poor and other climate-vulnerable groups, taking into account the ability of these groups to adequately heat and cool their homes, adapt to, cope with and recover from excess heat and cold episodes, and the associated impacts on household fuel costs, energy use and carbon emissions, and health inequalities.*

Older individuals may have higher risk of wintertime fuel poverty, given the higher heating energy use intensities found in areas with a greater proportion of those aged 65+. We find that a *blanket*-approach to domestic retrofitting will not resolve these inequalities for this age group, which may lead to health impacts and cold-induced mortality (Hajat et al., 2007). The majority of individuals aged 65 and over in England own their homes outright (DCLG., 2016; ONS, 2020b) and this age group is more likely to occupy detached properties and bungalows (DCLG., 2016). The work here finds these two archetypes have higher space heating demand across all four UK countries. We, therefore, suggest that increasing the appeal of more stringent, energy retrofit measures to homeowners living in these property types may lead to higher uptake amongst this demographic and reduce the associated winter energy burden.

Conversely, low income individuals and ethnic minorities may have disproportionate exposure to high indoor temperatures in summertime in England and Wales, and low income individuals in Scotland, particularly towards the latter 21st century due to living in areas with dwelling types which are at greater risk of overheating, such as flats and terraces. The health effects associated with exposure to high indoor temperatures include cardiovascular and respiratory complications (Arbuthnott & Hajat, 2017; Ebi et al., 2021). The evidence for heatwaves exacerbating mental health conditions varies in strength, but continues to build (Lee et al., 2023; Liu et al., 2021; Thompson et al., 2018).

Socioeconomic and racial inequalities in heat-related health risks has been demonstrated in the US (Madrigano et al., 2015), and a lack of access to air conditioning may be a potential cause (O'Neill et al., 2005). A multi-country analysis of air conditioning and heat-related mortality suggested adoption of domestic air conditioning explained 16.7%, 20.0%, 14.3% and 16.7% of the reductions in heat-related mortality in Canada, Japan, Spain and the USA, respectively (Sera et al., 2020). Despite a reduction in heat-related mortality, the increased uptake of air conditioning across UK homes will likely have a number of negative consequences, including increased energy costs, which we find will be higher for buildings located in areas with a large proportion of lower income individuals across all four countries due to the types of buildings this subgroup are likely to occupy being more susceptible to overheating. Results for other population subgroups varied between each of the other four countries. Inequalities in EUIs and exposure to summertime indoor temperatures were overall lower across Northern Ireland, likely reflecting the lower housing demand and income inequality in the country relative to other areas of the UK (Tinson et al., 2016). That said, reducing winter energy demand across Northern Ireland remains a priority given the country's high fuel poverty rates and reliance on oil for domestic heating (Hinson & Bolton, 2022; Piddington et al., 2020).

3. *In close collaboration with key stakeholders, identify low-cost, low-carbon, 'win-win' measures that could be adopted in order to minimise adverse societal and environmental impacts of climate change-induced changes in the thermal performance of the UK housing stock.*

We find that air conditioning may be necessary to prevent overheating and the associated health burden across the UK housing stock under future climate scenarios. Of the passive measures tested, external shading was able to offset cooling demand for most, with external shutters generally most effective at reducing demand, corroborating past modelling studies (Mavrogianni et al., 2014; Porritt et al., 2013). Internal blinds may also be effective, particularly for free-standing dwellings, such as detached properties. We find that the energy demand for cooling and the extent of indoor overheating in dwellings where windows remain closed was considerably higher, especially in English dwellings. This agrees with other modelling and monitoring studies which found keeping windows closed causes indoor temperatures to rise significantly (Morgan et al., 2015; Taylor et al., 2018). There are a number of reasons people may keep windows closed. Findings from a monitoring study in 101 London homes during August 2009 found more than half of participants would avoid opening windows due to security concerns (Mavrogianni et al., 2017). A survey study in Exeter found occupant perceptions of temperature may influence how they respond to indoor heat, primarily by opening windows, and this was cited as a driver of differences in indoor overheating between vulnerable and non-vulnerable households (Vellei et al., 2017). The modification of surface albedo had negligible effect on summertime indoor temperatures, with reasons for this discussed. Evidence for the effectiveness of reducing the solar absorption of building façades on overheating reduction via albedo modification varies in the literature (Salvati & Kolokotroni, 2020; Salvati et al., 2022; Taylor et al., 2018). A key limitation of the meta-model presented here is that it does not account for changes in the *outdoor* temperature induced by reducing the absorption of built façades, which can have significant impacts (Macintyre & Heaviside, 2019). An empirical assessment of urban albedo led by the University of Kent provides further valuable insights on the effectiveness of this strategy for overheating mitigation at northern latitudes (Kotopouleas et al., 2021).

4.2 Model performance

An analysis of model energy performance against empirical subnational gas use data from the NEED database (BEIS, 2021b), and modelled estimates from Liddiard et al. (2021) is provided in Appendix D. A comparison of modelled heating energy use for London 2020 was run for the London stock and aggregated by LSOA, linked to LSOA subnational gas estimates. Linear regression was performed and an R^2 value of 0.78 was obtained between modelled and measured LSOA aggregated values. Modelled energy use was generally lower than subnational estimates as the housing stock model estimate energy consumption for space heating only, whereas empirical data will not differentiate household gas consumption for space heating and hot water usage. Indoor temperatures estimates under 2030 produced here agree well with findings from an empirical study during a particularly hot summer in London (Pathan et al., 2017). Further, a number of empirical studies have identified flats as having an increased risk of overheating (Lomas et al., 2021). Meta-model performance results under current climatic conditions have been compared with empirical data (Taylor et al., 2019), but there is a lack of empirical data at the required scale with which to validate the model outputs. We acknowledge that due to the large number and range of categorical and continuous building input variables there are a number of limitations and sources of uncertainty, outlined below.

4.3 Limitations and key uncertainties

Here we describe the limitations and key uncertainties in detail. A summary table (Table 13) is provided at the end of this section for reference.

4.3.1 Model uncertainty

Uncertainties in the building fabric (air permeabilities, U-values, etc.) may be assessed in the model due to the random sampling of these inputs, but categorical variables, such as dwelling archetype were held static. The eight archetypes used are deemed to be broadly representative of the English housing stock (Oikonomou et al., 2012), but they will not represent the full range of dwellings across England, Wales, Scotland and Northern Ireland. For comparison, Figure 39 shows a profile of the UK housing stock by construction age and type, derived from the most recently available nationally representative housing stock surveys. Scotland has a high proportion of tenement buildings, which were homes provided for the working population during the industrial revolution (Piddington et al., 2020) and are recognised as a challenging area for Scottish domestic energy policy due to their poor energy performance and heritage restraints (Sharpe & Shearer, 2013). This archetype has not been assessed in the model presented here. Other dwelling layouts and modifications, such as the addition of extensions and conservatories are likely to have a significant role in overheating and energy use (Amoako-Attah & B-Jahromi, 2015; Wright et al., 2018) that has not been considered here. Additionally, the model is derived from a large number of EnergyPlus simulations. Whilst the tool has been validated for a number of building performance metrics, a comparison of EnergyPlus simulations for indoor temperature with large-scale empirical datasets collected in a 2011 English survey found EnergyPlus estimates aggregated over regions performed better against empirical data than simulations for individual dwellings (Symonds et al., 2017).

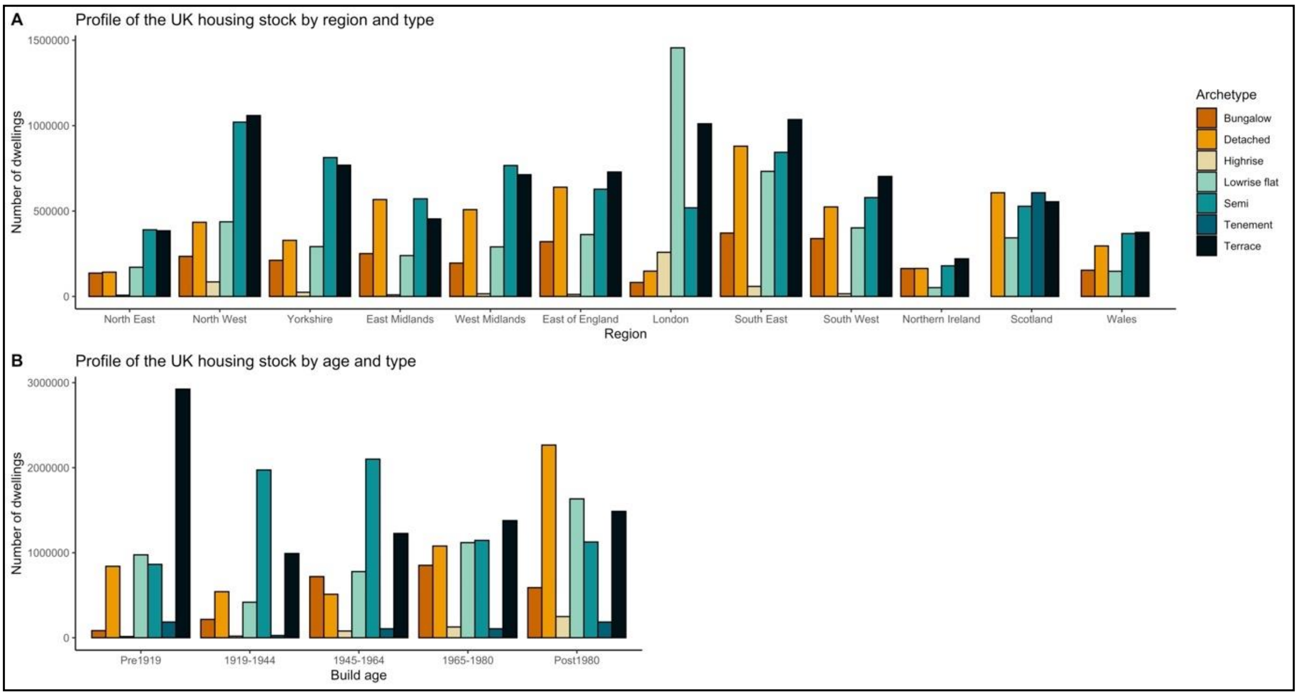


Figure 40. A profile of the UK housing stock by construction age and type. Figures are compiled using data from the most recently available national housing survey for each country.

4.3.2 Occupant behaviour

Occupant behaviour is commonly identified as the largest source of uncertainty in building stock models and will play a significant role in modifying overheating risk (Li et al., 2019). The model presented here used a baseline indoor temperature threshold of 22°C to dictate when windows were opened during summer. Indoor temperature is consistently found to be one of the primary reasons people open windows, but there a number of sociotechnical drivers not considered in this model (Fabi et al., 2012; Yao & Zhao, 2017). A simplified heating system was modelled to estimate changes in annual energy use following a stock-wide retrofit. The model uses a heating set-point sampled from a distribution derived the nationally representative EFUS (BEIS, 2021) to capture varied heating set point preferences but this was not applied across the stock systematically. Household income, size, tenure status and urban/rural classification have all been found to influence household energy consumption and set-point temperature (Abrahamse & Steg, 2009; Druckman & Jackson, 2008), which will not be fully accounted for here. Further, the heating set-point is commonly found to be below the mean of 20.4 °C as assumed here (Huebner et al., 2013).

However, building characteristics have been found to explain most of the variability observed in domestic energy consumption, with sociodemographic factors found to add little explanatory power in a sample of 924 English households (Huebner et al., 2015). Higher thermostat values may also be partly expected in the future due to rising thermal comfort expectations, which was not considered here (Mavrogianni et al., 2013).

Additionally, the reductions in heating energy use observed following the energy retrofit are crucially based on the assumption that the distribution from which the heating set-point for each household was sampled remained the same following the home retrofit and do not account for the temperature 'take-back' effect, also known as the rebound effect, where the reduction in expected building energy use following a retrofit is not realised due to behavioural responses by the occupants (Hamilton et al., 2011).

4.3.3 The EPC database

It is acknowledged that there are a number of biases within the EPC database. No high or low-rise flats were present in the parameterised EPC dataset for Scotland and Northern Ireland. The register overestimates the number of converted flats relative to other flat archetypes, due to difficulties assessing the location of the flat within the building and the nature of the surrounding area (Hardy & Glew, 2019). Additionally, as a property enters the register when it is sold, constructed, let or retrofitted, newer and more energy efficient homes are overrepresented in the database (Taylor et al., 2019). Many older and *hard-to-treat* homes, where solid walls, no loft space or connection to the gas network are common features (Dowson et al., 2012; Raslan & Ambrose, 2022), may not be on the EPC register. As hard-to-treat homes make up an estimated 38% of the housing stock (Duan & Pelsmakers, 2016), this could lead to a significant portion of the stock being overlooked. Additionally, a recent analysis comparing EPC-modelled EUIs with smart metered annual energy use for 1,374 British households found EPCs overpredicted EUIs by between 8% - 48% (Few et al., 2023).

4.3.4 Outdoor weather data

We use outdoor weather files developed for the most recently available UK climate change projections (UKCP18). Whilst these weather files may better account for outdoor temperature extremes than the previous weather files developed for UKCP09, the spatial resolution of UKCP18 weather files is currently limited to the four largest urbanised areas of each UK country (London, Glasgow, Belfast and Cardiff). Even the 45 UK locations covered by the previous UKCP09 weather files may be too few to investigate spatial variation in overheating and energy use across large geographic areas (Liu et al., 2020).

We, therefore, recommend that the results presented here are not used to assess *absolute* levels of indoor overheating risk and energy use across large geographical areas. For this reason, this report refrains from producing maps of overheating risk and/or energy use across the entire housing stock of each UK country (e.g. for all of England). Rather, results are designed to assess relative differences in overheating risk between the type and features of dwellings across a relatively small geographic area, such as a single local authority, where variations in the outdoor climate will be limited.

Table 13. Summary of key model uncertainties and the potential implications of these uncertainties.

Uncertainty	Details	Implications
Lack of representativeness or errors in the EPC dataset	Energy efficient dwellings are overrepresented	The implications of this is that many older, hard-to-treat properties that may have not been sold or rented in recent years are overlooked in the EPC register, resulting in an underestimation of heating energy demand and potential overestimation of the demand reductions produced by the more modest retrofit programme suggested by the CCC. At the population level, these implications could be felt most by private renters and older individuals, who are more likely to live in hard-to-treat and energy inefficient properties (EHS, 2013).
	High- and low-rise flats poorly represented in the EPC database	This could lead to misclassifying the energy use and extent of overheating in these dwellings, which were consistently found to have an elevated risk of high summertime indoor temperatures. High rise flats, in particular, are more likely to be occupied by vulnerable residents, including renters, ethnic minorities and income deprived (EHS, 2018).
Air conditioning uptake scenario	Simplified uptake scenario according to area income measures	We model air conditioning uptake in all rooms of dwellings that adopted this intervention. In reality, the size of air conditioning units ranges from small mobile units to fixed, high-power air conditioners, which has not been accounted for here. Likewise, whilst the uptake trajectory is comparable to twentieth-century America, the socioeconomic factors limiting uptake in that context may not be directly transferable to present day UK as units currently and in the future may be cheaper as a proportion of annual income, meaning uptake could exceed the projections produced here. This could lead to an underestimation of cooling demand across the

		housing stock, and importantly the predicted disparities in summertime fuel poverty.
Modelled building interventions	Changes in the temperature of the local outdoor environment due to changes in building surface albedo not fully accounted for in EnergyPlus simulations	The effect of the building on the outdoor environment that occurs when sunlight is reflected away from the immediate vicinity of the building is not fully accounted for in the simulations. This could partly explain the observed limited effect from surface albedo modification of building façades. This is in contrast to a number of international studies (Carnielo & Zinzi, 2013; Mansouri et al., 2017) and may lead to the effectiveness of this intervention being underestimated. However, our results here show combining albedo modification with roof and wall insulation may additionally limit the effectiveness of this measure. More detailed investigation into the feasibility of this overheating mitigation measure given the Government's decarbonisation goals is necessary. An empirical assessment of urban albedo led by the University of Kent provides further valuable insights on the effectiveness of this strategy for overheating mitigation at northern latitudes (Kotopouleas et al., 2021).

5. References

Abrahamse, W., & Steg, L. (2009). How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings? *Journal of Economic Psychology*, *30*(5), 711–720.

Age UK. (2022). *Poverty amongst older Londoners*. https://insidecroydon.com/wp-content/uploads/2022/10/ageuk_london_poverty_final.pdf

Amoako-Attah, J., & B-Jahromi, A. (2015). Impact of conservatory as a passive solar design of UK dwellings. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, *169*(5), 198–213.

Arbuthnott, K. G., & Hajat, S. (2017). The health effects of hotter summers and heat waves in the population of the United Kingdom: a review of the evidence. *Environmental Health*, *16*(1), 1–13.

ARUP. (2022). *Addressing overheating risk in existing UK homes. An ARUP report comissioned by the Climate Change Committee*. https://www.theccc.org.uk/publication/addressing-overheating-risk-in-existing-uk-homes-arup/

Beagon, P., Boland, F., & Saffari, M. (2020). Closing the gap between simulation and measured energy use in home archetypes. *Energy and Buildings*, *224*, 110244.

BEIS. (2020). *UK sets ambitious new climate target ahead of UN Summit. Climate change and Energy*.

BEIS – Department for Business Energy and Industrial Strategy. (2017). *Energy Follow Up Survey: thermal comfort, damp and ventilation*.

BEIS – Department for Business Energy and Industrial Strategy. (2021a). *Cooling in the UK*.

BEIS – Department for Business Energy and Industrial Strategy. (2021b). *Energy Follow Up Survey: Heating patterns and occupancy*.

BEIS – Department for Business Energy and Industrial Strategy. (2021c). *National Energy Efficiency Data-Framework (NEED): Summary of Analysis, Great Britain, 2021*.

BEIS – Department for Business Energy and Industrial Strategy. (2022). *Fuel poverty detailed tables 2022*.

Biddle, J. (2008). Explaining the spread of residential air conditioning, 1955–1980. *Explorations in Economic History*, *45*(4), 402–423.

Bolton, P., & Stewart, I. (2023). *Domestic energy prices*. https://commonslibrary.parliament.uk/research-briefings/cbp-9491/#:~:text=Trends in prices up to 2021&text=The average bill for the,%2C a 36%25 real increase.

Bradshaw, J. R., & Keung, A. (2022). Fuel poverty estimates for the UK. *Poverty*.

Carnielo, E., & Zinzi, M. (2013). Optical and thermal characterisation of cool asphalts to mitigate urban temperatures and building cooling demand. Building and Environment, 60, 56–65.

CIBSE TM59. (2017). *Design methodology for the assessment of overheating risk in homes*.

CISBE. (2003). *British Standards: Heating Systems in Buildings. Method for calculation of the design heat load.*

Climate Change Committee. (2020). *The Sixth Carbon Budget. Methodology Report*.

Climate Change Committee. (2022). *Progress in reducing emissions: 2022 Report to Parliament*.

Committee, C. C. (2021). *Independent Assessment of UK Climate Risk: Advice to Government For The UK's Third Climate Change Risk Assessment (CCRA3)*.

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*.

Cui, C., Raslan, R., Korolija, I., & Chalabi, Z. (2022). On the robustness of thermal comfort against uncertain future climate: A Bayesian bootstrap method. *Building and Environment*, *226*, 109665.

Department for Communities and Local Government. (2016). *English housing survey: Housing for older people report, 2014–15.* Department for Communities and Local Government.

Department for Communities and Local Government. (2022). *Energy Performance Certificates*.

Department for Work and Pensions. (2022). *Stat-Xplore, tool.* https://stat-xplore.dwp.gov.uk/webapi/jsf/login.xhtml

Díaz, J., Garcia, R., Velázquez de Castro, F., Hernández, E., López, C., & Otero, A. (2002). Effects of extremely hot days on people older than 65 years in Seville (Spain) from 1986 to 1997. *International Journal of Biometeorology*, *46*(3), 145–149.

Dowson, M., Poole, A., Harrison, D., & Susman, G. (2012). Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. *Energy Policy*, *50*, 294–305.

Druckman, A., & Jackson, T. (2008). Household energy consumption in the UK: A highly geographically and socio-economically disaggregated model. *Energy Policy*, *36*(8), 3177–3192.

Duan, S., & Pelsmakers, S. (2016). *Retrofit Challenges of Energy-efficient Upgrades of Terraced Housing in the UK:*

Reviewing and Analyzing Strategies From Case Study Projects.

Eames, M., Kershaw, T., & Coley, D. (2011). On the creation of future probabilistic design weather years from UKCP09. *Building Services Engineering Research and Technology*, *32*(2), 127–142.

Ebi, K. L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R. S., Ma, W., & Malik, A. (2021). Hot weather and heat extremes: health risks. *The Lancet*, *398*(10301), 698–708.

Econometrics, C. (2022). *The economic impact of decarbonising household heating in the UK in an era of high fossil fuel prices*.

Energy Saving Trust. (2023). *Scottish Energy Performance Certificate Register*.

English Housing Survey (EHS). (2018). Household Report, English Housing Survey, 2017-2018.

English Housing Survey (EHS). (2013). Energy efficiency of English housing: Chapter 3, Hard to treat and energy inefficient properties.

Fabi, V., Andersen, R. V., Corgnati, S., & Olesen, B. W. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2012.07.009

Ferguson, L., Taylor, J., Zhou, K., Shrubsole, C., Symonds, P., & Davies, M., Dimitroulopoulou, S. (2021). Systemic inequalities in indoor air pollution exposure in London, UK. *Buildings and Cities*.

Few, J., Manouseli, D., McKenna, E., Pullinger, M., Zapata-Webborn, E., Elam, S., Shipworth, D., & Oreszczyn, T. (2023). The over-prediction of energy use by EPCs in Great Britain: A comparison of EPC-modelled and metered primary energy use intensity. *Energy and Buildings*, 113024.

Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749–758.

Gasparrini, A., Masselot, P., Scortichini, M., Schneider, R., Mistry, M. N., Sera, F., Macintyre, H. L., Phalkey, R., & Vicedo-Cabrera, A. M. (2022). Small-area assessment of temperature-related mortality risks in England and Wales: a case time series analysis. *The Lancet Planetary Health*, *6*(7), e557–e564.

Green, H. K., Andrews, N. J., Bickler, G., & Pebody, R. G. (2012). Rapid estimation of excess mortality: nowcasting during the heatwave alert in England and Wales in June 2011. *J Epidemiol Community Health*, *66*(10), 866–868.

Guide, A. (2015). Environmental design. *Chartered Institute of Building Services Engineers (CIBSE)*.

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

Gupta, R., & Gregg, M. (2013). Preventing the overheating of English suburban homes in a warming climate. *Building Research & Information*, *41*(3), 281–300.

Hajat, S., Kovats, R. S., & Lachowycz, K. (2007). Heat-related and cold-related deaths in England and Wales: who is at risk? *Occupational and Environmental Medicine*, *64*(2), 93–100.

Hamilton, I G, Davies, M., Ridley, I., Oreszczyn, T., Barrett, M., Lowe, R., Hong, S., Wilkinson, P., & Chalabi, Z. (2011). The impact of housing energy efficiency improvements on reduced exposure to cold—the 'temperature take back factor.' *Building Services Engineering Research and Technology*, *32*(1), 85–98.

Hamilton, Ian G., Shipworth, D., Summerfield, A. J., Steadman, P., Oreszczyn, T., & Lowe, R. (2014). Uptake of energy efficiency interventions in English dwellings. *Building Research & Information*, *42*(3), 255–275. https://doi.org/10.1080/09613218.2014.867643

Hardy, A., & Glew, D. (2019). An analysis of errors in the Energy Performance certificate database. *Energy Policy*, *129*, 1168–1178.

He, C., Kim, H., Hashizume, M., Lee, W., Honda, Y., Kim, S. E., Kinney, P. L., Schneider, A., Zhang, Y., & Zhu, Y. (2022). The effects of night-time warming on mortality burden under future climate change scenarios: a modelling study. *The Lancet Planetary Health*, *6*(8), e648–e657.

Health Protction Agency. (2006). *Rapid Evaluation of 2006 Heatwave: Epidemiological aspects*.

Heaviside, C., Vardoulakis, S., & Cai, X.-M. (2016). Attribution of mortality to the urban heat island during heatwaves in the West Midlands, UK. *Environmental Health*, *15*(1), 49–59.

Hinson, S., & Bolton, P. (2022). Fuel Poverty. *The House of Commons Library: London, UK*. https://researchbriefings.files.parliament.uk/documents/CBP-8730/CBP-8730.pdf

HM Government. (2017). *The Clean Growth Strategy*.

HM Government. (2021a). *Approved Document O - Requirement O1: Overheating mitigation*.

HM Government. (2021b). *The Building Regulations 2010: Conservation of fuel and power. Approved Document L.*

Huebner, G. M., Hamilton, I., Chalabi, Z., Shipworth, D., & Oreszczyn, T. (2015). Explaining domestic energy consumption–the comparative contribution of building factors, socio-demographics, behaviours and attitudes. *Applied Energy*, *159*, 589–600.

Huebner, G. M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., & Summerfield, A. (2013). Heating patterns in English homes: Comparing results from a national survey against common model assumptions. *Building and Environment*, *70*, 298–305.

IET - The Institute of Engineering and Technology. (2020). *Scaling up retrofit 2050.*

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Johnson, H., Kovats, R. S., McGregor, G., Stedman, J., Gibbs, M., Walton, H., Cook, L., & Black, E. (2005). The impact of the 2003 heat wave on mortality and hospital admissions in England. *Health Statistics Quarterly*, *25*, 6–11.

Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A., Sparks, T., & Garforth, J. (2021). State of the UK Climate 2020. *International Journal of Climatology*, *41*, 1–76.

Kerr, N., Gouldson, A., & Barrett, J. (2017). The rationale for energy efficiency policy: Assessing the recognition of the multiple benefits of energy efficiency retrofit policy. *Energy Policy*, *106*, 212–221.

Khare, S., Hajat, S., Kovats, S., Lefevre, C. E., De Bruin, W. B., Dessai, S., & Bone, A. (2015). Heat protection behaviour in the UK: results of an online survey after the 2013 heatwave. *BMC Public Health*, *15*(1), 1–12.

Kotopouleas, A., Giridharan, R., Nikolopoulou, M., Watkins, R., & Yeninarcilar, M. (2021). Experimental investigation of the impact of urban fabric on canyon albedo using a 1: 10 scaled physical model. *Solar Energy*, *230*, 449–461.

Krüger, E., Drach, P., Emmanuel, R., & Corbella, O. (2013). Urban heat island and differences in outdoor comfort levels in Glasgow, UK. *Theoretical and Applied Climatology*, *112*(1), 127–141.

Lee, M. J., McLean, K. E., Kuo, M., Richardson, G. R. A., & Henderson, S. B. (2023). Chronic diseases associated with mortality in British Columbia, Canada during the 2021 western North America extreme heat event. *GeoHealth*, *7*(3), e2022GH000729.

Levermore, G. J., Parkinson, J. B., Laycock, P. J., & Lindley, S. (2015). The urban heat island in Manchester 1996–2011. *Building Services Engineering Research and Technology*, *36*(3), 343–356.

Li, J., Yu, Z. J., Haghighat, F., & Zhang, G. (2019). Development and improvement of occupant behavior models towards realistic building performance simulation: A review. *Sustainable Cities and Society*, *50*, 101685.

Liddiard, R., Godoy-Shimizu, D., Ruyssevelt, P., Steadman, P., Evans, S., Humphrey, D., & Azhari, R. (2021). Energy use intensities in London houses. *Buildings and Cities*, *2*(1), 336–353.

Liu, C., Chung, W., Cecinati, F., Natarajan, S., & Coley, D. (2020). Current and future test reference years at a 5 km resolution. *Building Services Engineering Research and Technology*, *41*(4), 389–413.

Liu, J., Varghese, B. M., Hansen, A., Xiang, J., Zhang, Y., Dear, K., Gourley, M., Driscoll, T., Morgan, G., & Capon, A. (2021). Is there an association between hot weather and poor mental health outcomes? A systematic review and meta-analysis. *Environment International*, *153*, 106533.

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*, 107986.

Lowe, J. A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., & Fosser, G. (2018). UKCP18 science overview report. *Met Office Hadley Centre: Exeter, UK*.

Macintyre, H. L., & Heaviside, C. (2019). Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city. Environment international, 127, 430-441.

Makantasi, A.-M., & Mavrogianni, A. (2016). Adaptation of London's social housing to climate change through retrofit: a holistic evaluation approach. *Advances in Building Energy Research*, *10*(1), 99–124.

Mansouri, O., Belarbi, R., & Bourbia, F. (2017). Albedo effect of external surfaces on the energy loads and thermal comfort in buildings. Energy Procedia, 139, 571–577.

Mavrogianni, A, Johnson, F., Ucci, M., Marmot, A., Wardle, J., Oreszczyn, T., & Summerfield, A. (2013). Historic variations in winter indoor domestic temperatures and potential implications for body weight gain. *Indoor and Built Environment*, *22*(2), 360–375.

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

Mavrogianni, Anna, Davies, M., Taylor, J., Oikonomou, E., Raslan, R., Biddulph, P., Das, P., Jones, B., & Shrubsole, C.

(2013). The unintended consequences of energy efficient retrofit on indoor air pollution and overheating risk in a typical Edwardian mid-terraced house. *Future Build*.

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

McLachlan, C., Glynn, S., Hill, F., Edwards, R., Kuriakose, J., Wood, F. R., & Manchester, T. (2016). Air conditioning demand assessment. *Prepared for Electricity North West, Manchester, UK*.

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?*

MetOffice. (2021). *UK Climate Projections 2018 (UKCP18)*.

MHCLG. (2021). *Housing supply; net additional dwellings, England: 2019-20 Statistical release*.

Ministry of Housing, Communities, and L. G. (2020). *Plan to regenerate England's cities with new homes*. Press Release, 16 December 2020.

Morgan, C., FOSTER, J. A., Sharpe, T., & Poston, A. (2015). Overheating in Scotland: Lessons from 26 monitored low energy homes. *Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale*, *CONF*, 167–172.

Murray, V., Keshishian, C., & Urquhart, G. (2010). Chemical Hazards and Poisons Report: from the Centre for Radiation, Chemical and Environmental Hazards, June 2010 Issue 17. *Chemical Hazards and Poisons Report*, *17*, 3–72.

Murtagh, N., Badi, S., Shi, Y., Wei, S., & Yu, W. (2022). Living with air-conditioning: experiences in Dubai, Chongqing and London. *Buildings and Cities*, *3*(1), 10–27.

National Records of Scotland. (2022). *Mid-2021 Small Area Population Estimates, Scotland*. https://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/population/population-estimates/2011-based-special-area-population-estimates/small-area-population-estimates

Nickson, A., Woolston, H., Daniels, J., Dedring, I., Reid, K., Ranger, K., Clancy, L., Street, R., & Reeder, T. (2011). Managing risks and increasing resilience: the Mayor's climate change adaptation strategy. *Greater London Authority, London*.

NISRA - Northern Ireland Statistics and Research Agency. (2018). *Northern Ireland Multiple Deprivation Measures 2017*.

NISRA - Northern Ireland Statistics and Research Agency. (2020). *Population Estimates Broad Age Bands (statistical geographies)*.

O'Neill, M. S., Zanobetti, A., & Schwartz, J. (2005). Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. *Journal of Urban Health*, *82*(2), 191–197.

Office for National Statistics & UK Health Security Agency. (2022). *Excess mortality during heat-periods: 1 June to 31 August 2022*.

Oikonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P., & 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. https://doi.org/10.1016/j.buildenv.2012.04.002

ONS - Office for National Statistics. (2020a). *Income estimates for small areas, England and Wales*.

ONS - Office for National Statistics. (2020b). *Living longer: changes in housing tenure over time*.

ONS - Office for National Statistics. (2021). *Population estimates by output areas, electoral, health and other geographies, England and Wales: mid-2020.* https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualsmallareapopulationestimates/latest

ONS - Office for National Statistics. (2022a). *Energy efficiency of housing in England and Wales: 2021*.

ONS - Office for National Statistics. (2022b). *Ethnic group. Census 2021 estimates. TS021*.

Ortiz, M., Itard, L., & Bluyssen, P. M. (2020). Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. *Energy and Buildings*, *221*, 110102.

Pasek, J. (2022). Package 'weights.' *Weighting and Weighted Statistics. R Package Version 0.85 (Https://Cran. r-Project. Org/Web/Packages/Weights/Weights. Pdf)*. https://cran.r-project.org/web/packages/weights/weights.pdf

Pathan, A., Mavrogianni, A., Summerfield, A., Oreszczyn, T., & Davies, M. (2017). Monitoring summer indoor overheating in the London housing stock. *Energy and Buildings*, *141*, 361–378.

Piddington, J., Nicol, S., Garrett, H., & Custard, M. (2020). The housing stock of the United Kingdom. *BRE Trust: Garston, UK*.

Porritt, S. M., Cropper, P. C., Shao, L., & Goodier, C. I. (2013). Heat wave adaptations for UK dwellings and development of a retrofit toolkit. *International Journal of Disaster Resilience in the Built Environment*.

Public Health England. (2019). *PHE Heatwave Mortality Monitoring: Summer 2019*. Public Health England London.

Public Health England. (2020). *Heatwave mortality monitoring report: 2020*. https://www.gov.uk/government/publications/phe-heatwave-mortality-monitoring/heatwave-mortality-monitoring-report-2020

Raslan, R., & Ambrose, A. (2022). Solving the difficult problem of hard to decarbonize homes. *Nature Energy*, *7*(8), 675–677.

Reid, M. (2011). Behind the" Glasgow effect". *World Health Organization. Bulletin of the World Health Organization*, *89*(10), 706.

Royé, D., Sera, F., Tobías, A., Lowe, R., Gasparrini, A., Pascal, M., de'Donato, F., Nunes, B., & Teixeira, J. P. (2021). Effects of hot nights on mortality in southern Europe. *Epidemiology*, *32*(4), 487–498.

Salvati, A., & Kolokotroni, M. (2020). *Impact of urban albedo on microclimate and thermal comfort over a heat wave event in London*.

Sanchez-Guevara, C., Peiró, M. N., Taylor, J., Mavrogianni, A., & González, J. N. (2019). Assessing population vulnerability towards summer energy poverty: Case studies of Madrid and London. *Energy and Buildings*, *190*, 132–143.

Santamouris, M., & Fiorito, F. (2021). On the impact of modified urban albedo on ambient temperature and heat related mortality. *Solar Energy*, *216*, 493–507.

Schwartz, Y., Raslan, R., & Mumovic, D. (2022). Refurbish or replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London. *Energy*, *248*, 123585.

Sera, F., Hashizume, M., Honda, Y., Lavigne, E., Schwartz, J., Zanobetti, A., Tobias, A., Iñiguez, C., Vicedo-Cabrera, A. M., & Blangiardo, M. (2020). Air conditioning and heat-related mortality: a multi-country longitudinal study. *Epidemiology*, *31*(6), 779–787.

Sharpe, T., & Shearer, D. (2013). Adapting the Scottish tenement to twenty-first century standards: An evaluation of the performance enhancement of a nineteenth century "Category B" listed tenement block in Edinburgh. *Journal of Cultural Heritage Management and Sustainable Development*.

Shrubsole, C., Taylor, J., Das, P., Hamilton, I. G., Oikonomou, E., & Davies, M. (2016). Impacts of energy efficiency retrofitting measures on indoor PM<inf>2.5</inf>concentrations across different income groups in England: a modelling study. *Advances in Building Energy Research*, *10*(1). https://doi.org/10.1080/17512549.2015.1014844

SIMD. (2020). *Scottish Index of Multiple Deprivation*.

Smith, J. D., Mitsakou, C., Kitwiroon, N., Barratt, B. M., Walton, H. A., Taylor, J. G., Anderson, H. R., Kelly, F. J., & Beevers, S. D. (2016). London Hybrid Exposure Model: Improving Human Exposure Estimates to NO<inf>2</inf>and PM<inf>2.5</inf>in an Urban Setting. *Environmental Science and Technology*, *50*(21). https://doi.org/10.1021/acs.est.6b01817

Symonds, P., Taylor, J., Mavrogianni, A., Davies, M., Shrubsole, C., Hamilton, I., & Chalabi, Z. (2017). Overheating in English dwellings: comparing modelled and monitored large-scale datasets. *Building Research & Information*, *45*(1–2), 195–208.

Taylor, J., Shrubsole, C., Davies, M., Biddulph, P., Das, P., Hamilton, I., Vardoulakis, S., Mavrogianni, A., Jones, B., & Oikonomou, E. (2014). The modifying effect of the building envelope on population exposure to PM2.5 from outdoor sources. *Indoor Air*. https://doi.org/10.1111/ina.12116

Taylor, Jonathan, Davies, M., Mavrogianni, A., Chalabi, Z., Biddulph, P., Oikonomou, E., Das, P., & Jones, B. (2014). The relative importance of input weather data for indoor overheating risk assessment in dwellings. *Building and Environment*, *76*, 81–91.

Taylor, Jonathon, Davies, M., Mavrogianni, A., Shrubsole, C., Hamilton, I., Das, P., Jones, B., Oikonomou, E., & Biddulph, P. (2016). Mapping indoor overheating and air pollution risk modification across Great Britain: A modelling study. *Building and Environment*, *99*, 1–12.

Taylor, Jonathon, 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*. https://doi.org/10.1177/0143624414566474

Taylor, Jonathon, McLeod, R., Petrou, G., Hopfe, C., Mavrogianni, A., Castano-Rosa, R., Pelsmakers, S., & Lomas, K. (2023). Ten questions concerning residential overheating in Central and Northern Europe. *Building and Environment*, 110154.

Taylor, Jonathon, Shrubsole, C., Symonds, P., Mackenzie, I., & Davies, M. (2019). Application of an indoor air pollution metamodel to a spatially-distributed housing stock. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2019.02.341

Taylor, Jonathon, Symonds, P., Heaviside, C., Chalabi, Z., Davies, M., & Wilkinson, P. (2021). Projecting the impacts of housing on temperature-related mortality in London during typical future years. *Energy and Buildings*, *249*, 111233.

Taylor, Jonathon, Symonds, P., Wilkinson, P., Heaviside, C., Macintyre, H., Davies, M., Mavrogianni, A., & 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), 190.

Taylor, Jonathon, Wilkinson, P., Davies, M., Armstrong, B., Chalabi, Z., Mavrogianni, A., Symonds, P., Oikonomou, E., & Bohnenstengel, S. I. (2015). Mapping the effects of urban heat island, housing, and age on excess heat-related mortality in London. *Urban Climate*, *14*, 517–528.

Thompson, R., Hornigold, R., Page, L., & Waite, T. (2018). Associations between high ambient temperatures and heat waves with mental health outcomes: a systematic review. *Public Health*, *161*, 171–191.

Thomson, H., Simcock, N., Bouzarovski, S., & Petrova, S. (2019). Energy poverty and indoor cooling: An overlooked issue in Europe. *Energy and Buildings*, *196*, 21–29.

Tinson, A., Aldridge, H., & MacInnes, T. (2016). Economic inequality in Northern Ireland. *Centre for Economic Empowerment & New Policy Institute. Retrieved on January*, *23*, 2017.

Tomlinson, C. J., Chapman, L., Thornes, J. E., & Baker, C. J. (2012). Derivation of Birmingham's summer surface urban heat island from MODIS satellite images. *International Journal of Climatology*, *32*(2), 214–224.

Tong, K., Ramaswami, A., Xu, C., Feiock, R., Schmitz, P., & Ohlsen, M. (2021). Measuring social equity in urban energy use and interventions using fine-scale data. *Proceedings of the National Academy of Sciences*, *118*(24), e2023554118.

US DOE. (2020). *EnergyPlus V8. United States Department of Energy (DOE).*

US Energy Information Administration. (2020). *2020 Residential Energy Consumption Survey*. https://www.eia.gov/consumption/residential/data/2020/

Vellei, M., Ramallo-González, A. P., Coley, D., Lee, J., Gabe-Thomas, E., Lovett, T., & Natarajan, S. (2017). Overheating in vulnerable and non-vulnerable households. *Building Research and Information*, *45*(1–2), 102–118. https://doi.org/10.1080/09613218.2016.1222190

Wan, K., Feng, Z., Hajat, S., & Doherty, R. M. (2022). Temperature-related mortality and associated vulnerabilities: evidence from Scotland using extended time-series datasets. *Environmental Health*, *21*(1), 1–14.

Watkins, R., Palmer, J., Kolokotroni, M., & Littlefair, P. (2002). The London Heat Island: results from summertime monitoring. *Building Services Engineering Research and Technology*, *23*(2), 97–106.

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.

Wright, D. L., Haines, V., & Lomas, K. (2018). *Overheating in UK homes: Adaptive opportunities, actions and barriers*.

Wright, M. K., Hondula, D. M., Chakalian, P. M., Kurtz, L. C., Watkins, L., Gronlund, C. J., Larsen, L., Mallen, E., &

Harlan, S. L. (2020). Social and behavioral determinants of indoor temperatures in air-conditioned homes. *Building and Environment*, *183*, 107187.

Yang, J., Wang, Z.-H., & Kaloush, K. E. (2015). Environmental impacts of reflective materials: Is high albedo a 'silver bullet'for mitigating urban heat island? *Renewable and Sustainable Energy Reviews*, *47*, 830–843.

Yao, M., & Zhao, B. (2017). Window opening behavior of occupants in residential buildings in Beijing. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2017.08.035

Zero Carbon Hub. (2015a). *Evidence review: OVERHEATING RISK MAPPING*. https://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview-Risks2.pdf

Zero Carbon Hub. (2015b). *OVERHEATING IN HOMES: Drivers of change*.

Zero Carbon Hub. (2016). *SOLUTIONS TO OVERHEATING IN HOMES: Evidence review*.

6. Appendices

6.1 Appendix A: Metamodel

The model used to assess indoor temperatures across the building stock is a metamodel previously developed at UCL derived from a number of *EnergyPlus* simulations. EnergyPlus is a whole-building energy simulation software which dynamically models building performance, taking the outdoor climate and terrain; building characteristics such as geometry, fabric, airtightness, floorspace; and occupant behaviour (e.g. window-opening frequency) as inputs (US DOE, 2020). The tool has previously been used to model indoor temperatures (Mavrogianni et al., 2017; Oikonomou et al., 2012), building energy use (Beagon et al., 2020) and indoor exposure to air pollution (Shrubsole et al., 2016; Taylor et al., 2014) for dwellings representative of the English and London housing stock.

An in-house tool developed by UCL, EPG2, allows for the mass-generation of EnergyPlus input definition files (IDFs). An IDF defines the input parameters mentioned previously for a single building. EPG2 randomly samples combinations of input parameters from pre-defined distributions to generate several hundred IDFs within a few minutes, thus making it suited to modelling building performance at the stock level as representative samples of buildings can be generated within a short space of time. The candidate distribution, mean and range of the input parameters are informed by nationally representative housing stock surveys such as the English Housing Survey (EHS). Individual IDFs are then be batch-simulated via the EnergyPlus engine using UCL Research Computing facilities.

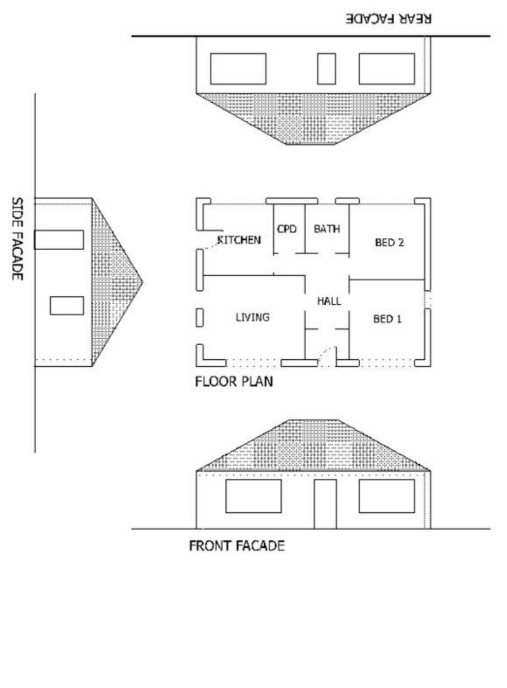
Indoor temperature and energy outputs from the simulations are then compiled and the relationship between input and output parameters is quantified using a feed-forward neural network (NN). Full details of the different metamodels tested and the development and performance of the chosen metamodel are available in Symonds et al. (2016). Alternative scenarios are then modelled using a housing stock dataset containing the same input parameters the metamodel was trained on for a different set of dwellings.

6.1.1 Data cleaning

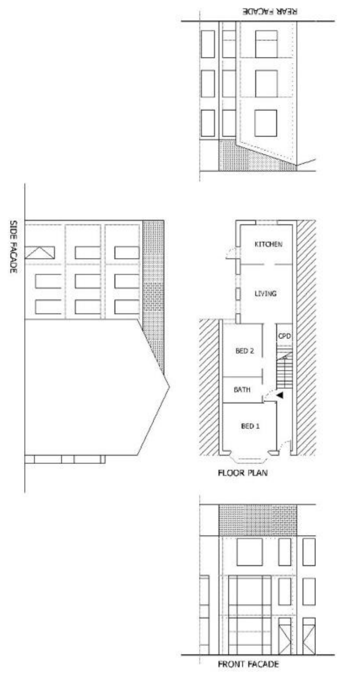
The dataset is filtered to remove instances of multiple certificates for a single dwelling, taking the most recent EPC for each property. Dwelling type is classified using a number of variables recorded in the EPC dataset including *Property type, built form, flat storey, floor level and flat top storey.* Dwellings are modelled based on eight archetypes broadly representative of the English building stock, which represent 75% of the housing stock in England (Oikonomou et al., 2012), shown in Figure 40 below.

Dwelling permeability was estimated according to the UK Government Standard Assessment Procedure (SAP) for energy in buildings (BRE, 2009). Thermal conductivity values for window, wall, floor and roof building elements are assigned based on the thermal transmittance value reported in the EPC database, where possible. If a numerical value is missing, U-values were assumed from the type of insulation and thickness recorded, or the classification of the building element (e.g. energy efficiency of windows may be ‘Very Good’, ‘Good’, ‘Average’, ‘Poor’ or ‘Very Poor’), as per SAP look up tables. Where the EPC data for a building is largely missing or obvious errors are identified, the entry for this building is omitted. This resulted in a sample of 2.37 million dwellings (65% of the existing London stock). Comparison of the EPC with nationally representative housing surveys has shown good agreement in previous studies (Taylor et al., 2019).

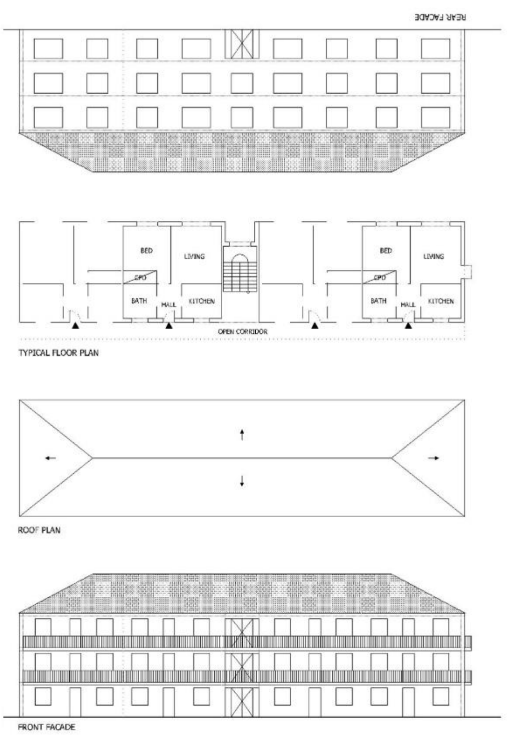
Bungalow



Converted Flat



Low-Rise Flat



High-Rise Flat

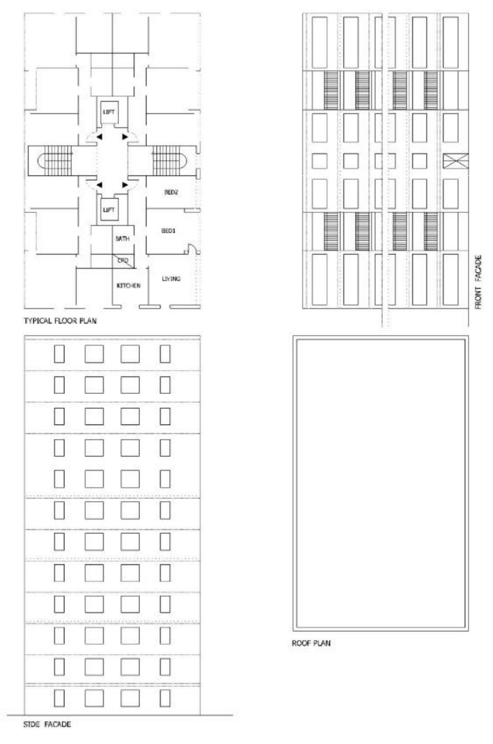


Figure 41. Dwelling façade and floor plans of the eight archetypes.

6.2 Appendix B: Identification of vulnerable subgroups

A literature review was carried out to synthesise the evidence on population-level measures of vulnerability which may lead to disproportionate health impacts following exposure to high and low ambient temperatures. The three mechanisms of vulnerability to environmental hazards are *exposure*, *sensitivity* and *adaptation.* As population exposure to indoor temperatures in this work package is quantified using dynamic thermal modelling, this review focuses on population-level indicators which may result in health impacts following exposure to high and low ambient temperatures. An individual's sensitivity to temperature and the degree to which they can adapt to high and low indoor temperatures can be considered under three categories: health vulnerability, socio-economic vulnerability and community factors. Underlying health will determine the likelihood of an individual experiencing deleterious effects following exposure to extreme temperatures. Socio-economic factors, such as personal income and age are also common proxies of underlying health, but such factors will also determine the extent to which each individual is able to adapt their surroundings to cope with extreme internal temperatures. Additionally, a given amount of financial wealth may not provide the same protection to temperature exposure for individuals of a different age or race. Thus, indicators characterising socio-economic vulnerability to temperature are discussed separately from health vulnerability.

6.2.1 Health vulnerability

Baseline population health is influenced by a number of factors such as age, gender and existing co-morbidities. In high-income countries such as the UK, there are few examples of hyperthermia (Hajat et al., 2014), which occurs when core body temperature is above average following exposure to sustained, excessive environmental *heat*. The converse physiological response to cold temperatures, *hypothermia*, is more common but overall represents a small portion of excess winter mortality and morbidity (Dear & McMichael, 2011). Rather, temperature-related health impacts arise indirectly from the body's adaptations to regulate temperature: Skin thermoreceptors will detect changes in external temperature, triggering the redistribution of blood flow. For low external temperatures, the diameter of blood vessels decreases, known as vasoconstriction, to direct blood away from the surface of the skin and prevent heat loss. Conversely, *vasodilation* occurs during high external temperatures to widen blood vessels and increase heat loss through the skins surface. This redistribution of blood flow during vasodilation and vasoconstriction increases cardiac demand and individuals with underlying heart problems may struggle to meet this demand, leading to tissue damage (known as ischaemia), heart attacks or even cardiac collapse (Ebi et al., 2021).

Within the UK today, approximately 7.6 million people, 3.6 million women and 4 million men, are living with a heart or circulatory problem (BHF, 2022a). Though England has a greater number of coronary heart disease (CHD) cases, the prevalence of CHD is highest for Scotland than other areas of the UK (Bhatnagar et al., 2016; BHF, 2022b). The prevalence of cardiovascular conditions increases almost linearly with age: 47% of those aged 55-64 years old and 65% of those aged 65 and over are affected in the UK, compared with 31% of the total population (Stewart, 2020). These figures may partially explain the higher incidence of mortality observed in older age groups during hot and cold weather events (Bennett et al., 2014; Hajat et al., 2006; Ishigami et al., 2008). Further, CHD is more common in individuals of African, Caribbean or South Asian heritage (Cappuccio et al., 1997; Okwuosa et al., 2016). Though no association between heat-related health risks and race has been documented in the literature for the UK, the effect has been observed in the US (Madrigano et al., 2015).

Pre-menopausal women have a lower risk of cardiovascular disease compared to men of the same age, but this advantage does not continue as women age, and older women have an increased risk of mortality during heatwaves (Núñez-Peiró et al., 2019). The mechanisms behind this are not well understood, but the presence of oestrogen in female bodies, social isolation and sex-based financial disadvantage are thought to play a role (van Steen et al., 2019). For cold outdoor temperatures, mortality risk has been found to be higher for men (Achebak et al., 2019) or shown no sex-based patterning (Folkerts et al., 2022).

Despite relatively less research, children have a lower cardiac index[3] than adults, which limits their ability to thermoregulate, for example via vasodilation, placing stress on the kidneys (Xu et al., 2014). This stress may lead to renal disease in children and infants, and an increase in infant hospital admissions for renal dysfunction during heatwaves has been reported in Europe (Kovats & Kristie, 2006) and London (Kovats et al., 2004). There is limited research alluding to cardiovascular disease amongst children during cold weather events, but respiratory illnesses in younger age groups during winter are well studied (Fang et al., 2021; Xu et al., 2018). As temperatures decrease, circulation of viruses and indoor pollutants will increase, especially in overcrowded homes, as intentional ventilation will be limited to reduce heat loss. This leads to an increase in respiratory infections and asthma attacks, which is felt primarily by the children living in cold homes due to their premature immune and lung systems (Barrett et al., 2022). Respiratory diseases have

[3] Cardiac index is a parameter relating heart performance to the size of an individual, measured in litres per minute per square metre (L/min/m^2).

also been identified as a driver of *heat*-related hospital admissions in London for children under five (Kovats et al., 2004; Xu et al., 2014).

Respiratory disease in older age groups is the second leading cause of excess winter deaths in the UK (Dear & McMichael, 2011), as cold air reduces the protective function of the respiratory tract (D'Amato et al., 2018). Likewise, breathing in hot and humid air during heatwaves may exacerbate existing respiratory conditions in older age groups, such as chronic obstructive pulmonary disease (COPD). Approximately three million people in the UK have COPD, with prevalence linked to smoking and closely aligned with deprivation levels across the UK (NICE, 2016), thus such populations are likely to have higher risk of mortality and morbidity from high and low temperatures during heatwaves and cold spells, respectively.

Cold homes and fuel poverty are associated with poor mental health across all age groups (Dear & McMichael, 2011). The literature suggests that households with young children are most at risk, with children growing up in cold homes more likely to experience anxiety, depression and slower cognitive development (Whitehead et al., 2022) and higher odds of depression in cold homes for the parents of younger children due to care obligations (Mohan, 2022).

6.2.2 Socio-economic vulnerability

Deprivation and health are intrinsically linked in the UK, with the risk of death from preventable diseases three times higher for those living in the poorest versus those living in the most affluent parts of England (Bennett et al., 2018). Respiratory and cardiovascular diseases, such as COPD and CHD mentioned in Section 2.1., are two health conditions primarily responsible for the growing health inequalities gap (Bennett et al., 2018) and the primary risk factors for temperature-related mortality risks (Dear & McMichael, 2011; Ebi et al., 2021). Deprived areas of England have higher rates of mortality from CHD (Bajekal et al., 2013; Theocharidou & Mulvey, 2018), and in a study of 1.2 million women across the UK this was largely explained by differences in smoking prevalence, alcohol consumption, physical activity and body mass index (Floud et al., 2016). Likewise, deprivation is associated with higher incidence of respiratory diseases: Deprived individuals had increased hospital admissions for respiratory infections, with the effect pronounced in the 0-4 years age group where admission rates were 91% higher for the most versus the least deprived children (Hawker et al., 2003) and mortality rates were higher for more deprived patients in a sample of 424 patients with COPD (Collins et al., 2018). Such illnesses will influence the likelihood of experiencing adverse health effects during hot and cold weather events, but deprivation may similarly limit an individual's ability to adjust their surroundings to cope with high and low ambient temperatures.

Fuel poverty definitions in the UK have traditionally applied to households who cannot keep their home warm using a reasonable proportion of their income. In England a household is considered to be in fuel poverty if they are living in a property with an EPC rating of band D or below; and if they spent the amount of income required to adequately heat their home they would be left with a residual income which is below the official poverty line[4] (BEIS, 2022). Thus, it is a relative measure of household income, fuel prices and building energy efficiency. Across the UK, there are 13%, 25%, 12% and 18% of households in fuel poverty in England, Scotland, Wales and Northern Ireland, respectively (Hinson & Bolton, 2022). These households will have a greater risk of developing cold-related health impacts compared with those not in fuel poverty, given the same level of underlying health, as they do not possess the resources to improve their environmental conditions. The current cost of living crisis is expected to push 15 million households into fuel poverty (Bradshaw & Keung, 2022), with those most at risk in England identified as private renters, households with children, single-parent households, ethnic minority households and those occupied by people with disabilities (BEIS, 2022a; Bouzarovski et al., 2022; Snell et al., 2015).

Household cooling needs are not currently considered in the UK's definition of fuel poverty, despite approximately 20% of homes already experiencing indoor overheating, with poorer households disproportionately affected (Lomas et al., 2021) and areas previously-thought low-risk similarly suffering, such as Scotland (Morgan et al., 2017). In countries where household air-conditioning is prevalent, there is growing recognition of the need to incorporate cooling needs into the definition of energy poverty (Bienvenido-Huertas et al., 2021; Thomson et al., 2019) and access to air conditioning in the US has been identified as a driver of disparities in heat-related mortality (O'Neill et al., 2005). Despite a lack of UK data on uptake of air conditioning in homes, prevalence is estimated to be less than 3% (Hulme et al., 2013), with this figure is expected to rise to between 5% - 32% by 2050 (Crawley et al., 2020) and uptake is likely to be bias in more affluent homes. Low-income individuals may be unable to afford air conditioning units and government aid is unlikely to extend to such installations as this may undermine national carbon targets, typically preferring passive strategies. Energy-poor homes are therefore likely to additionally suffer from high ambient temperatures in the future (Sanchez-Guevara et al., 2019).

[4] Households are considered to be below the UK poverty line if their income is 60% below the median household income after housing costs for that year.

The short-term solution of home electric fans has been found to be protective against heat-related mortality (Morris et al., 2021) and is a likely driver of the increased electricity demand observed during the 2018 UK heatwave (Larcom et al., 2019). In a UK survey on health protection behaviour following the 2013 heatwave, high-income earners were three times more likely to use an electric fan than those on lower incomes (Khare et al., 2015).

6.2.3 Community factors

Social isolation is associated with increased risk of all-cause mortality and is more common in urban areas, older individuals, the unemployed, among women and those with a lower educational attainment (Naito et al., 2021). The degree of social isolation an individual experiences has been identified as a factor influencing *heat* vulnerability. Single and divorced individuals had a higher risk of heat-related mortality in the 2003 French heatwave (Fouillet et al., 2006). Authors highlighted the role of social isolation in mediating vulnerability to heat waves, as indicated in earlier research from the US (Naughton et al., 2002; Semenza et al., 1996). Wistow et al. (2015) illustrated heat vulnerability using the theory of formal and informal networks of care, suggesting that for older individuals who are disproportionately reliant on formal health and social care networks, such as the NHS, heatwaves and other extreme weather events may disrupt the usual performance of these networks. This can result in endangered health for individuals who are socially isolated as they will not have the *informal* networks to bring this discontinuity of care to attention (Wistow et al., 2015). However, qualitative case-study interviews carried out in London and Norwich in England found that strong social networks can *exacerbate* vulnerability to overheating by perpetuating the narrative that vulnerable individuals are likely to be able to cope with high temperatures rather than challenging it (Wolf et al., 2010). Authors acknowledged that further research is needed to define the role social capital may have in climate change adaptation, in particular for health protection.

6.2.4 Area-measures of vulnerability

Area-level indicators were sought for the three domains discussed above to use in the main report, which each characterise an aspect of population vulnerability to ambient temperature. Each indicator, its rationale for inclusion and the source of the data is outlined in Table 12. Table 12 assigns each indicator a level of confidence one a five-point scale, (1 – very low; 2 – low; 3 – medium; 4 – high; 5 – very high) according to the Intergovernmental Panel on Climate Change (IPCC) Guidance Note, adopted for CS-N0W projects. Figure 41 shows how findings are rated, considering the associated number of studies and the strength of the *evidence*, and the extent of *agreement* between sources.

Agreement	**High**	**3**	**4**	**5**
	Medium	**2**	**3**	**4**
	Low	**1**	**2**	**3**
		Limited	**Medium**	**Robust**
		Evidence (amount and strength of evidence)		

Figure 42. Scale for rating confidence in key findings of literature reviews.

For the main report, we chose to assess climate-induced effects for the four population subgroups for which there was most available evidence, namely, those aged 65 and above; infants; low-income individuals and ethnic minorities. Whilst the evidence was strongest for individuals with underlying COPD and CHD, a number of populations are disproportionately burdened with these two health conditions (e.g. lower income individuals, those aged 65 and over), along with additional risk factors for climate-induced health impacts due to the multi-dimensional nature of vulnerability. We therefore focus on specific population groups that are vulnerable to climate risk in a number of ways. We acknowledge that there is significant diversity within and between population groups (e.g. ethnic minorities). Due to time constraints, we limited the analysis to a small number of groups. Future work could look at distributions of vulnerability for sub-categories within these groups.

Table 14. Area-measures of temperature vulnerability identified from the literature review, shown with their definition, rationale for inclusion and data source.

Domain	Indicator	Rationale	Source
Health vulnerability	Percentage of patients with a diagnosis of **chronic obstructive pulmonary disease** (COPD), per LSOA.	Beathing in hot and humid air can exacerbate COPD; and cold external temperatures make breathing more difficult which is worse in those already suffering from breathing problems.	(Rose et al., 2021a)
	Percentage of GP patients with a diagnosis of **coronary heart disease** (CHD), per LSOA.	The redistribution of blood flow that occurs when the body perceives high (vasodilation) and low (vasoconstriction) external temperatures places additional demand on the heart, which those with existing heart conditions will struggle to meet.	(Rose et al., 2021b)
	Income deprivation score, by LSOA	Low-income populations have higher incidence of COPD and CHD; more likely to be	(ONS, 2019)

Socio-economic vulnerability		fuel poor; less likely to be able to afford building interventions to reduce exposure to high and low ambient temperatures.	
	Proportion of the population who are **female**, by LSOA	Are at increased risk of mortality during heatwaves; due to social isolation, sex-based financial disadvantage and physiology.	(ONS, 2021)
	Percentage of population aged **65 years** or above, by LSOA	Those 65+ have higher incidence of CHD and COPD; and are more likely be socially isolated, relying on formal care networks which are typically disrupted during extreme weather events.	(ONS, 2021)
	Proportion of the population identifying as an **ethnic minority***, by LSOA	Ethnic minorities have higher incidence of CHD and are more likely to live in fuel-poor households.	(ONS, 2022)
	Percentage of population who are **infants** (≤4 years old), by LSOA	Prone to respiratory and renal dysfunction during heatwaves; have less adaptive capacity due to lower mobility; more likely to live in fuel-poor homes.	(ONS, 2021)
Community factors	Percentage of **one person households** of the total number of households, per LSOA	Socially isolated individuals had a higher risk of heat-related mortality in heatwaves across Europe and the US.	

*Ethnic minority was defined as those belonging to a racial or ethnic group outside of the majority white British population of the UK. It is important to note that ethnic minority groups in the UK are not a monolith, but that all may be affected by structural discrimination to some extent across a number of health and socio-economic outcomes, leading to differences in risk from climate-induced effects.

6.3 Appendix C: Additional results

6.3.1 England

Figure 42 shows the cooling energy-use intensities (EUIs) aggregated by population quintiles under 2085 4.0°C warming in England. The figure suggests that the higher uptake of the intervention measures across the stock in 2085 would largely attenuate present-day inequalities in

EUIs for different population groups, excluding low-income individuals who generally have larger disparities in cooling EUIs across all scenario except Scenario 2a where external shutters were used.

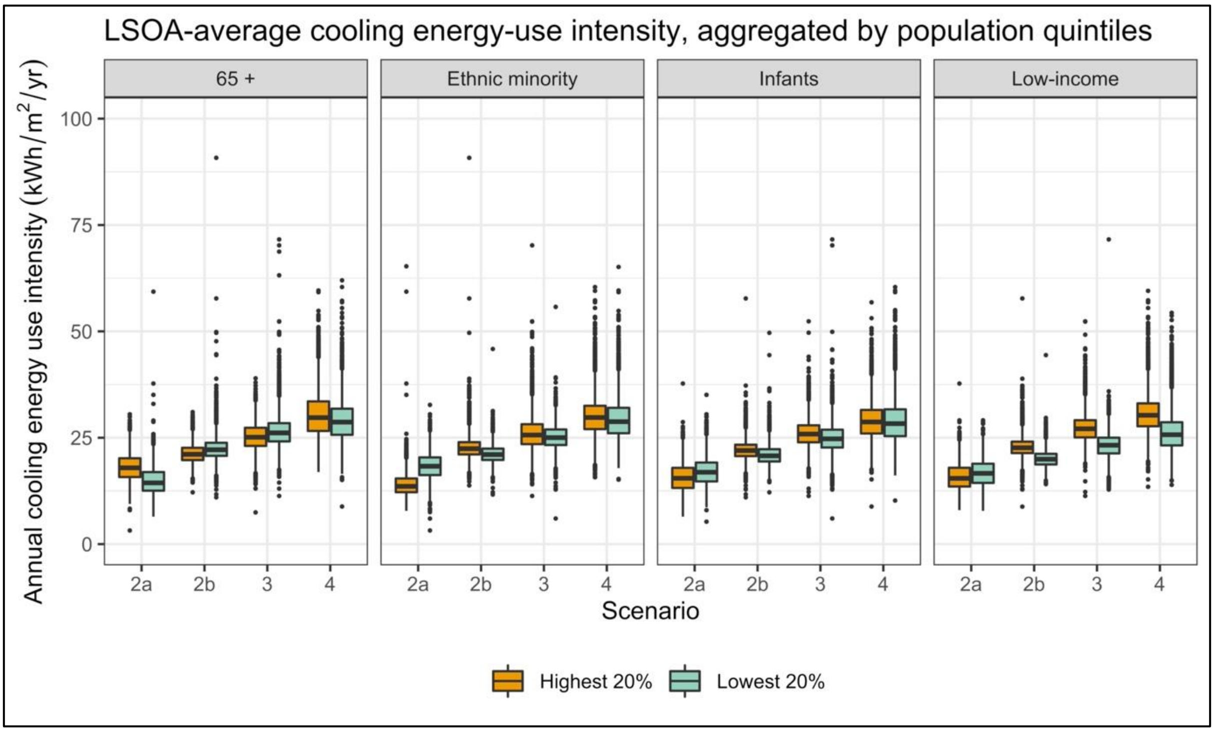


Figure 43. LSOA-average cooling EUIs for population quintiles in Scenarios 2a – 4 in the 2085 time horizon under 4.0C warming for the English housing stock.

Figure 43 shows an analysis of dwelling summertime overheating under 1.5°C warming in the 2050 time horizon for each of the building intervention scenarios across the English housing stock. The figure supports the findings from Figure 10 and 11 in the main report that internal and external shading are most effective at reducing overheating.

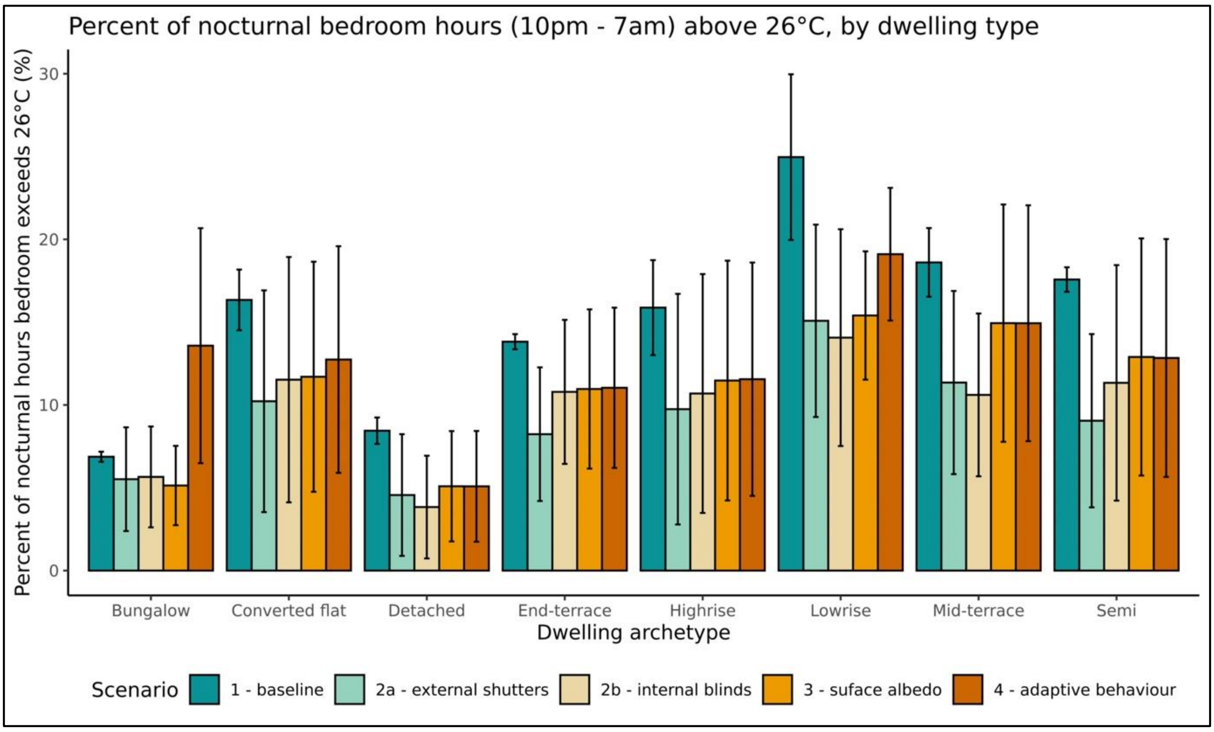


Figure 44. The percent of annual night time hours the bedroom temperature exceeded 26C in the 2050 time horizon under 1.5C warming, by dwelling type, across all building intervention scenarios for the English housing stock.

6.3.2 Wales

Likewise, Figure 44 shows dwelling overheating under 1.5 warming in the 2050 (a) and 2085 (b) time horizons across Welsh dwellings. The percent of hours above 26°C is lower in Welsh dwellings due to the lower ambient temperature of the Cardiff weather file. The high uptake of air conditioning across the stock in 2085 (79%) reduces the extent of indoor overheating compared to the 2050 time horizon. Both figures suggest that shading devices are most effective at reducing indoor overheating. The large error bars in the 2085 time horizon are due to the high variance as 21% of the stock are still without air conditioning, leading to appreciable differences in overheating. Flats also show a large amount of variation across both time horizons, owing to the differences in overheating across different floor levels.

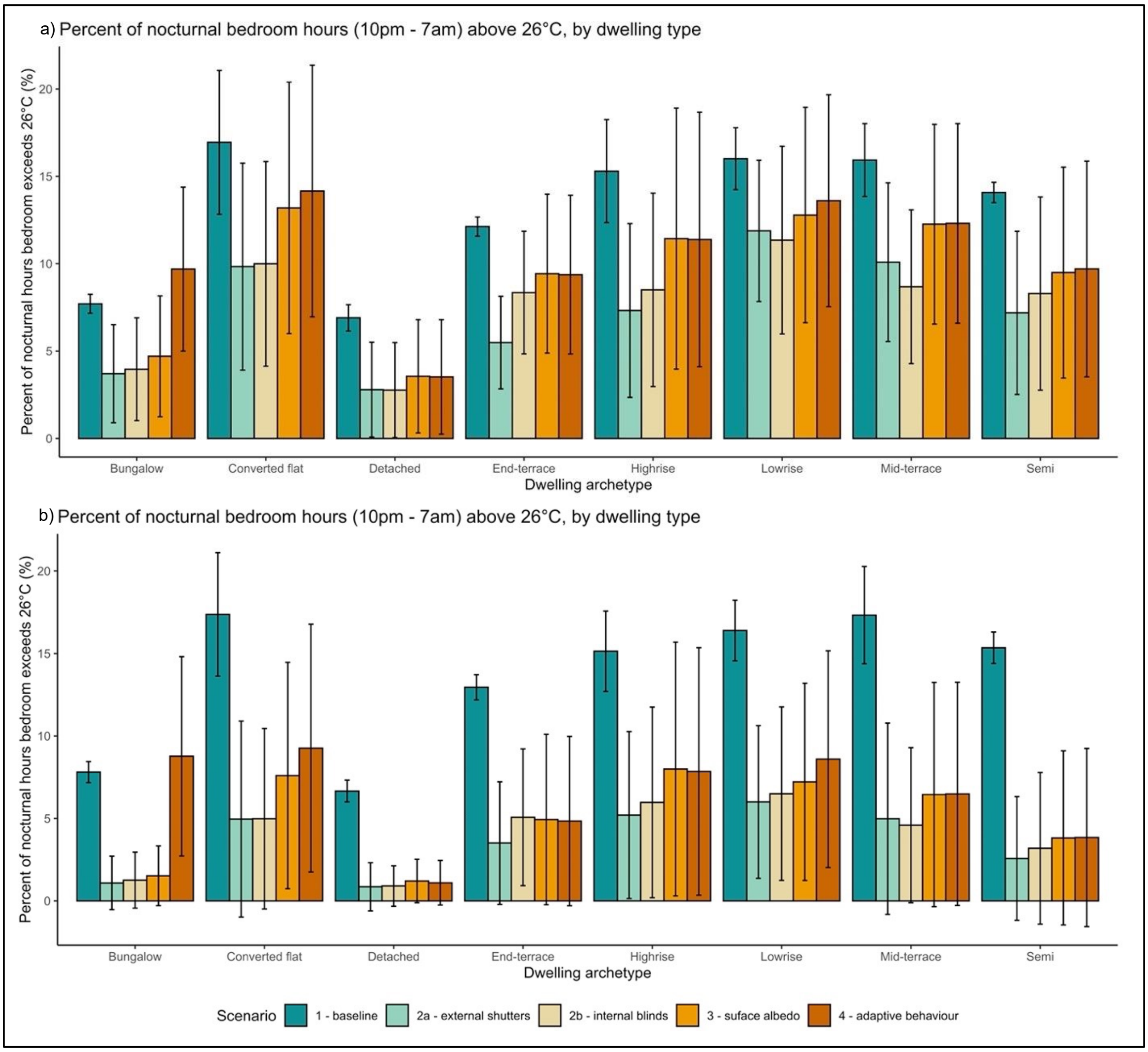


Figure 45. The percent of annual night time hours the bedroom temperature exceeded 26C in the 2050 (a) and 2085 (b) time horizon under 1.5C warming, by dwelling type, across all building intervention scenarios for the Welsh housing stock.

6.3.3 Northern Ireland

The equivalent results for Northern Ireland at different time horizons are shown in Figure 45.

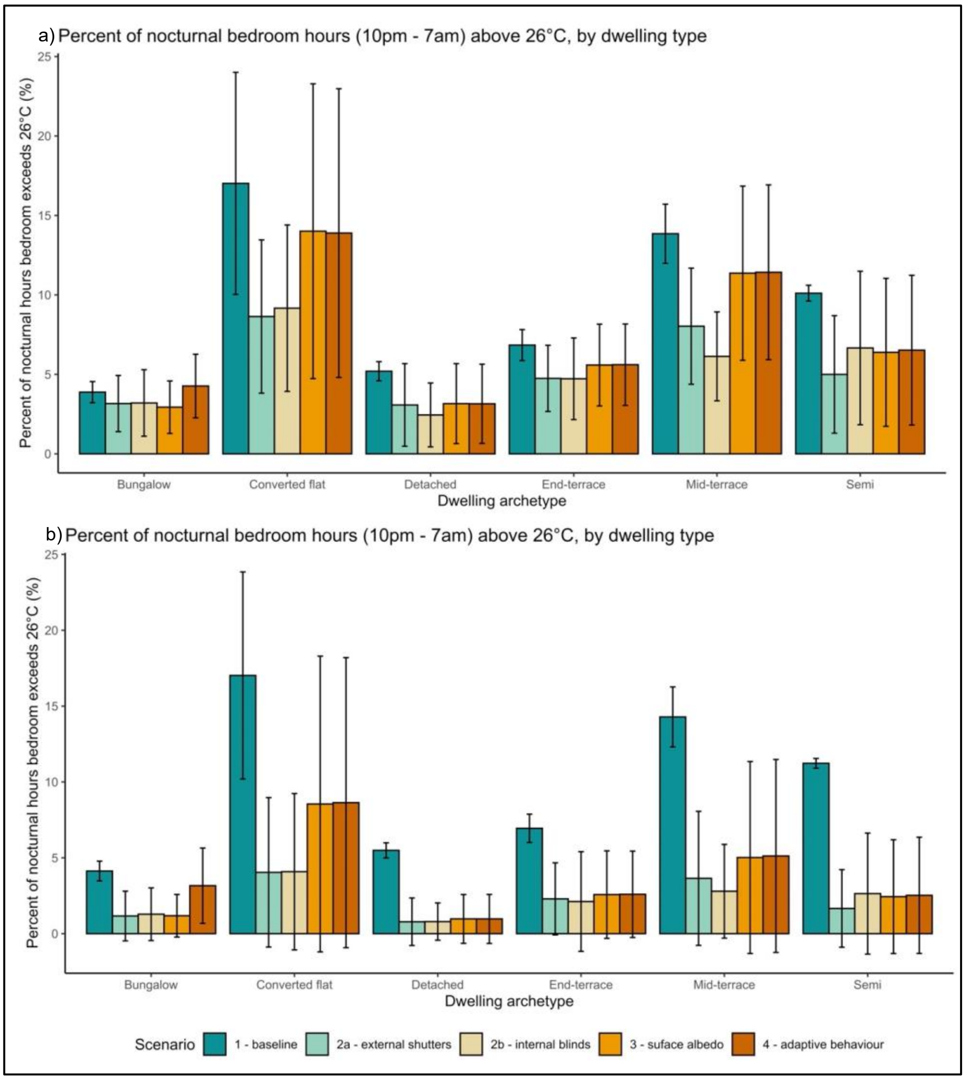


Figure 46. The percent of annual night time hours the bedroom temperature exceeded 26C in the 2050 (a) and 2085 (b) time horizon under 1.5C warming, by dwelling type, across all building intervention scenarios for the Northern Irish housing stock.

6.3.4 Scotland

Figure 46 shows the percent of annual hours the nocturnal bedroom temperature (10pm – 7am) exceed 26°C across all building intervention scenarios for Scottish dwellings in the 2050s time horizon under 1.5°C degree warming. Internal and external shading devices are generally most effective at minimising indoor overheating across all dwelling types. The large error bars are a result of ~70% of the stock are still without air conditioning at this time horizon.

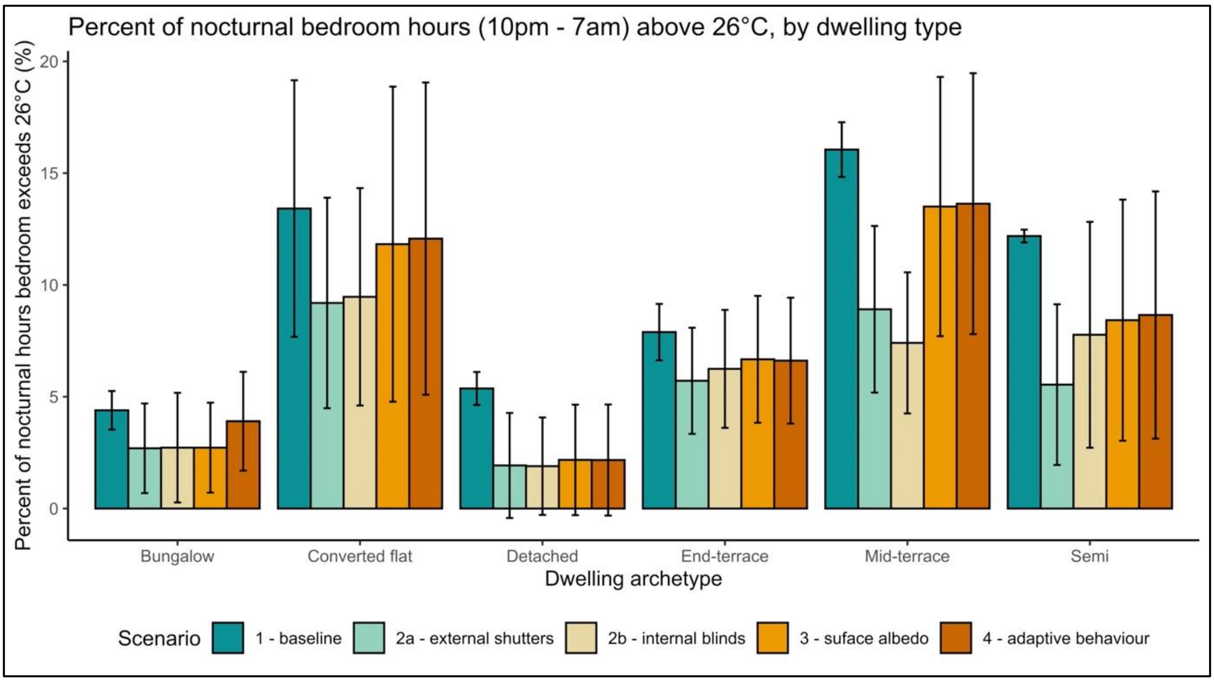


Figure 47. The percent of annual night time hours the bedroom temperature exceeded 26C in the 2050 time horizon under 1.5C warming, by dwelling type, across all building intervention scenarios for the Scottish housing stock.

6.4 Appendix D: Comparison with existing data

To assess how outputs for heating energy use compare with empirical data, annual heating energy demand was simulated across the London stock using a London 2020s weather file. Results were aggregated at the LSOA level and compared with subnational gas consumption data from BEIS using a linear regression, shown in in Figure 47. Adjusted R-squared between modelled and empirical energy consumption was 0.782 (df=4825, p=2.2e^{-16}). In general, modelled data underestimated annual energy demand but it is useful to note that modelled estimates are for heating demand only, whilst subnational gas estimates will be for all gas use including that from heating, cooking and hot water.

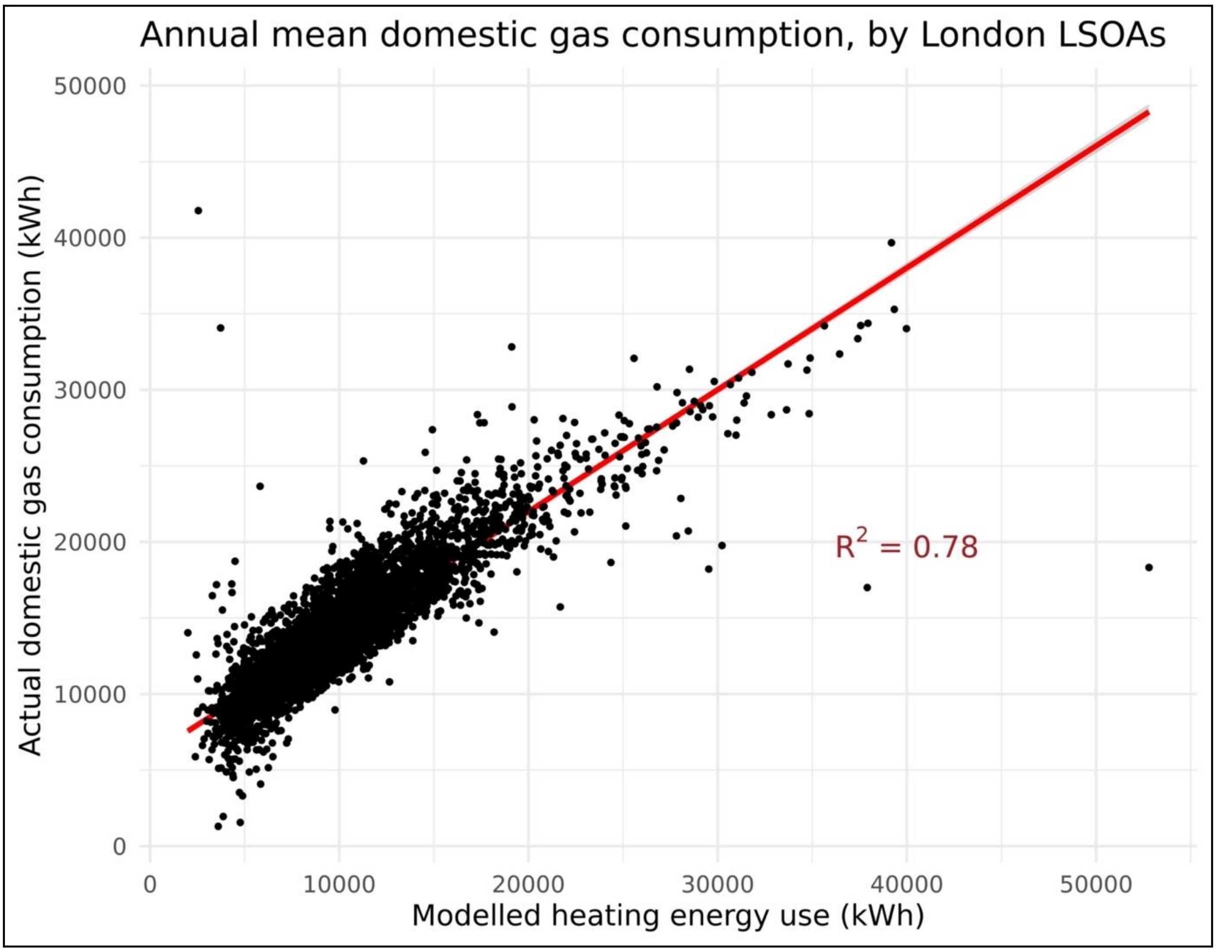


Figure 48. Linear regression between subnational gas consumption estimates and metamodel outputs across London LSOAs in 2020.

Subnational estimates of domestic gas use are not available by archetype, but results were compared with previous modelled data by Liddiard et al. (2021) in Table 13. Outputs by attached status broadly align with estimates produced by Liddiard et al. (2021). The marginally lower estimates produced by the metamodel can likely be explained by the warmer climate of 2020, compared to 2016 for which the estimates by Liddiard (2021) were produced.

Table 15. Comparison of annual heating energy use and heating energy use intensities between the metamodel and Liddiard et al. (2021)

Dwelling type	Liddiard et al. (2021)		Metamodel	
	Annual gas (kWh/yr)	Annual gas use intensity (kWh/m²/yr)	Annual heating energy use (kWh)	Annual heating energy use per floor area (kWh/m²/yr)

Detached*	24,366	170	22,361	171
Semi-detached	18,874	171	17,156	153
End-terrace	16,384	165	14,475	150
Mid-terrace	14,865	144	12,958	129

6.5 Appendix: References

Achebak, H., Devolder, D., & Ballester, J. (2019). Trends in temperature-related age-specific and sex-specific mortality from cardiovascular diseases in Spain: a national time-series analysis. The Lancet Planetary Health, 3(7), e297–e306.

Bajekal, M., Scholes, S., O'Flaherty, M., Raine, R., Norman, P., & Capewell, S. (2013). Unequal trends in coronary heart disease mortality by socioeconomic circumstances, England 1982–2006: an analytical study. PLoS One, 8(3), e59608.

Barrett, C., Lee, A. R., Abrams, E. M., Mayell, S. J., Hawcutt, D. B., & Sinha, I. P. (2022). Eat or heat: fuel poverty and childhood respiratory health. The Lancet Respiratory Medicine, 10(3), 229.

BEIS – Department for Business Energy and Industrial Strategy. (2022a). Annual Fuel Poverty Statistics in England, 2022 (2020 data).

BEIS – Department for Business Energy and Industrial Strategy. (2022b). Fuel Poverty Factsheet. England, 2020.

Bennett, J. E., Blangiardo, M., Fecht, D., Elliott, P., & Ezzati, M. (2014). Vulnerability to the mortality effects of warm temperature in the districts of England and Wales. Nature Climate Change, 4(4), 269–273.

Bennett, J. E., Pearson-Stuttard, J., Kontis, V., Capewell, S., Wolfe, I., & Ezzati, M. (2018). Contributions of diseases and injuries to widening life expectancy inequalities in England from 2001 to 2016: a population-based analysis of vital registration data. The Lancet Public Health, 3(12), e586–e597. https://doi.org/10.1016/S2468-2667(18)30214-7

Bhatnagar, P., Wickramasinghe, K., Wilkins, E., & Townsend, N. (2016). Trends in the epidemiology of cardiovascular disease in the UK. Heart, 102(24), 1945–1952.

Bienvenido-Huertas, D., Sánchez-García, D., Rubio-Bellido, C., & Pulido-Arcas, J. A. (2021). Applying the mixed-mode with an adaptive approach to reduce the energy poverty in social dwellings: The case of Spain. Energy, 237, 121636.

Bouzarovski, S., Burbidge, M., Sarpotdar, A., & Martiskainen, M. (2022). The diversity penalty: Domestic energy injustice and ethnic minorities in the United Kingdom. Energy Research & Social Science, 91, 102716.

Bradshaw, J. R., & Keung, A. (2022). Fuel poverty estimates for the UK. Poverty.

British Heart Foundation. (2022a). Facts and figures: Heart statistics.

British Heart Foundation. (2022b). Scotland Factsheet: British Heart Foundation. https://www.bhf.org.uk/what-we-do/our-research/heart-statistics

Cappuccio, F. P., Cook, D. G., Atkinson, R. W., & Strazzullo, P. (1997). Prevalence, detection, and management of cardiovascular risk factors in different ethnic groups in south London. Heart, 78(6), 555–563.

Collins, P. F., Stratton, R. J., Kurukulaaratchy, R. J., & Elia, M. (2018). Influence of deprivation on health care use, health care costs, and mortality in COPD. International Journal of Chronic Obstructive Pulmonary Disease, 13, 1289.

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.

D'Amato, M., Molino, A., Calabrese, G., Cecchi, L., Annesi-Maesano, I., & D'Amato, G. (2018). The impact of cold on the respiratory tract and its consequences to respiratory health. Clinical and Translational Allergy, 8(1), 1–8.

Dear, K. B. G., & McMichael, A. J. (2011). The health impacts of cold homes and fuel poverty. In BMJ (Vol. 342, Issue 7806). British Medical Journal Publishing Group. https://doi.org/10.1136/bmj.d2807

Ebi, K. L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R. S., Ma, W., & Malik, A. (2021). Hot weather and heat extremes: health risks. The Lancet, 398(10301), 698–708.

Fang, J., Song, J., Wu, R., Xie, Y., Xu, X., Zeng, Y., Zhu, Y., Wang, T., Yuan, N., & Xu, H. (2021). Association between ambient temperature and childhood respiratory hospital visits in Beijing, China: a time-series study (2013–2017). Environmental Science and Pollution Research, 28(23), 29445–29454.

Floud, S., Balkwill, A., Moser, K., Reeves, G. K., Green, J., Beral, V., & Cairns, B. J. (2016). The role of health-related behavioural factors in accounting for inequalities in coronary heart disease risk by education and area deprivation: prospective study of 1.2 million UK women. BMC Medicine, 14(1), 1–9.

Folkerts, M. A., Bröde, P., Botzen, W. J., Martinius, M. L., Gerrett, N., Harmsen, C. N., & Daanen, H. A. M. (2022). Sex differences in temperature-related all-cause mortality in the Netherlands. International Archives of Occupational and Environmental Health, 95(1), 249–258.

Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guihenneuc-Jouyaux, C., Clavel, J., Jougla, E., & 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.

Hajat, S, Kovats, S., & Lachowycz, K. (2006). The determinants of heat-related mortality in England and Wales. Epidemiology, 17(6), S164.

Hajat, Shakoor, Vardoulakis, S., Heaviside, C., & Eggen, B. (2014). Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J Epidemiol Community Health, 68(7), 641–648.

Hawker, J. I., Olowokure, B., Sufi, F., Weinberg, J., Gill, N., & Wilson, R. C. (2003). Social deprivation and hospital admission for respiratory infection:: an ecological study. Respiratory Medicine, 97(11), 1219–1224.

Hinson, S., & Bolton, P. (2022). Fuel Poverty. The House of Commons Library: London, UK. https://researchbriefings.files.parliament.uk/documents/CBP-8730/CBP-8730.pdf

Hulme, J., Beaumont, A., & Summers, C. (2013). Energy Follow-Up Survey 2011: Report 9-Domestic Appliances, Cooking & Cooling Equipment. Watford, UK, 13.

Ishigami, A., Hajat, S., Kovats, R. S., Bisanti, L., Rognoni, M., Russo, A., & Paldy, A. (2008). An ecological time-series study of heat-related mortality in three European cities. Environmental Health, 7(1), 1–7.

Khare, S., Hajat, S., Kovats, S., Lefevre, C. E., De Bruin, W. B., Dessai, S., & Bone, A. (2015). Heat protection behaviour in the UK: results of an online survey after the 2013 heatwave. BMC Public Health, 15(1), 1–12.

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.

Kovats, R. S., & Kristie, L. E. (2006). Heatwaves and public health in Europe. European Journal of Public Health, 16(6), 592–599.

Larcom, S., She, P.-W., & van Gevelt, T. (2019). The UK summer heatwave of 2018 and public concern over energy security. Nature Climate Change, 9(5), 370–373.

Liddiard, R., Godoy-Shimizu, D., Ruyssevelt, P., Steadman, P., Evans, S., Humphrey, D., & Azhari, R. (2021). Energy use intensities in London houses. Buildings and Cities, 2(1), 336–353.

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, 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), 672–678.

Mohan, G. (2022). The impact of household energy poverty on the mental health of parents of young children. Journal of Public Health, 44(1), 121–128.

Morgan, C., Foster, J. A., Poston, A., & Sharpe, T. R. (2017). Overheating in Scotland: contributing factors in occupied homes. Building Research & Information, 45(1–2), 143–156.

Morris, N. B., Chaseling, G. K., English, T., Gruss, F., Maideen, M. F. Bin, Capon, A., & Jay, O. (2021). Electric fan use for cooling during hot weather: a biophysical modelling study. The Lancet Planetary Health, 5(6), e368–e377.

Naito, R., Leong, D. P., Bangdiwala, S. I., McKee, M., Subramanian, S. V, Rangarajan, S., Islam, S., Avezum, A., Yeates, K. E., & Lear, S. A. (2021). Impact of social isolation on mortality and morbidity in 20 high-income, middle-income and low-income countries in five continents. BMJ Global Health, 6(3), e004124.

Naughton, M. P., Henderson, A., Mirabelli, M. C., Kaiser, R., Wilhelm, J. L., Kieszak, S. M., Rubin, C. H., & McGeehin, M. A. (2002). Heat-related mortality during a 1999 heat wave in Chicago. American Journal of Preventive Medicine, 22(4), 221–227.

National Institute for Health and Care Excellence [NICE]. (2016). Chronic obstructive pulmonary disease in adults. In NICE quality standard QS10.

Núñez-Peiró, M., Sánchez, C. S.-G., Sanz-Fernández, A., Gayoso-Heredia, M., López-Bueno, J. A., González, F., Linares, C., Díaz, J., & Gómez-Muñoz, G. (2019). Exposure and vulnerability toward summer energy poverty in the city of Madrid: a gender perspective. International Conference on Smart and Sustainable Planning for Cities and Regions, 481–495.

O'Neill, M. S., Zanobetti, A., & Schwartz, J. (2005). Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. Journal of Urban Health, 82(2), 191–197.

Okwuosa, I. S., Lewsey, S. C., Adesiyun, T., Blumenthal, R. S., & Yancy, C. W. (2016). Worldwide disparities in cardiovascular disease: challenges and solutions. International Journal of Cardiology, 202, 433–440.

ONS. (2019). English indices of deprivation 2019.

ONS - Office for National Statistics. (2021). Population estimates by output areas, electoral, health and other geographies, England and Wales: mid-2020. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualsmallareapopulationestimates/latest

ONS - Office for National Statistics. (2022). Ethnic group. Census 2021 estimates. TS021.

Rose, T., Daras, K., & Barr, B. (2021a). Quality and Outcomes Framework Indicators: Chronic obstructive pulmonary disease prevalence. Place-based Logitudinal Data Resource. https://doi.org/http://dx.doi.org/10.17638/datacat.liverpool.ac.uk/1351

Rose, T., Daras, K., & Barr, B. (2021b). Quality and Outcomes Framework Indicators: Coronary heart disease prevalence. https://doi.org/http://dx.doi.org/10.17638/datacat.liverpool.ac.uk/1197

Sanchez-Guevara, C., Peiró, M. N., Taylor, J., Mavrogianni, A., & González, J. N. (2019). Assessing population vulnerability towards summer energy poverty: Case studies of Madrid and London. Energy and Buildings, 190, 132–143.

Semenza, J. C., Rubin, C. H., Falter, K. H., Selanikio, J. D., Flanders, W. D., Howe, H. L., & Wilhelm, J. L. (1996). Heat-related deaths during the July 1995 heat wave in Chicago. New England Journal of Medicine, 335(2), 84–90.

Snell, C., Bevan, M., & Thomson, H. (2015). Justice, fuel poverty and disabled people in England. Energy Research & Social Science, 10, 123–132.

Stewart, C. (2020). Cardiovascular conditions in the United Kingdom (UK) 2018, by age. https://www.statista.com/statistics/420233/cardiovascular-conditions-by-gender-and-age-in-the-united-kingdom/

Theocharidou, L., & Mulvey, M. R. (2018). The effect of deprivation on coronary heart disease mortality rate. Bioscience Horizons: The International Journal of Student Research, 11.

Thomson, H., Simcock, N., Bouzarovski, S., & Petrova, S. (2019). Energy poverty and indoor cooling: An overlooked issue in Europe. Energy and Buildings, 196, 21–29.

van Steen, Y., Ntarladima, A.-M., Grobbee, R., Karssenberg, D., & Vaartjes, I. (2019). Sex differences in mortality after heat waves: are elderly women at higher risk? International Archives of Occupational and Environmental Health, 92(1), 37–48.

Whitehead, M., Taylor-Robinson, D., & Barr, B. (2022). Fuel poverty is intimately linked to poor health. In bmj (Vol. 376). British Medical Journal Publishing Group.

Wistow, J., Dominelli, L., Oven, K., Dunn, C., & Curtis, S. (2015). The role of formal and informal networks in supporting older people's care during extreme weather events. Policy & Politics, 43(1), 119–135.

Wolf, J., Adger, W. N., Lorenzoni, I., Abrahamson, V., & Raine, R. (2010). Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities. Global Environmental Change, 20(1), 44–52.

Xu, Z., Crooks, J. L., Davies, J. M., Khan, A. F., Hu, W., & Tong, S. (2018). The association between ambient temperature and childhood asthma: a systematic review. International Journal of Biometeorology, 62(3), 471–481.

Xu, Z., Sheffield, P. E., Su, H., Wang, X., Bi, Y., & Tong, S. (2014). The impact of heat waves on children's health: a systematic review. International Journal of Biometeorology, 58(2), 239–247.

UK Government

CS-NOW

Climate services for a net zero resilient world