ARUP

Addressing overheating risk in existing UK homes

An Arup report commissioned by the Climate Change Committee

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Addressing overheating risk in existing UK homes

Summertime overheating in homes affects health and productivity, and this year's record breaking temperatures in the UK brought this into sharp focus.

This report appraises the current and future risks posed by summertime overheating to the UK housing stock at scale. The work considers what factors influence risk, how homes can be adapted or upgraded to mitigate the impacts and how much that might cost.

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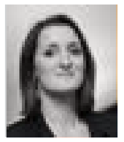

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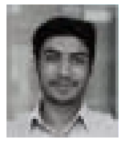

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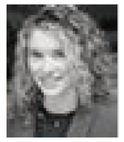

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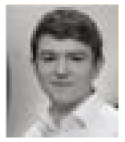

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Overheating context in the UK: do we have a problem?

The CCRA3 report from the Climate Change Committee (CCC, 2021) warns that global and UK average land temperatures have risen by around 1.2°C since the 1850-1900 period (pre-industrial levels) and are expected to rise further by at least 0.5°C by 2050, regardless of efforts to cut global greenhouse gases emissions.

The current analysis shows that there is already a significant overheating risk in parts of the UK domestic housing stock, and higher global temperature will increase the frequency, severity and geographic extension of this risk.

Overheating negatively impacts people's lives, causing sleep disruption that affects health and productivity. It can also cause illness, and significantly more deaths will result as a direct consequence of increased temperatures in the 2050s.

The new Part O of the Building Regulations has been recently introduced to drive design of new homes to minimise the risk of overheating. However, millions of existing homes in the UK also face the overheating challenge and many people will have directly experienced this through the record-breaking heatwaves across much of the UK this summer (2022). The prevalence of overheating is particularly significant in cities and, as the recent Department for Business, Energy and Industrial Strategy (BEIS) Energy Follow-Up survey highlighted, it is often the poorest and most vulnerable members of society who are at the greatest risk due to poorer design of the homes in which they live and the inability to put in place measures to reduce indoor temperatures.

Scope of this work

This study assesses the scale of the overheating challenge across the UK housing stock under current and future weather scenarios. It examines the physical parameters of homes, alongside their geographical location and seeks to quantify the risk of overheating. The study then considers potential measures which could be applied to mitigate overheating and the costs of applying such measures at scale across the UK housing stock as well as other associated opportunities and consequences.

The study only focuses on the existing housing stock and is aimed at giving a general picture of the relative impacts that certain interventions can have in reducing overheating risk. It should not be used as a design guide and building designers are encouraged to carry out specific investigations and, ideally, dynamic thermal modelling exercises to define the optimal retrofit strategy to maximise comfort and minimise energy consumption throughout the year based on the specific internal and external conditions of each building.

The current report is an independent study undertaken by Arup with the support of Parity Projects and the University of Loughborough upon appointment by the Climate Change Committee.

Task 1: Assessing the scale and severity of overheating risk in the existing UK housing stock

The first part of the study aimed to quantify overheating risk for the UK's existing housing stock in the present and future climate scenarios. The work sought to define which parts of the current UK housing stock would experience overheating and to what level.

The TM59 methodology from the Chartered Institute of Building Services Engineers (CIBSE, 2017) was selected as the most suitable method of determining the overheating risk in homes at present. TM59 presents two criteria to assess the risk in homes that are 'predominantly naturally ventilated':

- Criterion A (for living rooms, kitchen and bedrooms) assesses overheating during all summer occupied hours using an adaptive approach that defines the maximum acceptable temperature based on the external temperature;
- Criterion B (for bedrooms only) assesses night-time overheating based on a fixed temperature threshold of 26°C.

Modelling was carried out on a range of representative home types, testing future warming scenarios of +2°C and +4°C above pre-industrial levels, alongside the current climate conditions of the UK. Parametric modelling techniques were used to carry out a very large quantity of simulations which helped to compare a huge range of permutations such as different house type (flats, detached houses, etc.) and factors such as levels of insulation and orientation. This helped to define the scale of the problem, as well to highlight which features of typical UK homes are most important in determining the severity of overheating risk.

The study showed the following outcomes for the UK housing stock under different climate scenarios;

Current climate

The majority of representative buildings failed the bedroom overheating criterion, representing around 55% of the UK housing stock (15.7 million homes).

The remaining 45% of dwellings (circa 12.6 million) do not require any mitigation packages as they pass both overheating risk criteria for living areas and bedrooms.

+2°C 2080 warming scenario

None of the representative buildings outside Scotland passed the overheating risk assessment as they all failed the bedroom criterion. Several archetypes, mainly in London, also failed in the living areas.

Across the entire UK housing stock, 2.4 million dwellings (around 8%) would not require intervention, 21.1 million dwellings failed only the bedroom criterion (roughly 75%) and 4.8 million dwellings failed both criteria (the remaining 17%).

+4°C 2080 warming scenario

All dwellings will need some type of intervention to mitigate against overheating and almost all selected representative buildings showed an extreme failure of the bedroom criterion, an order of magnitude above the determined acceptable level of overheating.

At the UK scale, 4.8 million dwellings failed the bedroom criterion only (17%) and 23.5 million dwellings failed both criteria (83%).

Based on the modelling undertaken for this initial task, the following key conclusions can also be drawn:

- Under the current weather conditions, half of UK homes suffer from overheating risk, based on TM59 criteria. The risk is particularly high in the south of England, with London being the hottest spot in the country, and a moderate problem is present in the Midlands and Wales under current weather conditions. Northern England, Northern Ireland and Scotland currently face a limited risk.
- Around 90% of the existing homes will overheat under a 2°C GW scenario and the totality of the UK will face overheating risks in a 4°C GW scenarios.
- Smaller houses and flats are generally at more risk of overheating than larger homes.
- Smaller bedrooms and loft rooms are more prone to overheating than other rooms, particularly where loft insulation is not present.
- Even under current weather conditions, a majority of homes did not pass TM59 Criterion B (night-time bedroom comfort).
- The impact of insulation on overheating risk is very dependent on other correlated factors; while roof insulation produced a reduction in overheating risk in the majority of modelled cases, the insulation of walls can produce variable effects. Particularly, additional wall insulation would increase the overheating risk in homes with limited windows openability where natural ventilation was not effective in expelling heat gains from the space and the insulation would contribute to trap the heat inside; on the other hand, in cases where enough ventilation was provided and especially where cross ventilation was present, the addition of wall insulation was beneficial and contributed to further reducing overheating risk by reducing the heat gains through the walls. This shows that measures undertaken to improve homes' energy efficiency can produce undesirable effects on overheating performance, if not properly designed and calibrated on the specific characteristics of the building.

Task 2: Defining and costing possible mitigation strategies

Impact on overheating risk

The second stage of the study was to define the practical options to reduce current and future overheating risk in existing homes. This was a wide-ranging quantitative and qualitative assessment considering effectiveness of measures in improving summer thermal comfort, the ease and cost of installation, potential additional operating costs as well as likely cultural limitations and other additional benefits and trade-offs.

The analysis provided the following findings about the effectiveness and ease of implementation of mitigation measures:

- The pattern of which mitigation measure is most effective is consistent across each climate scenario. However, as expected, the percentage reduction in both overheating criteria broadly decreases as warmer weather scenarios are applied.
- In general, measures that reduce solar gain into homes, such as shading and low g-value, are more impactful in flats than houses due to the higher ratio between window area and internal volume.
- Measures that increase the solar reflectivity of walls and roofs were found to be more effective on houses than flats due to the larger ratio between the surface area they would be applied onto versus internal volume.
- In living spaces, shading devices tend to be most effective in reducing overheating risk. Of these measures, external shutters have the highest impact since they stop the solar radiation from entering the building, followed by blinds and internal shutters. The effectiveness of shading measures is much lower for mitigating night-time overheating in bedrooms on which solar gains have a very limited impact.
- Low g-value glazing is effective at reducing overheating in both living rooms and bedrooms. The low g-value window film is much less effective for both criteria than a full window replacement but is much cheaper and less disruptive to install.
- Increasing the openable area of windows for natural ventilation has the greatest benefit on improving night-time ventilation in bedrooms. The ability to achieve a larger exchange of air was effective at reducing night-time bedroom temperatures.
- Ceiling fans are an effective mitigation measure and have a reasonably low installation cost. They don’t reduce space temperatures but the increased air speed they create provides improved comfort. Their use results in some increased electricity costs.
- Some mitigation measures will be limited by regulations on fire safety; for example, some external shading measures may not be appropriate for taller buildings. Others may be restricted by external noise and pollution or security issues, such as windows openability, or by specific configurations of the existing buildings, for example external louvres could not be installed on windows opening outwards.
- Many of the measures considered in this study are common in warmer climates already and are often part of the fabric of homes. This is not the case in the UK which has had a cooler climate historically and where some measures could encounter cultural challenges in relation to the need of a change in the appearance of homes and occupants' behaviour.

Cost of overheating mitigation interventions

Costing the mitigation measures was carried out by obtaining elemental cost rates for each measure extracted from Spon’s Price Books, past project data and market benchmarks and assessing the costs for the representative building archetypes based on their geometry. Location factors were applied to reflect regional variations in costs. The costs were initially built up assuming each measure is installed in isolation. Key findings from the initial costing exercise are as follows:

- Costs of implementation of each measure vary by type of home they are applied to. In general, costs are higher for flats than they are for houses and this is generally because more expensive means of access are required to external areas of the home.
- Some shared costs could be reduced by implementing multiple mitigation solutions on the same construction element at the same time such as a lower g-values and increased openable area when replacing windows. This could ease the cost impact of the works packages as some of the builder’s work and costs would be accounted for once and shared across measures, therefore having a lower impact on the cost of the single mitigation measure.
- Some combinations of measures may be carried out at the same time to share access costs, for example shared scaffolding with concurrent external works not related to overheating mitigation would reduce the impact of scaffolding on the single mitigation cost.
- The cost of some overheating measures can be shared with those that also improve energy efficiency; these include the costs to replace windows with improved performance, the costs to install curtains (thermal insulation), the costs to insulate the external walls and roof. There will therefore be overlap between overheating mitigation costs and costs for energy efficiency upgrades.
- The costs for works have been considered to be carried out and procured on one single dwelling in isolation. However, it is right to assume there might be savings when procuring packages of work for multiple dwellings, e.g. a block of flats or rows of houses, or grouping works to similar areas of the building.

	Package 1	Package 2	Package 3	Package 4	Package 5
Measures included for houses	Blinds, roof insulation (where not present in baseline), low g-value window film.	External shutters instead of blinds, roof insulation (where not present in baseline), low g-value window film, ceiling fan.	Package 2 + solar reflective walls.	Package 3 + window replacement (low g-value and openable).	Package 1 + active cooling.
Measures included for flats	Blinds, low g-value window film.	Package 1 + ceiling fans.	External shutters instead of blinds, low g-value window film, ceiling fan.	Package 3 + window replacement (low g-value and openable).	Package 1 + active cooling.
Key results under current weather scenario	Package 1 eliminates extreme overheating entirely and severe overheating is only evident within flats in London. Half of the representative buildings passed Criterion B when Package 1 was applied, meaning no further mitigation measures would be needed.	Applying this package eliminates all severe overheating – only the flat archetypes in London have residual moderate overheating. When Package 2 is applied, all buildings outside London pass overheating criteria.	This package eliminates the overheating from the older flat archetype in London but only reduces overheating in the newer flat type.	The new flat archetype located in London still marginally fails with this package applied but it is close enough to the acceptable threshold not to apply further measures.	Some modern flats in London would need Package 5 to eliminate completely overheating risk based on TM59 criteria. This corresponds to approximately 5% of the UK building stock.
Key results under 2°C GW scenario	All representative building archetypes pass Criterion A when Package 1 measures are applied. Criterion B failures are also reduced but not significantly.	This package delivers a significant improvement in overheating risk. Extreme overheating is eliminated for all but London flat archetypes and other areas see significant improvements.	Some measures within this package improved outcomes for houses, particularly the detached and semi-detached. No major improvement was seen on flats.	This package solves the majority of the overheating challenges in the South of England, however the modern flat and mid-terrace archetypes still see a significant risk.	Active cooling measures are required to cope with overheating in approximately 22% of the UK housing stock.
Key results under 4°C GW scenario	The application of Package 1 measures is effective for Criterion A compliance for all houses but had limited impact on reducing bedroom overheating with most representative buildings showing an extreme fail for Criterion B.	Package 2 measures eliminates almost all Criterion A failures. In all locations outside London, these package measures also significantly improved Criterion B outcomes.	This package produced limited benefits above Package 2 with some small improvements in Criterion B compliance.	This package shows improvements across Midlands geographies, but southern regions still report severe night-time overheating.	Active cooling measures are required under this scenario for almost all archetypes outside of Scotland to fully comply with CIBSE TM59 criteria.

Table 1: Summary of effect of each mitigation package under different climate scenarios

Task 3: Assessing intervention deployment at scale

Impact of mitigation packages on overheating risk at UK scale

Following the assessment of cost and effectiveness, the possible individual mitigation measures were then grouped into five packages of measures. Table 1 summarises the measures included in each package for flat and house archetypes. This grouping helped to assess the impact at scale of different levels of intervention with each package providing increasing levels of effectiveness with associated increasing cost and disruption. It also allowed priority to be given to 'passive' or 'low energy' measures that don't require significant additional electricity consumption which were applied prior to any mechanical cooling measures. For practical reasons and to account for the different response to overheating given by different types of dwellings, slightly different sets of packages were determined for flats and for houses.

The aim of the final task was to apply each of these mitigation packages to the representative buildings under the three climate scenarios to understand the levels of intervention that would have to be implemented to reduce the risk of overheating under TM59 thresholds and to estimate the costs of such interventions. Effective mitigation packages and their costs were then extrapolated at UK stock level to estimate the level of investment needed at scale for a full overheating adaptation strategy at scale.

TM59 assessments provide a binary pass/fail result for both assessment criteria which is primarily meant for design of new buildings. For the purpose of this study, the results were further graded as 'pass', 'moderate fail', 'severe fail' and 'extreme fail' to better show the relative improvement produced by each mitigation package compared to the current conditions under the different climate scenarios; in particular:

- A 'pass' condition referred to results for Criterion A up to 3% and Criterion B results up to 32 hours;
- A 'moderate' failure referred to Criterion A in the range of 3-6% and Criterion B results in the range of 32-64 hours;
- A 'severe' failure referred to Criterion A results in the range of 6-15% and Criterion B results in the range of 64-160 hours;
- An 'extreme' failure referred to Criterion A results over 15% and Criterion B results over 160 hours.

A summary of findings across the modelled housing stock is shown in Table 1. Table 2 summarises the total number of homes and the minimum mitigation package required for each to comply with TM59 requirements under the current 2°C and 4°C global warming scenarios across the whole country.

Figure 1 shows how different packages impact the total number of UK homes failing TM59 under each weather scenario, starting from the current baseline where no package is applied.

Mitigation Package	Climate Scenario		
	Current	2°C GW	4°C GW
None	12.6 (44.5%)	2.4 (8.5%)	0.0 (0.0%)
1	7.0 (24.7%)	0.1 (0.4%)	1.6 (5.7%)
2	7.0 (24.7%)	15.65 (54.8%)	0.8 (2.8%)
3	0.3 (1.1%)	1.5 (5.3%)	0.0 (0.0%)
4	0.0 (0.0%)	2.6 (9.2%)	0.4 (1.4%)
5	1.4 (4.9%)	6.2 (21.9%)	25.45 (90.1%)

Table 2: Total number of UK homes requiring mitigations in each climate scenario (millions)

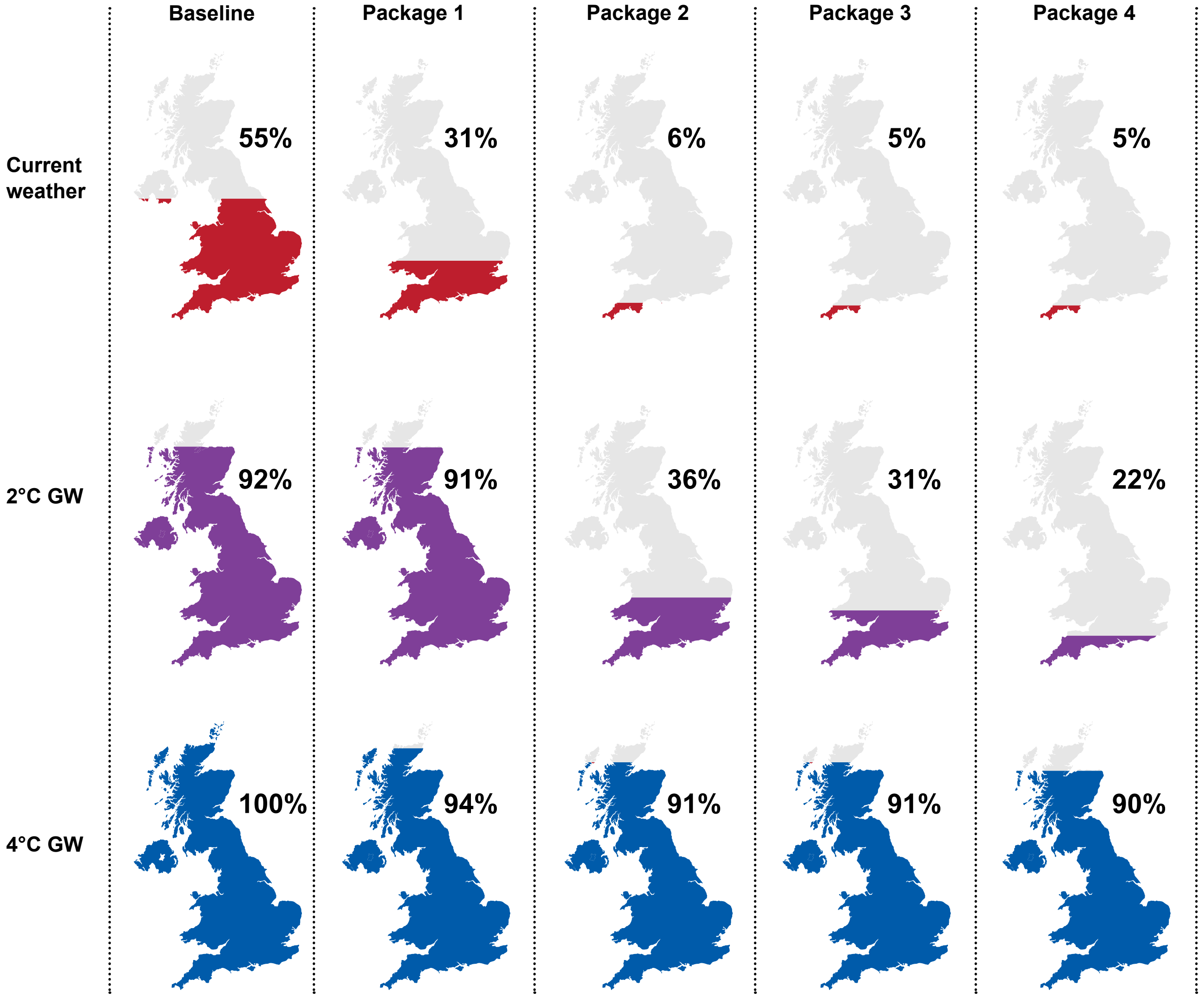

Figure 1: Impact of mitigation packages at UK scale: percentage of UK homes overheating under each weather scenario and with different packages applied

Cost of intervention packages at UK scale

Cost estimates were built up for each package including supply, installation and ancillary works as well as other contractor costs (overheads, preliminaries, etc.) and applied to the number of homes to which each package was applied in each weather scenario.

The cost study also differentiates between measures that would only be installed purely as overheating mitigation measures, measures which are complimentary with other home upgrades (such as energy efficiency) and those which are simply extra-over costs to other upgrades (such as the cost related to specifying higher solar control properties compared to standard solar control when replacing a window at its end of life). The cost estimated for applying the packages at scale are high but it should be acknowledged that these would likely be carried out over a long time given the extremely high number of houses under consideration in this analysis. Depending on the warming scenario, a programme of 30 years would mean works to around 800,000 homes on average every year.

Figure 2 shows the total capital costs at UK scale estimated to install the packages needed to fully offset overheating risk based on TM59 criteria, considering Package 5 applied to all homes where no other package could achieve a pass. This shows a lower overall capital cost for the 4°C GW scenario than that for the 2°C GW, due to the fact that, in the warmest scenario, even the most effective (but expensive to install) passive measures are unable to fully mitigate overheating risk in the majority of dwellings, therefore active cooling (cheaper to install) is needed in a greater proportion of dwellings, and the capital cost for reducing overheating risk under TM59 thresholds becomes lower because passive packages are applied to a smaller proportion of the housing stock.

However, it should be noted that the installation of active cooling would produce a large increase in electrical demand and operational energy cost, which would weigh on the occupants' energy bills. This was estimated to be around £200 per year for a typical house in a 4°C GW weather (considering a setpoint of 26°C) which equates to about £10,000 over a house's 50-year lifetime. This was based on current energy prices, but with rising energy costs the annual expense – and the cost over a home's lifetime – could quickly escalate.

Figure 3 shows the cost estimated if only passive and low energy measures were considered (packages 1 to 4). It is evident that the cost to mitigate overheating in existing homes without creating additional energy consumption for cooling and related additional carbon emissions would be much higher in a 4°C GW scenario than in a 2°C GW scenario, by around 160%.

Additional key findings from the cost analysis (considering Package 5 applied when needed to pass TM59) are:

- In the current climate scenario, the cost for upgrading all homes in the UK requiring some form of mitigation to meet TM59 criteria is circa £250 billion. Around £180 billion of this figure are 'pure' overheating mitigation measures only.
- Under the current climate scenario, the average capital cost per home is around £15,000 of which around £11,000 is for pure mitigation measures, e.g. not extra over/uplift costs or costs for complimentary measures.
- Significantly more investment is required in the 2°C and 4°C GW scenarios compared to the current weather conditions, circa £559 billion and £488 billion respectively. The 'pure' mitigation costs associated with the packages costs for these scenarios are circa £415 billion and £340 billion respectively.
- Under these warming scenarios, the total capital costs per household are around £22,000 for the 2°C GW scenario and £17,000 for the 4°C GW scenario. Of these totals, around £16,000 and £12,000 are for purely mitigation measures respectively.
- Assumptions around costing are detailed in Appendix B of this the report. A variation to many of these assumptions would affect the estimate and produce different figures, however the costs in this report provide an order of magnitude if the selected intervention packages were deployed as standalone and not as part of a wider retrofit strategy.

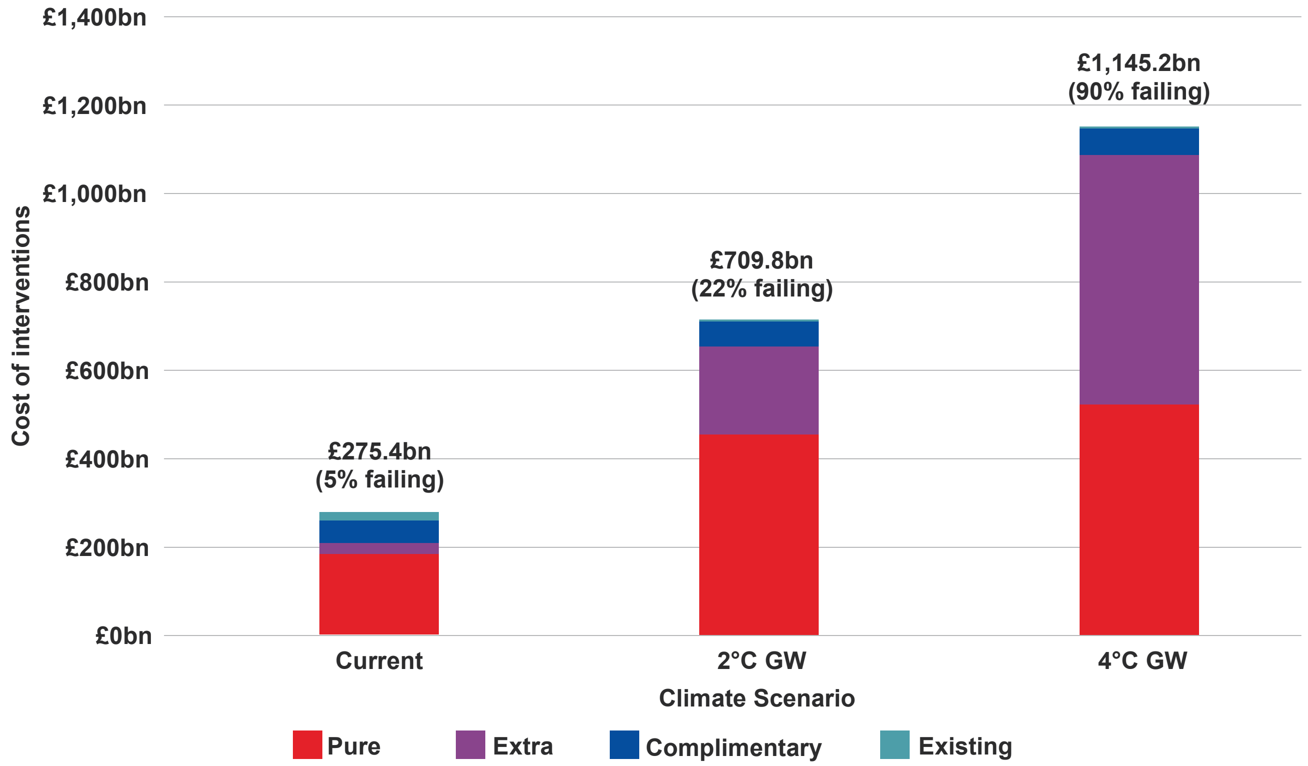

Figure 2: Cost of overheating mitigation at scale using packages that achieve a full pass under TM59

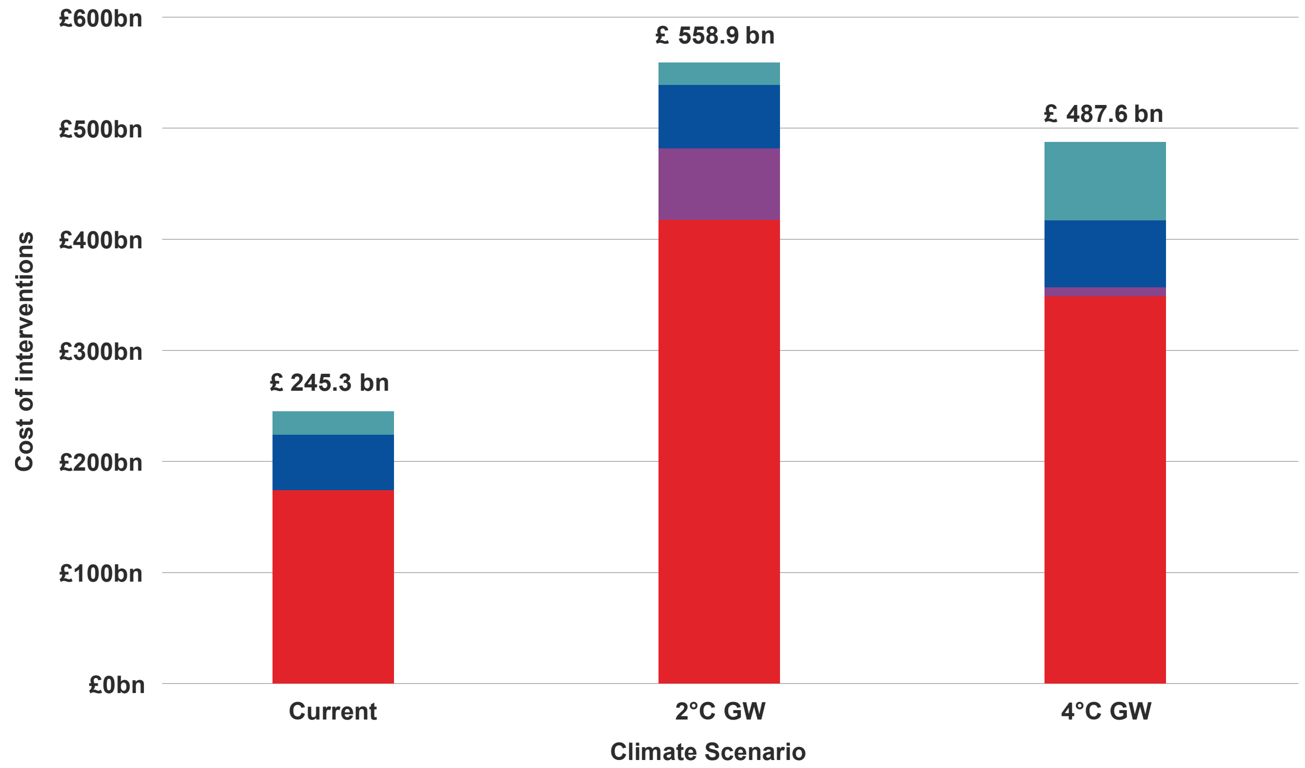

Figure 3: Cost of overheating mitigation at scale excluding Package 5. The percentages in brackets report the residual percentages of UK homes failing TM59 under each weather scenario if cooling is not installed

Impact on operational costs

Some of the mitigation measures will impact on home energy demand as they change the balance of energy flow in a home and/or introduce systems which use energy. In contrast to passive measures, active measures require the use of electricity with its resulting carbon emissions. Some passive measures that reduce solar gain will result in slightly higher heating demands in winter because solar energy contributes to heating up a space. This study included an assessment of these impacts for all of the representative archetypes; a summary of key points follows.

– Where archetypes have an insulated roof as a baseline, applying any of the mitigation packages results in a small increase in energy cost compared to the baseline. This is due to the increased heating demand generated by the measures that reduce solar gains throughout the year, plus the additional energy for fan operation in Packages 2-4 and active cooling in Package 5. Increased costs for the 2°C scenario are around £50/annum for packages 2-4 and £80/annum for Package 5.

– When applied to the uninsulated roof baseline model, a similar pattern of increasing operating costs is evident when each mitigation package is applied. However, the additional costs are small and lower than for the insulated roof baseline (around £30/annum for packages 2-3 and circa £65/annum for Package 5) due to the beneficial reduction in heat demand from the added roof insulation which is included as a mitigation intervention. Applying Package 1 also results in an overall cost savings of around £15-£30 against the baseline in all three weather scenarios and Package 2 and 3 are practically operating cost-neutral in the current weather scenario.

– Package 5 did not result in large operational cost increases in the current weather scenario (an additional £15-£40/annum depending on the dwelling type) or the 2°C GW weather scenario (an additional £65-£85/annum) since the number of hours in which cooling is needed and the capacity needed to achieve comfort conditions are lower than in warmer conditions. However, the increase in annual operating costs under the 4°C GW scenario is around £170-£185/annum due to the increase in cooling demand over a warmer summer period.

– All mitigation packages produce an increase in household carbon emissions compared to the baseline. For the insulated roof baseline there is up to an additional 40kgCO_2e/annum in the current weather scenario and an additional 130kgCO_2e/year when Package 5 is applied in the 4°C GW scenario. This mainly is due to the increase in heating demand related to the reduced solar gains which would be partly offset by a move to heat pump led space heating systems utilising a decarbonised electricity grid.

The study confirmed that all the mitigation packages increase energy consumption for homes to some extent and this needs to be considered alongside the capital expenditure required. The most significant impact is where active cooling is applied. While active cooling provides comfortable conditions, under a 4°C GW scenario applying this at scale would result in an additional £4 billion of energy costs per year across the housing stock relative to a 'no-intervention' baselines, and an additional 2 million tonnes of carbon emissions annually from operational energy alone. Active cooling systems would also have a greater impact on embodied carbon than passive measures.

It should be noted that the current analysis considered only the period May to September for the assessment, defined in accordance with CIBSE TM59 methodology, but operating costs are considered across the whole year. However, in the event of global warming, temperatures may rise for a longer period of the year generating higher cooling demands than those estimated in this report.

The impact of applying packages based more heavily on passive measures is significantly smaller in terms of additional energy cost and carbon emissions. The use of passive measures would also avoid any impacts on the electricity grid and the need to upgrade it to cope with the additional electrical energy requirements.

The Construction Leadership Council estimates that it would cost at least £500 billion over the next two decades to retrofit the UK housing stock.

Other observations

The overall costs of mitigation are very high across the UK housing stock. To put these into context, the Construction Leadership Council estimates that it would cost at least £500 billion over next two decades to retrofit the UK housing stock. There is potential to include many overheating mitigation upgrades within a national retrofit strategy which would help reduce costs through shared access.

The costings carried out here provide a view of the magnitude of costs and these are based on products available today. As set out in the report, economies of scale, carrying out works that are complimentary and focussing on upgrading elements of homes when other home improvements or required maintenance works are carried out could significantly reduce these.

One sensitivity analysis conducted in this study looked at what impact behavioural change could have on overheating risk. Throughout the main study, the occupants were assumed to behave identically to allow meaningful comparison between individual simulations, mostly based on TM59 settings; however, informed occupants could take positive actions to limit the effect of overheating within their homes. This sensitivity test aimed to simulate the actions of the 'perfect occupant', purely focussed on minimising summer overheating. Behavioural change simulated included how users control window openings and how blinds/curtains are deployed in an optimal way.

The study showed that the behaviour of a more informed (almost 'perfect') occupant can have a significant reduction in overheating risk. This was particularly pronounced in the old flat archetype where the 'perfect user' operation only experienced around 38% of the bedroom night-time overheating hours compared to the original simulation, whereas the detached house experienced around 67% of the overheating hours compared to the original simulation. Assuming windows can be opened securely, this reduction in overheating is achieved without any additional capital expenditure or physical alterations to the property, meaning that improving how people open and close windows can have a significant improvement in overheating mitigation.

The study was not able to quantify how air quality, noise, security concerns or urban greening could impact overheating results. Both noise and air quality in urban areas are factors which can limit the effectiveness of passive mitigation strategies, but data is not available at scale to determine what impact this may have in quantitative terms. Similarly, studies show that measures such as 'cool roofs' and green spaces within cities can provide local benefits to the microclimate that would positively influence overheating risk by reducing the local air temperature, but these are hard to quantify as well.

Key recommendations

The study suggests that a lot of retrofit works are required across the housing stock to mitigate the risk of overheating up to a 4°C global warming scenario. As shown by this study, this presents real challenges for the UK housing stock. Mitigation packages for global warming scenarios come with a high cost, and simple capacity limits within the construction industry mean it is not feasible to carry out this volume of building upgrades to all dwellings, all at once. This section provides some general next steps and recommendation measures that are considered appropriate to help to reduce the global warming risk and in turn reduce the overheating risk on the basis of the outcomes of this study.

Policy Makers

– A key aim for everyone would be to avoid getting to a 4°C global warming scenario for which active cooling seems the only solution in many parts of the country. Additional focus should be applied to tackling the challenges around reducing energy use and policy to deliver on carbon emissions reductions to slow down the rate of global warming.

– The study showed that typical energy saving measures such as improved insulation are mutually beneficial in mitigating overheating if the home has good natural ventilation. However, these may produce a negative impact on overheating risk where ventilation is restricted or not sufficient. It is key that retrofit strategies and policies promote a holistic approach to improving dwellings' performance throughout the whole year to limit these countereffects.

– The study demonstrates that deployment of blinds, curtains and the opening/closing of windows at the right time of day can be important in mitigating overheating effectively. Investing in public information campaigns which encourage behavioural change on how to operate windows and curtains/ blinds would prevent the need for immediate high capital cost changes.

– Higher temperatures are commonplace in warmer climates and a large majority of people generally find this acceptable without the need for active cooling. Regulations should be introduced to govern the installation and use of domestic air conditioning ensuring that passive measures have been considered and used as a first step so that energy consumption for cooling is limited.

– There are questions around the definition of overheating given the challenges presented by climate change. CIBSE TM59 is a stringent assessment method and the results show that the principal reason homes fail in current and future scenarios to fully meet TM59 criteria is because they do not pass the Criterion B which governs night-time bedroom overheating. Ongoing academic research (Lomas, et al., 2021) shows concerns in relation to the lack of experimental evidence to support Criterion B and suggests a need to validate it with further experimentation. Investing in academic studies which look at night-time bedroom comfort would be a sensible next step. Further research leading to a revised night-time comfort criterion could show a lower risk of overheating for bedrooms and therefore a lower number of dwellings at high risk, which could result in a smaller financial investment across the UK housing stock than this study suggests.

Urban Planners

Importance should be given to measures which limit and reduce the impact of the built environment on global warming and overheating risk. Planners should demand more greenery and cool roofs, and set lower limits for noise and pollution to create suitable conditions for windows to be opened and natural ventilation to be maximised.

– Many heritage buildings are unable to have extensive works carried out due to maintaining their conservation status. It should be considered whether some of these restrictions could be relaxed when retrofitting to enable the incorporation of interventions for lower energy and overheating mitigation.

– Some solutions may be visually different from traditional architecture within the UK; these should be allowed where possible.

– Some of the measures within the passive packages will impact on the visual appearance of homes. The nature of the changes and the regulations that might govern their implementation are beyond the scope of this study but are important considerations.

Building Designers

– Designers are encouraged to look to countries where warmer temperatures are commonplace and incorporate passive design solutions which are widely deployed in these areas and prove to be effective in the UK. Whilst some measures such as external shutters may change the look of the UK housing stock, design variations can be explored to fit the UK market and new trends can be established that can benefit buildings' performance.

– Project teams should be upskilled to understand which building factors affect overheating. Even when dynamic thermal modelling packages cannot be used, general concepts should be adopted such as external solar shading devices and windows with larger openable areas.

– Designers must maximise the potential for natural ventilation as this is key to reducing overheating and cooling down the building mass.

– Overheating mitigation should be included in holistic retrofit strategies that consider heating and cooling performance at once so that optimal solutions can be identified to maximise comfort and minimise energy consumption overall throughout the year.

– Designers should provide occupants with information on how to best operate buildings to maximise performance; an output of the design process should be a building operation manual which explains how building features can be used to reduce overheating on hot days.

End Users / Occupants

– Landlords and homeowners should be aware of possible interventions which they could incorporate and integrate these solutions when undertaking home improvements.

– Occupants should be made aware of the ideal behaviours which help to reduce overheating, i.e. correctly controlling windows and shading, and of the benefits that these behaviours can produce in improving their indoor comfort and reducing energy bills for cooling.

Introduction

The Climate Change Committee (CCC) has appointed Arup to undertake a study to assess how exposed different parts of the UK's existing housing stock are to overheating risks under expected future climate conditions, and how much deployment of credible options to retrofit existing homes can limit overheating risk.

This project will feed into the CCC's wider adaptation work programme and in particular ongoing work around what might be a credible scale of adaptation action to address the risks presented by climate change in the UK. This work package will integrate into efforts to improve the quantitative nature of the CCC's progress monitoring framework on adaptation.

This report presents the method used to conduct this research and the results obtained from dynamic simulation of over 2,000 dwellings in order to estimate the risk of overheating for existing UK homes in current and future weather conditions, assess the efficacy of possible mitigation measures in reducing this risk, and their costs.

1.1 Research context

1.1.1 The overheating context in the UK

The UK has a temperate maritime climate and, historically, homes were designed and built to minimise heat losses and energy demand for heating in winter, which was largely the priority in the UK Building Regulations (BR) on energy efficiency until recently.

The summer of 2022 saw some record-breaking heatwaves, with temperatures reaching above 40°C for the first time in July in some parts of the UK. At the time of writing, the Met Office had warned that the temperatures seen in these heatwaves could be average summer temperatures by 2035, even if countries were to meet their climate commitments as agreed in the 2015 Paris Agreement.

Things are rapidly changing, though: global warming is evidently raising summertime temperatures and increasing the frequency, severity and duration of heatwave, a trend that will continue irrespective of efforts to curb greenhouse gas emissions. Homes, especially those in the southeast of England and in large cities, are overheating during the summer (Lomas, et al., 2021). In extreme cases, overheating is chronic (McLeod & Swainson, 2016) and can lead to increased mortality and morbidity (Arbuthnott & Hajat, 2017). Consequences brought into sharp focus in the European heat wave of 2003. Recent research reports that heat-related deaths in the UK are expected to triple by the 2050s (Hajat, et al., 2014).

The possibility of overheating in existing UK homes was known since the mid-1970s, and possibly earlier, and the CIBSE Guides have, for decades, included criteria to define whether a room is overheated (CIBSE, 2017). But overheating, the causes of it, the mitigation measures and the criteria that define it have come into sharp focus only in recent years. Since 2003, academics across the UK have conducted monitoring campaigns and undertaken modelling studies to understand the problem (see, for example, Lomas & Porritt, 2017).

Things are rapidly changing: global warming is evidently raising summertime temperatures and increasing the frequency, severity and duration of heatwaves, a trend that will continue irrespective of efforts to curb greenhouse gas emissions.

1.1.2 The incidence of overheating

CIBSE has produced Technical Memoranda TM52 (CIBSE, 2013) and TM59 (CIBSE, 2017) to assess overheating risk in domestic and non-domestic buildings respectively and guide designers toward solutions that minimise this risk. The former Zero-Carbon Hub and the Good Homes Alliance have also produced valuable information, guidance and tools (Zero Carbon Hub, 2016 and Good Homes Alliance, 2019).

The CCC, through the Adaptation Sub-Committee (ASC), brought the matter formally to the attention of the British government in its 2014 report (ASC, 2014). The ASC noted that ‘one study […] found that 21% of homes studied exceeded overheating thresholds (Beizaee, et al., 2013)’. In 2017, the ASC reinforced its evidence base and reiterated its call for government action. The report cited numerous journal and other articles and, based on this evidence, classified ‘risks to health, wellbeing and productivity from high temperatures’ in its highest climate change risk category and a priority area for government adaptation action (CCC, 2021). In 2018, the House of Commons Environmental Audit Committee asked the Government to explain its actions in response to the ASC’s recommendations to protect homes and public buildings, improve the resilience to heat waves of health care provision and change the BR accordingly. Consequently, in late 2021, the new BR Approved Document, Part O: Overheating (HM Government, 2022), was published. This regulation enables thermal models to be used to test if dwellings will overheat but it only applies to new dwellings and not the more than 28 million UK homes that already exist.

Very recently, the prevalence of overheating in existing homes was highlighted through analysis of the data collected in the Energy Follow-up Survey (EFUS) (BEIS, 2021) to the English Housing Survey (DLUHC, 2013). This was ‘the largest survey of temperatures in English homes’, with measurements being made in 750 homes during England’s then hottest ever summer, 2018 (Lomas, et al., 2021). Some 15% of all English living rooms were deemed to be overheated and 19% of bedrooms although this value changes significantly depending on the criterion used (an appropriate criterion to define bedroom overheating is a matter of current research (Lomas, et al., 2022)). The study revealed that the risk of overheating is significantly greater in flats which disproportionately effects the poorest and most vulnerable in society.

Architects in many parts of the world have known for centuries how to avoid overheating in homes and great examples of passive ways to avoid overheating can be found in the traditional architecture of warmer countries like Italy and Spain. However, the UK’s history of persistent warm weather is very recent and therefore the biggest challenge is in adapting existing buildings to new climatic conditions using cost effective solutions, acceptable to homeowners, that can be implemented by small and mass market house builders.

The basic conditions for overheating mitigation in existing homes are set by the dwelling form, construction, orientation and location as well as cultural bias and personal taste: altering window sizes and installing external shading devices and shutters are often considered unacceptable by homeowners, on top of being expensive and sometimes unviable (as is currently the case for listed buildings or those in conservation areas, for example). The costs of mitigation measures are also crucial as the dwelling owner will have to foot the bill. However, holistic retrofit strategies can be designed to mitigate the risk of overheating and simultaneously improve buildings’ energy efficiency which would optimise the process and reduce costs when combined.

15%

of English living rooms currently overheat

19%

of English bedrooms currently overheat

1.1.3 Dynamic thermal modelling as a way of predicting future overheating

Dynamic thermal models are the best available analytical way of assessing and comparing the effects of different mitigation measures. For any chosen, quasi-realistic dwelling, assumed occupant behaviours (internal heat gain, window opening regiment, etc.) and weather conditions, models can compare predicted room temperatures with the temperatures predicted following an intervention – or mitigation measure. Only by using models can the effects of mitigation measures under future weather conditions be reliably assessed. By applying one mitigation measure at a time, then in combination, the individual and combined effects of measures can be explored. Dynamic thermal models have been used to explore the risk of overheating and impact of mitigation measures in numerous previous studies (Lomas & Porritt, 2017).

The accuracy of results from dynamic thermal modelling are, however, dependent on the accuracy of the information about the building input in model. For example, predicting the room temperature in naturally ventilated spaces in summer conditions is a difficult task since the predicted temperatures are highly sensitive to some inputs such as for ventilation rates, surface heat transfer coefficients and solar gains, accurate information on which is rarely available with accuracy for existing buildings. Thus, depending on the assumptions made, the predictions of different models differ, predictions differ from measurements, and they do so in a systematic way (Roberts, et al., 2019). Furthermore, small inter-model differences in hourly temperature predictions escalate to much larger differences in the predicted hours over any chosen threshold temperature (Lomas, 1996). These model characteristics have been known for many decades.

Three key questions can be answered by models:

– Are room summertime temperatures after the intervention higher or lower than before it?

– By how much does a mitigation measure reduce internal temperatures?

– Do the predicted temperatures exceed the overheating criterion threshold?

Dynamic models are more likely to be reliable for the first two types of prediction where relative comparisons can be made. The work reported here thus focusses on identifying if an intervention constitutes a useful mitigation measure and in ranking the effects of intervention. The third type of prediction requires a much higher level of accuracy and is much more challenging, especially when very little information is available about the building subject of the analysis, or when one building is used as a case study to represent a much larger group of buildings.

1.2 Scope and use of this report

The study was composed of three tasks:

- Task 1 assessed the extent of overheating risk in the future across the UK's current housing stock and the extent to which different parts of the current UK housing stock would experience different levels of overheating risk.
- Task 2 looked at assessing the options to reduce current and future overheating risks in existing properties, including effectiveness in improving summer thermal comfort, cost of installation, potential additional cost in operation as well as additional benefits and trade-offs and practical limits.
- Task 3 assessed possible levels of deployment of the defined mitigation measures and the level of investment needed at the UK scale.

This study aims at providing a quantitative but high-level picture of the overheating risk of the current UK housing stock and an indication of what would be the benefit of applying possible mitigation measures and the related high-level cost at scale. This study should not be used as design guidance for specific buildings since the effectiveness of mitigation strategies is strictly dependent on the specific conditions of each building.

1.3 Report structure

The report is structured as follows:

- Section 1 (current) gives an introduction to the work;
- Section 2 presents the overall method and approach used to conduct the study;
- Section 3 details the method for Task 1 and presents the results on the overheating risk of the current UK housing stock in present and future weather scenarios;
- Section 4 details the method for Task 2 and the results of the assessment of the impact of possible mitigation measures onto the UK housing stock, as well as the cost estimated for each mitigation measure;
- Section 5 presents the effects of applying different mitigation packages in the current and future weather scenarios as well as the estimated level of deployment of each package and a high-level estimate of the expected cost at scale of implementing the mitigation packages;
- Section 6 summarises the main conclusions from the study.

1.4 Collaborations

This work was undertaken by a technical team of building engineers, climate consultants and cost consultants from Arup with the support of Parity Projects who supplied information on the UK housing stock at scale and Prof. Kevin Lomas from Loughborough University who provided expert advice on overheating based on his extensive research on the topic.

1.4.1 Parity Project's English housing stock model

Parity Projects have produced a stock model of homes across England, based on statistical research from the English Housing Survey[1] (EHS). The EHS is a national survey of people's housing circumstances and the condition and energy efficiency of housing in England. It is based on an interview with householders and a physical survey of their property. The survey forms a statistical description of homes, consisting of 12,292 building entries, each of which has a grossing factor to indicate how many homes that entry represents within each region of England, such that the sample represents 24 million homes across England.

The physical structure of each archetype is described in terms of various factors impacting energy use, such as age, wall structure and heating system. Parity Projects have used the data within each archetype along with their knowledge of UK housing stock to produce a complete rdSAP model of each archetype. This can then be used to generate statistical reports on the characteristics of homes in England and their energy performance and potential impact of appropriate improvement works.

1.4.2 Loughborough University

Beginning in 2008, research at Loughborough University has quantified the severity and extent of summertime overheating in homes and hospitals, identified the buildings and people most at risk and described how policy and practice should change to mitigate the problem. The research team was led by Kevin Lomas, with significant effort from academics and research associates in the Building Energy Research Group.

Large-scale field trials have yielded two primary data sets to determine the extent and severity of overheating in homes and enable the creation of new empirical models. Before 2017, these were the only large-scale surveys of summertime overheating in UK buildings. The field trials involved a dwelling survey, face-to-face questionnaires and temperature monitoring in around 250 homes. In 2011, the BERG team was commissioned to analyse data from the temperature data from the 2017 Energy Follow-up Survey (BEIS, 2021) to the English Housing Survey (DLUHC, 2013), the largest ever survey of overheating in English homes.

Experiments and modelling have supported the field work. Full-scale trials were undertaken in two sets of matched-pair homes with simulated occupancy. These unique facilities have quantified the impact of thermal mass, ventilation, and shading on summertime overheating risk. Dynamic thermal simulation has enabled the evaluation of overheating risk in proposed hospitals and homes in both current and future climates. Validation of others' predictions was undertaken to test the suitability of dynamic thermal modelling for overheating risk assessment within new BR for England.

The research has identified the need for robust regulatory control of overheating, which is beginning to appear through the new BR Approved Document Part O. Current research includes a review of the existing CIBSE TM59 overheating criterion for bedrooms through a new field trial focussing on heat and sleep which is ongoing.

[1] https://www.gov.uk/government/collections/english-housing-survey

Section 2

Method and approach

The current study aimed at assessing the overheating risk in the existing UK housing stock under current and future weather conditions and define viable and cost-effective mitigation strategies to reduce this risk.

2.1 Overview of method

This assessment was divided into three tasks, as described in section 1.2. This section explains the method adopted to conduct the study under each task.

2.1.1 Task 1: Assessing the current UK stock

Task 1 aimed at assessing the extent of the overheating risk under current and future weather conditions in the UK's current housing stock.

The first step of this process was to define clearly the key elements of this study:

– The criteria to assess overheating risk;

– The current and future weather scenarios to consider for the analysis;

– The variables to be used to define building types that adequately represent the UK existing housing stock.

Selection of overheating risk criteria

The current best-practice guidance for overheating risk assessment in domestic buildings, CIBSE TM59 'Design methodology for the assessment of overheating risk in homes' (CIBSE, 2017) was used as the basis of the current overheating analysis. Results from TM59 assessments were used to present the overheating risk on the current UK housing stock and select the mitigation packages to avoid overheating for each weather scenario.

However, it should be noted that the TM59 criteria are currently under review; extensive research including laboratory studies on people's sleep patterns is being undertaken to understand what are the key factors that affect sleep comfort. Some recent research (Lomas, et al., 2022) seems to suggest that the mean night-time temperature might have more impact on people's sleep than peak temperature. This alternative approach to night-time comfort in bedroom was not used in the current assessment but can be considered to help understand the impact of possible mitigation measures on improving summer performance of dwellings.

Task 1: Assess current risk	Task 2: Define possible strategies	Task 3: Assess deployment at scale
Inputs – Weather scenarios – Building variables – Overheating criteria – Characteristics of existing housing stock **Outputs** – Risk of overheating in current building stock – Key factors affecting overheating – Selective representative buildings	**Inputs** – Selective representative buildings – List of possible mitigation measures **Outputs** – Effectiveness of mitigation measures – Cost of installation of each mitigation measure – Qualitative viability of measures – Selected representative buildings – Definition of possible mitigation packages	**Inputs** – List of selected mitigation packages – Characteristics of existing housing stock **Outputs** – Effectiveness of mitigation measures – Selected mitigation package for each representative building – Mitigation packages needed at UK scale – Expected level of investment cost needed under different weather scenarios

Figure 4: Summary of method

Definition of weather scenarios
A number of representative locations were selected to represent different climatic areas of the country, as detailed in section 3.1.2.

To assess the overheating risk under future weather conditions, 2°C and a 4°C Global Warming (GW) scenarios were selected, which were represented by a 2080 low emissions weather file and a 2080 high emissions weather file, respectively. These were agreed with the CCC, CIBSE and the Met Office, as also described in section 3.1.2.

Definition of the representative variables and building groups
A parametric modelling approach (see section 3.2) was used to assess a higher number of case studies compared to traditional dynamic simulation modelling. A number of representative archetypes and significative variables that could impact a dwelling response to warm weather were considered. The selection of these were based on the information available in Parity Projects' model of the English housing stock as well as information included in the EFUS study (BEIS, 2021).

All the possible combinations of archetypes and variables were modelled using parametric dynamic simulation modelling, as detailed in section 3.2.1. The results of the parametric modelling defined the baseline overheating risk of the current UK housing stock, using the results from modelled case studies and the extrapolation of these at scale as explained in section 3.5.

The results from this initial modelling exercise were also used to understand what variables had more impact on summer discomfort and what had less. Based on this, a smaller number of representative buildings were selected on which the impact of possible mitigation measures was assessed in Task 2.

2.1.2 Task 2: Defining possible mitigation strategies
Initially, a long list of possible mitigation measures was defined. These were assessed based on qualitative criteria, such as ease of installation and compatibility with other measures, possible impact on winter energy consumption or daylight, fire safety issue, effectiveness in reducing overheating risk (tested through dynamic modelling on selected archetypes) and the cost of installation, which was estimated using the method presented in section 4.2.

2.1.3 Task 3: Assessing potential level of deployment at scale
Based on the outcomes from Task 2, a number of possible mitigation packages were defined, which contain multiple mitigation measures that can be compatibly installed at one time. The packages were defined with a progressive cost and ease of implementation, going from Package 1 including 'easy wins' – measures that produced reduction in overheating risk with relatively low installation costs – to Package 4 that include the most expensive and hardest-to-install measures. An additional package (5) was considered which involved active cooling when other passive and low-energy measures were not sufficient to mitigate overheating risk according to TM59 criteria.

The passive and low-energy solutions were tested on the selected representative buildings under all the weather scenarios. Based on this, a package was selected for each weather scenario that achieved a complete pass under CIBSE TM59. For those conditions where none of the four packages could achieve a pass, Package 5 was selected and included in the cost.

The selected packages were applied to the initial case studies (based on the full parametric modelling) and, through extrapolation, the total number of homes to which a package was applied in each weather condition was calculated. Based on this, it was possible to estimate the number of existing UK homes for which adaptation through passive and low energy solutions can be achieved, and the number for which active cooling is the only viable solution, based on the predicted future weather conditions and the selected case studies.

2.2 Assumptions and limitations
The current study used a multi-parametric approach to model the overheating performance of the existing UK building stock to allow the simulation of a higher number of case studies given by the combination of multiple archetypes and variables.

However, in energy modelling, the reliability of the results is strictly related to the quality and accuracy of the information that is input to the model. Evidently, when modelling the whole UK housing stock, a very high number of simplifications and assumptions needs to be made. For example, the selection of six archetypes and geometries to represent the whole stock involves a high level of simplification as in reality almost every dwelling will have a unique geometry, as much as the selection of limited construction types, the impossibility of predicting the level of ventilation or the orientation of the existing homes – which impact greatly the solar gains in summer – and other parameters such as occupant numbers, patterns and behaviours.

Some of these simplifications can have a significant impact on the results of the modelling. For example, specific assumptions were made on natural ventilation, including the size and openability of widows, the temperature and times at which windows would open, the level of wind pressure that would affect the air flow in the room. All these parameters affect substantially the natural ventilation effectiveness and the related capacity to reduce internal temperatures but, at the same time, are extremely variable across the building stock and dependent on occupants' behaviours; therefore, there is no way to predict what an average or common condition would be. For this analysis, some assumptions had to be made and were applied to the whole housing stock, which were based widely on CIBSE TM59 and other research available (see section 3.2 for more details).

These and other assumptions, limitations and simplifications (detailed in Appendix D) should be considered when looking at the results of the analysis.

The current study simulated a sample of the existing housing stock built upon a number of set assumptions and variables to represent typical conditions of the existing housing stock.

The results of this study are strictly correlated to these assumptions. Thus, general trends and margins of improvements related to retrofit interventions are more significant than absolute numbers, which could change with different base assumptions.

Section 3

Task 1: Assessing the extent of overheating risk across the UK's current housing stock

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3.1 Key definitions

3.1.1 Building archetypes

The size, form and layout of a home will have a significant effect on its response to warm weather. Six archetypes were selected to represent the UK housing stock:

- Archetype 1: Mid-terrace house;
- Archetype 2: Semi-detached house;
- Archetype 3: Detached house;
- Archetype 4: End-terrace house;
- Archetype 5: Old flat (built pre-1995);
- Archetype 6: Modern flat (built post-1995).

The selection of archetypes was guided by a review of relevant literature and engagement with stakeholders and based on the typologies present in the English Housing Survey which allows extrapolation of results across the UK housing stock.

These archetypes have differing sizes and other geometrical characteristics which are relevant to modelling their overheating risk: for example, mid-terraced houses have less exposed surfaces than detached houses, newer flats have balconies and bigger windows compared to older flats but are commonly single-sided.

Despite flats representing a relatively small fraction of the housing stock – approximately 20% (BRE, 2020) – two flat archetypes were selected because previous research and modelling experience suggests flats are expected to be at higher risk of overheating, mainly due to the higher occupant density compared to a house.

An 'old' flat and a 'modern' flat were selected to represent respectively flats built before and after the publication of the first version of BR Approved Document Part L (HM Government, 1995) which introduced more rigorous energy performance requirements for buildings.

Both flat archetypes have one double bedroom and share a similar floor area. The modern flat has a balcony, which has the dual effect of increasing the glazing and openable area and providing shading for the flat below. The older flat archetype has a relatively small openable glazing area (around 25% of total glazing area) but has two exposed sides which allows for cross ventilation. Flats were chosen to be mid-floor to represent most flats within the UK. For the cost assessment, these would be on the third floor.

With the intention of building on existing work, the geometries of the archetypes (excluding the two flats) were taken from the previous LETI Climate Emergency Retrofit Guide (LETI, 2021). The flat archetype included in the LETI study was not used in this work as it was a maisonette and therefore was deemed to be not representative of the common flat typologies and issues in relation to overheating. Instead, two layouts from recent Arup projects were selected to provide the geometry for the flat archetypes.

Figure 5: Archetype 1 - Mid-terrace house case study

Figure 6: Archetype 2 - Semi-detached house case study

Figure 7: Archetype 3 - Detached house case study

Figure 8: Archetype 4 - End-terrace house case study

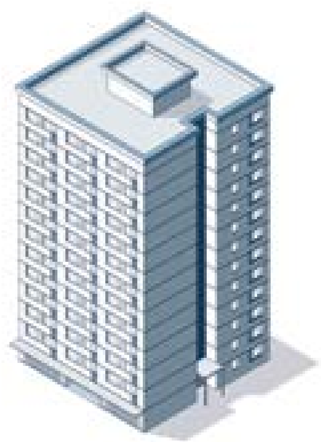

Figure 9: Archetype 5 - Old flat case study

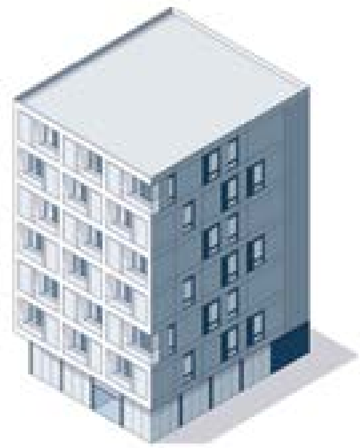

Figure 10: Archetype 6 - Modern flat case study

3.1.2 Weather scenarios and locations

3.1.2.1 Representative locations

The UK can be split into four broad climatic regions, as reported in CCC's 'Independent assessment of UK climate risk' (Climate Change Committee, 2021) and shown in Figure 11, which are characterised by increasingly warmer temperatures and a higher future warming risk going from north to south. For this reason, the geographic location was considered one of the key variables in assessing the overheating risk for the UK housing stock.

To cover the range of UK climatic conditions, the following weather locations were selected upon discussion with the Climate Change Committee, CIBSE and the MetOffice:

– Swindon for South of England;

– Birmingham for the Midlands and Wales;

– Manchester for North of England and Northern Ireland;

– Glasgow for Scotland;

– Central London, to represent the effect of the urban heat island (which is known to be the warmest condition).

A weather file is not available for the northern part of Scotland (in blue in Figure 11). However, this area represents a very low-density region with a very low number of homes and is characterised by cold weather; so the weather data for Glasgow was used as a conservative representation of the climatic conditions of this area.

The official CIBSE weather files were used for this analysis. Design Summer Year 1 (DSY1) data was used to assess overheating risk, as per CIBSE TM59. In order to estimate the baseline heating demand in winter and the impact of certain mitigation measures on this, Test Reference Year (TRY) data was used, as recommended by CIBSE for energy consumption calculations.

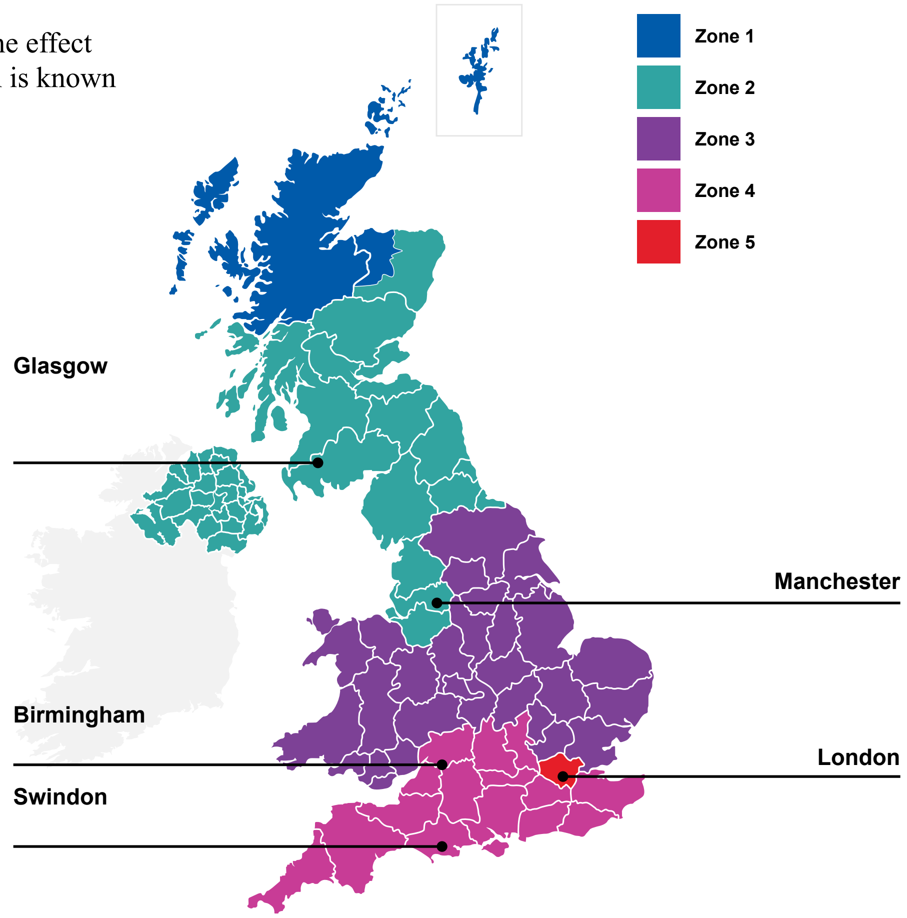

Figure 11: Map of climatic regions within the UK: Zone 1 to 5 from colder to warmer (Climate Change Committee, 2021)

3.1.2.2 Future weather scenarios

Future climate conditions were represented by two possible global warming scenarios, a 2°C GW and a 4°C GW. Based on research conducted by the CIBSE SDG Climate Change Adaptation Working Group in 2019, the following datasets were selected to represent the two future weather scenarios for each location:

– CIBSE 2080 Low Emissions, 50th percentile weather files were used to represent the 2°C GW scenario;

– CIBSE 2080 High Emissions, 50th percentile weather files were used to represent the 4°C GW scenario.

3.1.2.3 Focus on weather datasets

Two data sources were explored to obtain and select the most appropriate weather files representing future conditions for the weather scenarios selected. These are CIBSE Weather Data Sets and the weather files developed as part of the 'Cooling in the UK' research project led by BEIS (BEIS, 2021). The key difference between the CIBSE and BEIS files is that CIBSE files are based on UKCP09 climate projections while BEIS files are based on UKCP18 projections. UKCP18 represent the most up to date projections for the UK and are based on the Representative Concentration Pathways (RCPs) used by the Intergovernmental Panel on Climate Change (IPCC) to represent future emission scenarios. UKCP09 are the precursor projections for the UK and are based on the old emission scenarios used by the IPCC, the Special Report Emission Scenarios (SRES). See below a summary of the data available in each of these data sources for future weather files:

– CIBSE future weather files are based on UKCP09 data and available for fourteen locations in UK (as are the CIBSE historical climate weather files), for future time periods representing 2020s, 2050s and 2080s and for three emission scenario (low, medium and high) and uncertainty levels covering 10th, 50th and 90th percentile for each emission scenarios;

– BEIS future weather files are based on UKCP18 data and available for four locations (Belfast, Cardiff, Glasgow and London), time period covering from 2020 to 2100 and for two emission scenarios (RCP2.6 and RCP8.5).

– A high-level comparison of the data available from these two data sources for two locations (Glasgow and London) and two scenarios[2] was carried out to inform the selection of dataset to be used in the analysis. A summary of key findings from the comparison is included below:

– Overall, the comparison showed that for both Glasgow and London, temperature values are lower in BEIS weather files. Temperature values differences were expected given that there are several characteristics which are different in the datasets compared (i.e., data source, time period, and scenarios; it is assumed that morphing algorithm used is the same). Based on this comparison, the CIBSE future weather files represent a more conservative estimate for future climate.

– Larger differences between the two datasets were obtained for 2°C than 4°C. This is expected to be largely influenced by the different emissions scenarios used.

– Temperature differences between the two datasets are in some cases not insignificant (e.g., London for 2°C scenario where differences of more than 1°C were obtained). Further data analysis of future weather files might be required in next steps.

– Following the comparison described above, the CIBSE weather files were selected for use in this analysis. This selection was based on the findings from the comparison (i.e., CIBSE files lead to more conservative estimates of temperature increase in future climate), the fact that data for all locations is not available from the BEIS weather files, and the fact that CIBSE weather files are publicly available and approved for overheating assessments under CIBSE TM59.

[2] DSY 2080s Low emissions at 50th percentile from CIBSE was compared to DSY 2085 RCP2.6 from BEIS, and DSY 2080s High emissions at 50th percentile from CIBSE was compared to DSY 2085 RCP8.5 from BEIS. Note that an exact comparison between files is not possible as different emission scenarios and time periods are included in the datasets. The comparison carried out has been considered a reasonable representation of temperature in a 2°C and a 4°C global warming scenarios.

3.1.3 Overheating risk criteria

3.1.3.1 CIBSE TM59

To provide repeatable and widely comparable outcomes, the CIBSE TM59 overheating method was used. This is widely used and designed to provide a framework for consistent assessment and reporting of overheating risk in UK homes. The CIBSE TM59 method is also the basis for the BR Approved Document O on overheating. For each building archetype, results for each activity space were extracted (i.e. bedrooms, living areas and kitchens).

CIBSE TM59 presents two criteria for homes that are 'predominantly naturally ventilated':

– Criterion A for living rooms, kitchen and bedrooms: The number of hours where the operative temperature exceeds the comfort temperature by one degree Kelvin or more during the period May to September inclusive, shall not be more than 3% of occupied hours.

– Criterion B for bedrooms only: to provide comfort (CIBSE states to 'guarantee comfort') during typical sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1% of all annual hours. Since 1% of the annual hours between 22:00 and 07:00 for bedrooms is 32 hours, 33 or more hours above 26 °C will be recorded as a fail.

The failure of any one criterion for any occupiable room in the dwelling leads to failing the assessment for the whole dwelling, meaning that the dwelling is defined as being at risk of overheating.

The results were analysed for both standard users and vulnerable users, as defined in CIBSE TM52.

Although CIBSE TM59 Criterion are used to assess the overheating risk in this study, understanding the severity of the overheating risk in different areas of the country and for different building types, and the relative benefit of selected mitigation measures, is the primary focus of this study.

3.1.3.2 Alternative criteria to assess overheating risk in bedrooms

The current TM59 criterion for bedrooms (Criterion B) has repeatedly been shown by modellers, researchers and others to be particularly stringent and as such it often drives the design of dwelling to include active cooling which leads to additional energy consumption, additional heat rejection externally and greater carbon emissions for the building operation, even when the adaptive method does not highlight any overheating risk.

Research is ongoing at Loughborough University, assisted by Arup, CIBSE, DLUHC, BEIS and others (Lomas, et al., 2022), to understand the origin and credibility of this criterion. The focus of this research is on sleep quality, and the extent to which this is affected by night-time temperatures. The intention is to provide an alternative, evidence-based criterion which can prevail until new field studies on the effects of heat on sleep are completed.

The research to date has shown that the field data on which the existing criterion is based are not applicable to contemporary sleep behaviours. The research has also suggested that the mean night-time temperature, rather than the temperature of individual hours through the year, has a bigger impact on the quality of sleep. Some experiments have shown that a normal healthy person lying on a mattress may be thermal neutral at 28.5°C or above, suggesting that the mean temperature used to define an overheated bedroom could be rather higher than 26°C.

This research is to yet to be completed, but the emerging findings provide important context against which to consider the results for bedrooms presented here.

3.2 Modelling approach

3.2.1 Multi-parametric modelling

Multi-parametric modelling is an approach to energy and thermal modelling that includes, in addition to fixed inputs, the definition of variables that automatically change in a batch of simulations so that all possible combinations of these variables are assessed in a single modelling exercise. In this study, the parametric variables are used to describe the possible building features that characterise the UK building stock.

For each archetype defined in section 3.1.1, a baseline thermal energy model was created to simulate the future weather scenarios alongside a large number of other variables. DesignBuilder V7.0.1 software was used for the simulations which uses EnergyPlus V9.4 as a calculation engine and a parametric tool which runs all possible combinations of a number of variables at one time and outputs a selected set of results for each run.

For each archetype, a number of fixed parameters were set including geometry, material constructions for most elements, HVAC strategy and internal gains (see section 3.2.3). In addition to this, a series of parametric variables were defined, which can change an individual model setting to a pre-defined range of values. For example, the U value of a wall can be set as a parametric variable which can vary from 0.1 to 0.3 in steps of 0.05.

Parametric modelling was used in this study to change parameters such as building location, weather scenario, orientation, construction properties and eventually mitigation packages. For each individual design option a range of overheating criteria and energy consumption outcomes were recorded.

3.2.2 Key modelling assumptions

Archetype geometry was taken directly from architectural drawings and replicated in the thermal modelling software. All surfaces between dwellings were defined as adiabatic meaning no heat transfer was permitted to represent the fact that adjacent dwellings would have similar indoor conditions to the one modelled. Both flat archetypes were modelled as mid-storey flats, which represent the majority of flats in the housing stock.

This study has followed the CIBSE TM59 methodology. Where available TM59 guidelines were applied to all archetypes. This included prescribed occupancy, equipment, and lighting gains and schedules. The following sections give more details on the modelling settings.

The CIBSE TM59 method is a recognised, understood and published method for assessing residential overheating which is now referenced in BR Part O and various local planning guidance. However, it should be noted that, in this study the TM59 criteria were used as a measure of overheating risk rather than a pass / fail compliance measure. TM59 intentionally aims to assess a worst-case and standardised scenario. This includes high internal gains, constant occupancy and limited actions taken by the occupant to limit overheating. It is therefore expected that the results from this study will differ in absolute terms from the results from the English Housing Survey (DLUHC, 2013) but general trends and the effectiveness of the mitigation measures have shown strong similarities with this study.

3.2.3 Fixed parameters

Building fabric

Building fabric is a generic term for walls, windows, roofs and ground floor. Two aspects of the building fabric, the external wall construction and the roof insulation, were selected as variable parameters in the parametric modelling. The external wall construction was deemed to be correlated to the age of construction. This means that the newer the building, the higher performing the fabric as more recent building codes have required higher standards of energy efficiency.

The ground floor, internal wall, door and glazing constructions are consistent across all models. Whilst many homes will have originally been constructed with single glazing, little correlation was assumed between building age and glazing type as most dwellings have been upgraded to double glazing.

Table 3 below reports the building fabric performance considered in the study. U values in this study have reflected those used in the baseline modelling conducted in the LETI Climate Emergency Retrofit Guide (LETI, 2021). A standard g-value (the fraction of solar heat gain passing through the glazing) of 0.69 was considered for all windows.

Construction element	U Value (W/m^2K)
Ground floor	0.80
Internal floor / ceiling	1.23
Internal wall	1.19
External door	3.00
External window	2.00

Table 3: Thermal properties of modelled constructions

Heating, cooling and ventilation strategy

Each building is assumed to be heated from October to April inclusive. Bedrooms, kitchens and bathrooms were given a heating temperature set point of 18°C when occupied, whereas living rooms were heated to 21°C. In all spaces a set-back temperature set point of 12°C was applied representing the minimum possible temperature.

All homes are assumed to be naturally ventilated with window operation dependent on the internal temperature and occupancy of each space. Windows can only be opened when a space is occupied and, for security reasons, only bedroom windows were considered to be openable during the night.

The operation of windows for natural ventilation and cooling followed a similar logic to that defined in the recently published Buildings Regulation Part O (HM Government, 2022) and was informed through consultation with Loughborough University. Windows were modelled to open in a stepped way to avoid constant readjustment at every timestep. The following assumptions were made and applied uniformly across all archetypes:

- During the day, windows are opened depending on the indoor temperature to represent how a typical person might operate them. If the indoor temperature exceeds 22°C the window is opened to 25% of its maximum. If the temperature exceeds 23°C, the window is opened to 50%. Above 24°C the window is opened to 75%. If the indoor temperature exceeds 25°C the window is opened to is maximum extent.
- During the night, bedroom windows will remain open at 50% if the indoor temperature is above 23°C at 11pm. If the indoor temperature falls below 21°C, the occupant is assumed to wake up and close the window. When the window is closed, it will remain closed all night. The window position will only be changed a maximum of one time during the night.
- In line with CIBSE TM59, the windows remained open even if the outdoor temperature exceeded the indoor temperature.
- The openable area of each window determined from the architectural plans of each archetype geometry.

Internal gains
Internal gains are sources of heat that typically occur in homes. These include heat from lights, indoor equipment and activities (such as cooking) and people. In this analysis, the magnitude and operation profiles of all internal gains are as per CIBSE TM59.

3.2.4 Parametric variables
Parametric variables are those variables that vary within a selected range in the multi-parametric modelling. The parametric variables for this study were selected based on the information available in Parity Projects' stock model.

The tables below summarise the parametric variables adopted in the modelling process. The total number of simulations that were generated by combining all the parametric variables was 2,400, as presented in Table 10.

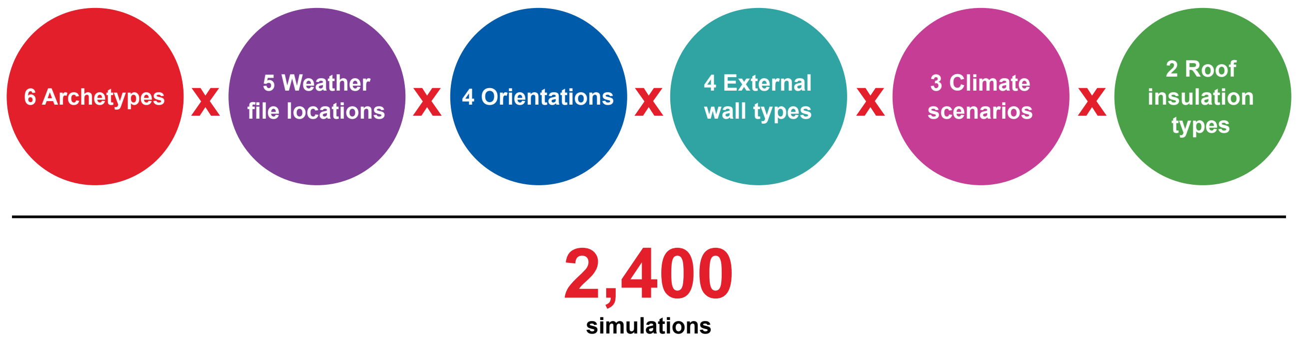

Figure 12: Variables included in Task 1 parametric modelling

Archetype	Case study	Source
Mid-terrace	Haddington Way	LETI Climate Emergency Retrofit Guide
Semi-detached	Zetland Road	LETI Climate Emergency Retrofit Guide
Detached	The Nook	LETI Climate Emergency Retrofit Guide
Old flat	1960s housing development in East London	Arup previous project
Modern flat	New housing scheme in Central London	Arup previous project
End-terrace	Gloucester Place Mews	LETI Climate Emergency Retrofit Guide

Table 4: Building typology parameters

3.2.5 Model outputs
The following results were output for each simulation:

- Criterion A for kitchens and living rooms (% of hours) for Category I – vulnerable user;
- Criterion A for bedrooms (% of hours) for Category I – vulnerable user;
- Criterion A for kitchens and living rooms (% of hours) for Category II – standard user;
- Criterion A for bedrooms (% of hours) for Category II – standard user;
- Criterion B for bedrooms (number of hours) – equal for both user type.

In the case that a dwelling had more than one living room or more than one bedroom, individual scores were produced and the worst case result was used to represent that particular dwelling.

Weather file location	Area represented
London	London
Birmingham	Midlands and Wales
Manchester	North of England and Northern Ireland
Glasgow	Scotland
Swindon	South England
End-terrace	Gloucester Place Mews

Table 5: Building location parameters

Climate scenario	Weather file
Current	DSY1 2020 High Em. 50th perc.
2°C GW	DSY1 2080 Low Em. 50th perc.
4°C GW	DSY1 2080 High Em. 50th perc.

Table 6: Climate scenario parameters

Orientation
North
East
South
West

Table 7: Building orientation parameters

External wall construction	U-Value (W/m².K)
Solid Uninsulated	1.35
Cavity Uninsulated	1
Solid Insulated	0.37
Cavity Insulated	0.43

Table 8: Wall construction parameters

Roof construction	U-Value (W/m².K)
Minimal Loft Insulation	1
Good Loft Insulation	0.17

Table 9: Roof construction parameters

Parametric variable	Number of options
Building typology	6
Building location	5
Climate scenario	3
Building orientation	4
Wall constructions	4
Roof Constructions (excluding flats)	2
Total combinations	2,400

Table 10: Summary of parametric variables

3.3 Baseline results

Figure 13 provides a pass or fail summary of the TM59 criteria for all 2,400 simulations: 800 for each climate scenario. The dwellings in this study perform significantly worse against Criterion B than they do against Criterion A.

In the current weather scenario, the majority of combinations passed Criterion A in living rooms, kitchens and bedrooms for standard and vulnerable users. However, around 62% of simulated combinations had at least one bedroom that failed Criterion B.

When considering future climate scenarios with additional global warming, the number of dwellings that fail both criteria significantly increased. In a 4°C global warming scenario, the majority of dwellings failed Criterion A with standard or vulnerable users. In this climate scenario, 99.5% of simulations failed Criterion B.

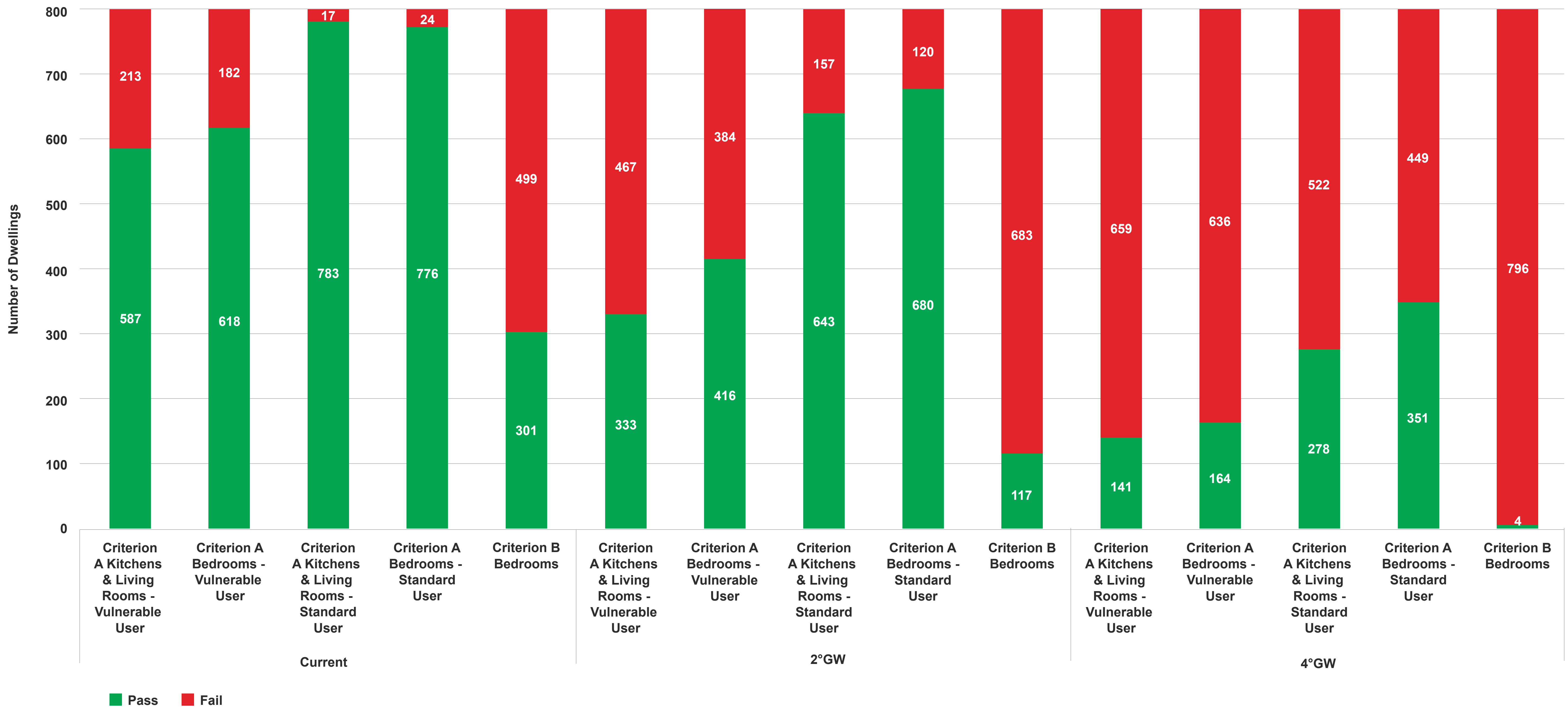

Figure 13: Number of dwellings passing or failing each TM59 criterion

The level of insulation of external walls did not show great impact on overheating risk looking at the full results set.

However, a more detailed sensitivity analysis showed that this impact depends on other conditions, primarily the effectiveness of ventilation in discharging any excess heat.

3.3.1 The influence of weather on overheating risk

The most influential variable on the overheating risk was the weather data applied. As demonstrated in Figure 14 to Figure 16, there is a clear increase in overheating moving southwards in the UK and as the climate changes from current summer design conditions to the conditions expected with 4°C GW scenario. In addition to increased overheating, the range of overheating outcomes becomes greater in warmer climates. This suggests that building characteristics and hence mitigations that could be applied could have a greater influence in these climatic conditions.

When the archetypes were simulated using the Glasgow weather data, the risk of overheating was shown to be significantly lower than the other locations. Even in the 4°C warming scenario, all buildings passed Criterion A for living spaces and bedrooms with standard users.

Dwellings in London were shown to have a significant overheating risk in the 4°C warming scenario. As shown in Figure 16, the mean value for Criterion A for bedrooms was 8.3% which is nearly three times the acceptable limit defined in TM59.

3.3.3 The influence of external wall construction on overheating risk

Unlike the location and weather scenario, the results didn't show any significant correlation to the external wall construction, as illustrated in Figure 17 and Figure 18. There was a minor negative correlation between U value and overheating severity, meaning that dwellings with better insulation are likely to be better protected from overheating. The effect of external wall construction did vary depending on the archetype and this is discussed further in Section 3.6.1.

3.3.4 The influence of roof insulation on overheating risk

Improved roof insulation was found to have a greater correlation to overheating in bedrooms than in other rooms. Figure 19 shows that improved roof insulation had little to no effect on the overheating within living rooms or kitchens; however, improving the roof insulation did have a noticeable impact on the overheating severity in the bedrooms (Figure 20). Given that bedrooms are mainly located on the upper storeys, roof insulation provided a more direct effect to bedrooms rather than the living spaces which were generally located on the ground floor. Improvised roof insulation was particularly effective at reducing the Criterion B overheating for loft bedrooms which tend to be more prone to overheating problems.

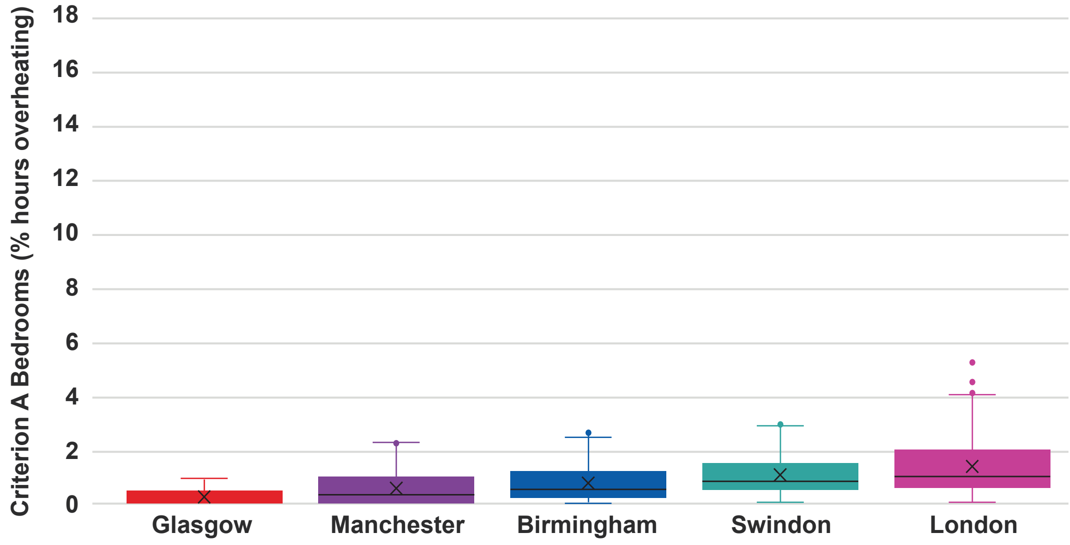

Figure 14: Box and whisker plot of the distribution of Criterion A (standard user) applied to bedrooms categorised by location – current weather

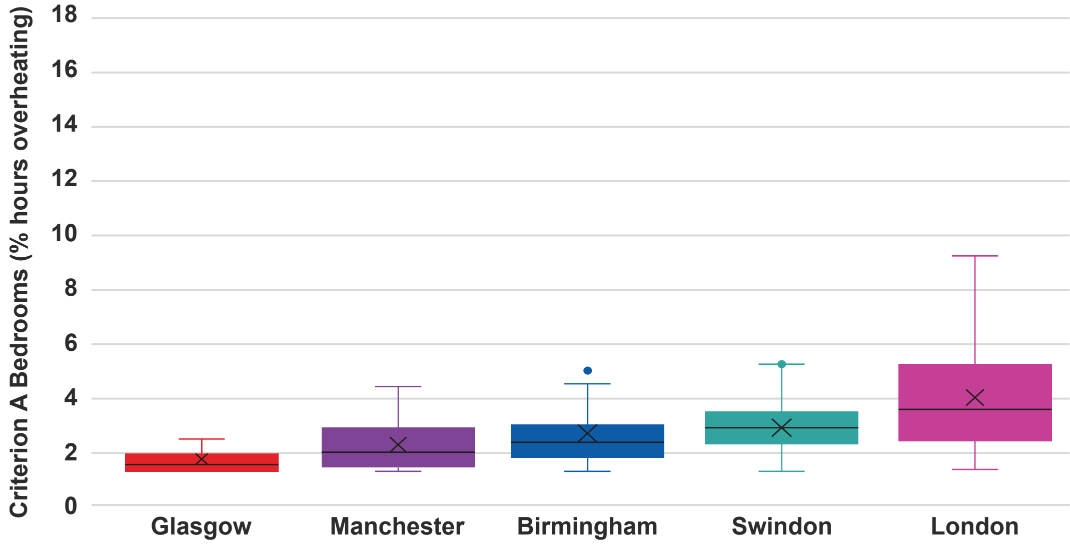

Figure 15: Box and whisker plot of the distribution of Criterion A (standard user) applied to bedrooms categorised by location – 2°C warming scenario

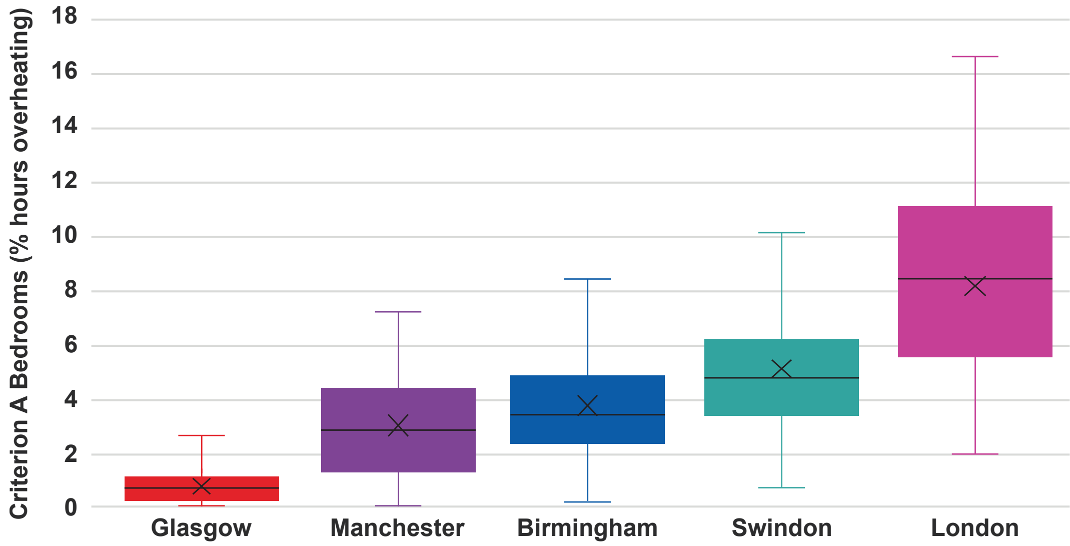

Figure 16: Box and whisker plot of the distribution of Criterion A (standard user) applied to bedrooms categorised by location – 4°C warming scenario

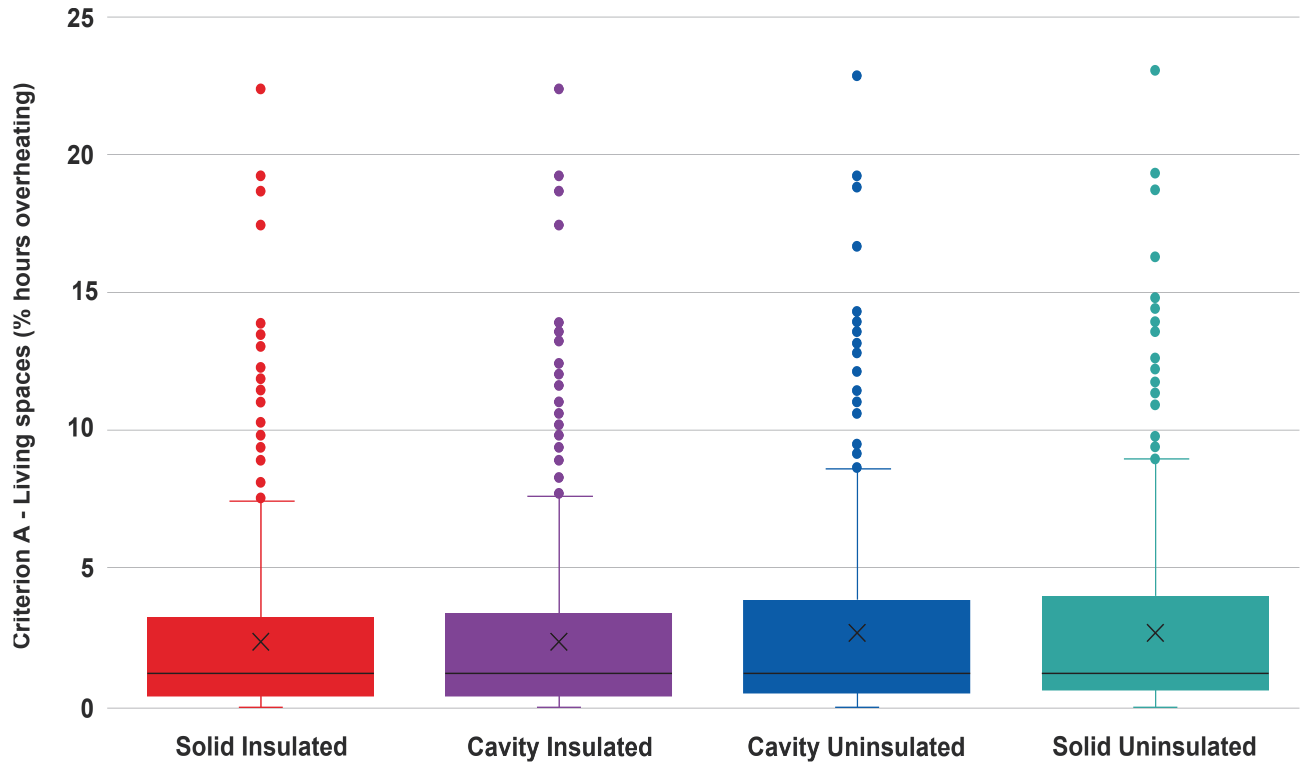

Figure 17: Box and whisker plot showing the distribution of the TM59 Criterion A in living spaces categorised by external wall construction – all weather scenarios

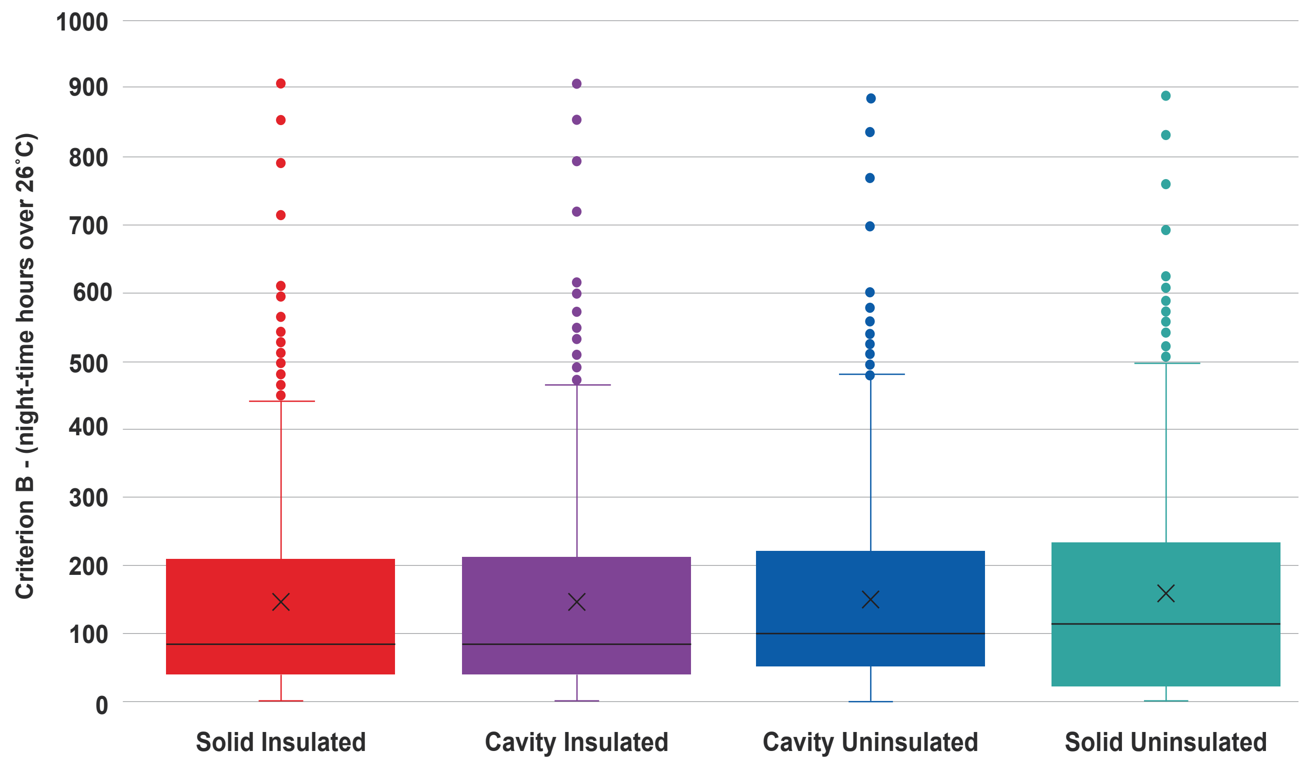

Figure 18: Box and whisker plot showing the distribution of the TM59 Criterion B categorised by external wall construction – all weather scenarios

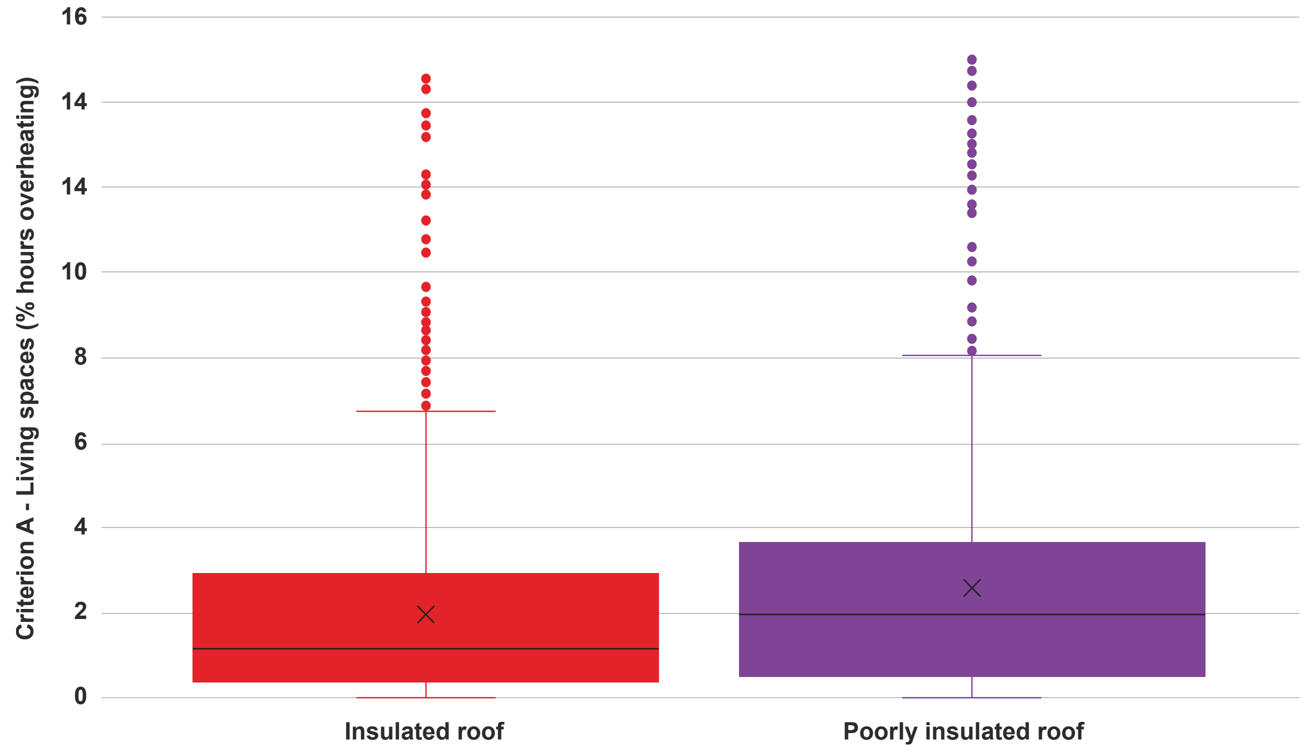

Figure 19: Box and whisker plot showing the distribution of the TM59 Criterion A in living spaces categorised by roof construction – all weather scenarios

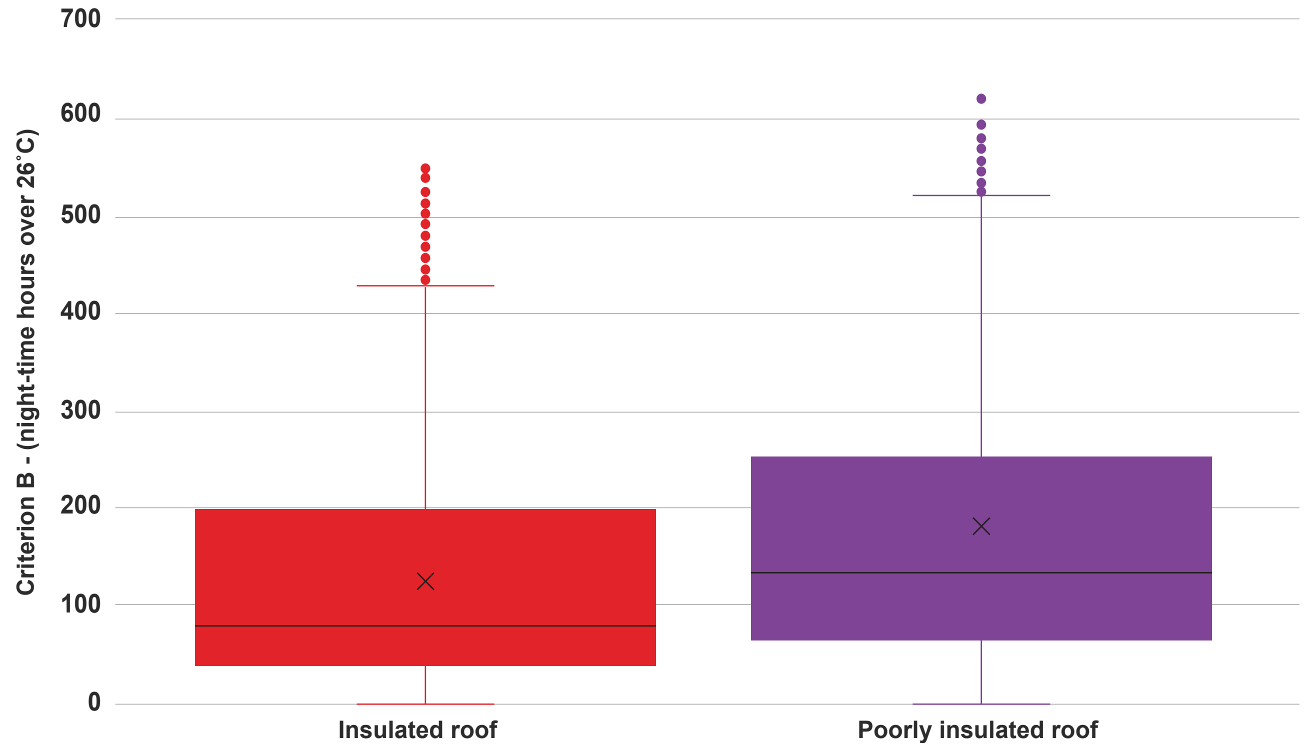

Figure 20: Box and whisker plot showing the distribution of the TM59 Criterion B categorised by roof construction – all weather scenarios

3.3.4 The influence of orientation on overheating risk

In the models, orientation was determined from the perspective of which compass point the main living space faced. This does not give an indication of the orientation of the bedrooms as these are placed in different positions for each archetype and some archetypes, e.g. the detached house, have bedrooms that face all orientations while some archetypes have two living spaces facing different directions or have dual aspect living spaces.

For this reason, general trends in relation to orientation could not be identified for bedrooms (see Figure 22). However, the results show that west-facing living spaces have a greater tendency to overheat, followed by south, east and lastly north (see Figure 21).

An example that illustrated the challenge of analysing the effect of orientation was the mid-terrace archetype. The bedroom with greatest tendency to overheat was a loft conversion facing the opposite direction to the primary living space. Therefore, when the east parameter was applied, the problematic bedroom actually faced west and therefore demonstrated more severe overheating. In contrast, the bedroom of the modern flat faced in the same direction as the living space so those two spaces showed similar overheating trends in relation to orientation.

The impact of orientation of buildings was investigated to identify key risk factors in terms of overheating. However, the stock model does not include this information for the homes and therefore it would not be possible to define mitigation strategies for different orientations and their level of deployment at scale. For this reason, this variable was excluded in the next phases of the study.

3.3.5 The influence of archetype on overheating risk

Drawing broad conclusions around the likelihood of overheating in entire building archetypes is avoided in this study as the archetypes are based on a single building example. Instead, the specific features of the example buildings, and their impact on overheating, are discussed. These features could be the wall to floor area ratio, the window to wall ratio, or the position and adjacency of particular spaces. For example, a spacious mid-terrace property with a low proportion of glazing could behave more like the detached house modelled in this study rather than the mid-terrace.

Figure 23 shows the likelihood of overheating within the living rooms of the sample archetypes. The detached house with its larger floor area produced the lowest overheating risk. The semi-detached and end-terrace properties show the next lowest level of risk and perform very similarly to each other. The mid-terrace has a greater risk of overheating owing to its smaller floor area and hence higher intensity of internal gains. The worst performing archetypes are the two flats. The older style flat produced a wider variability in overheating risk and appears to be affected to a greater extent by the weather compared to the modern flat. In warmer locations and climate scenarios the old flat showed larger overheating than the modern flat, but this trend was reversed in cooler climates. This was likely caused by the relatively low window opening free area available in the old flat which became a more important feature in warmer scenarios.

The Criterion B bedroom overheating per archetype is given in Figure 24. Once again, the detached house shows a lower risk of overheating, however, the modern flat also performs relatively well against this criterion. The mid-terrace and semi-detached archetypes performed poorly as these archetypes contained loft bedrooms. Particularly in instances with poor roof insulation, these loft rooms displayed a greater tendency to overheat. The old flat archetype showed the largest overheating risk. This archetype had a relatively small bedroom and hence a high internal gain intensity and had a very limited window opening area.

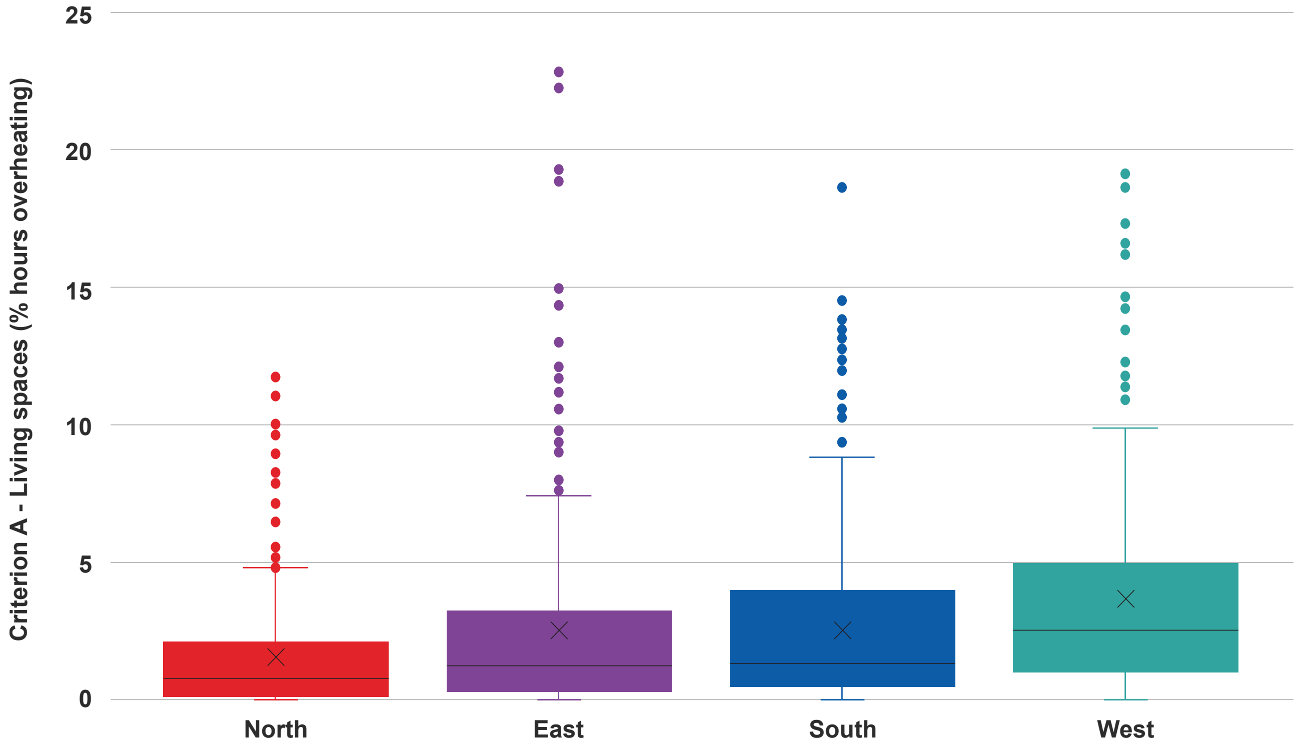

Figure 21: Box and whisker plot showing the distribution of the TM59 Criterion A in living spaces categorised by orientation – all weather scenarios

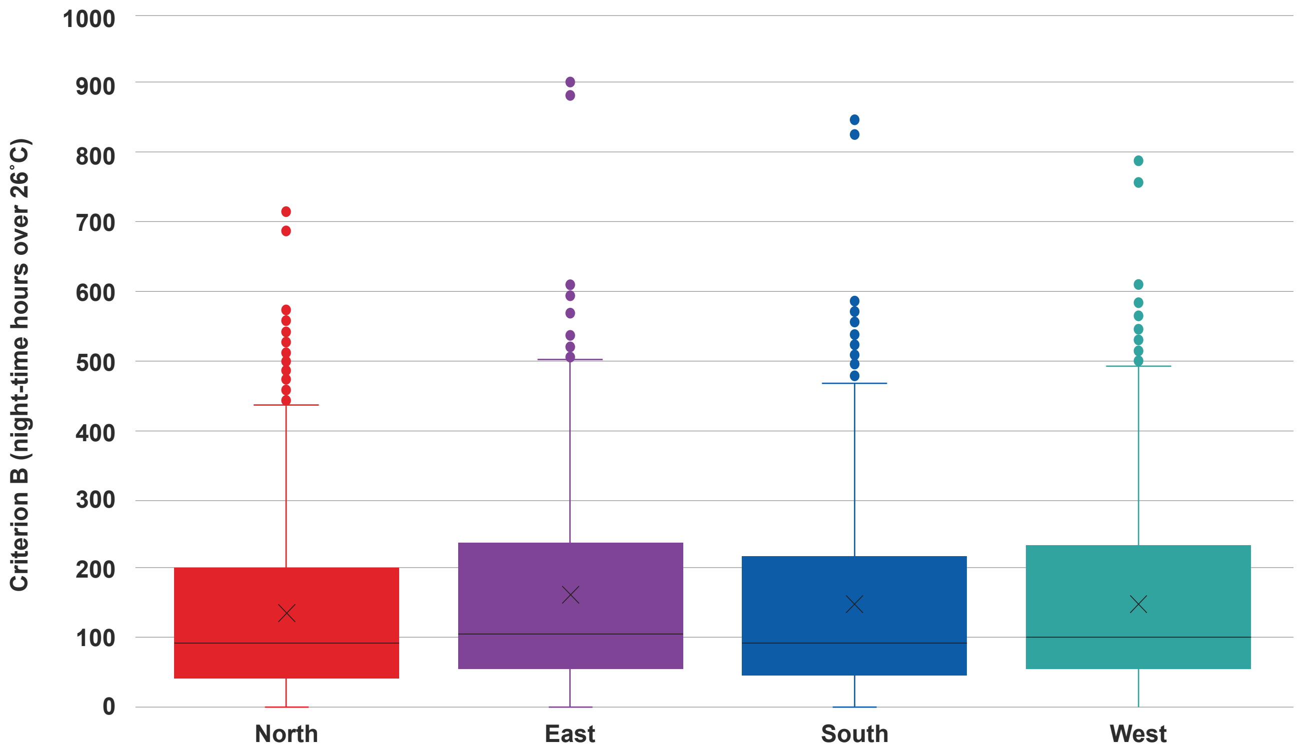

Figure 22: Box and whisker plot showing the distribution of the TM59 Criterion B categorised by orientation – all weather scenarios

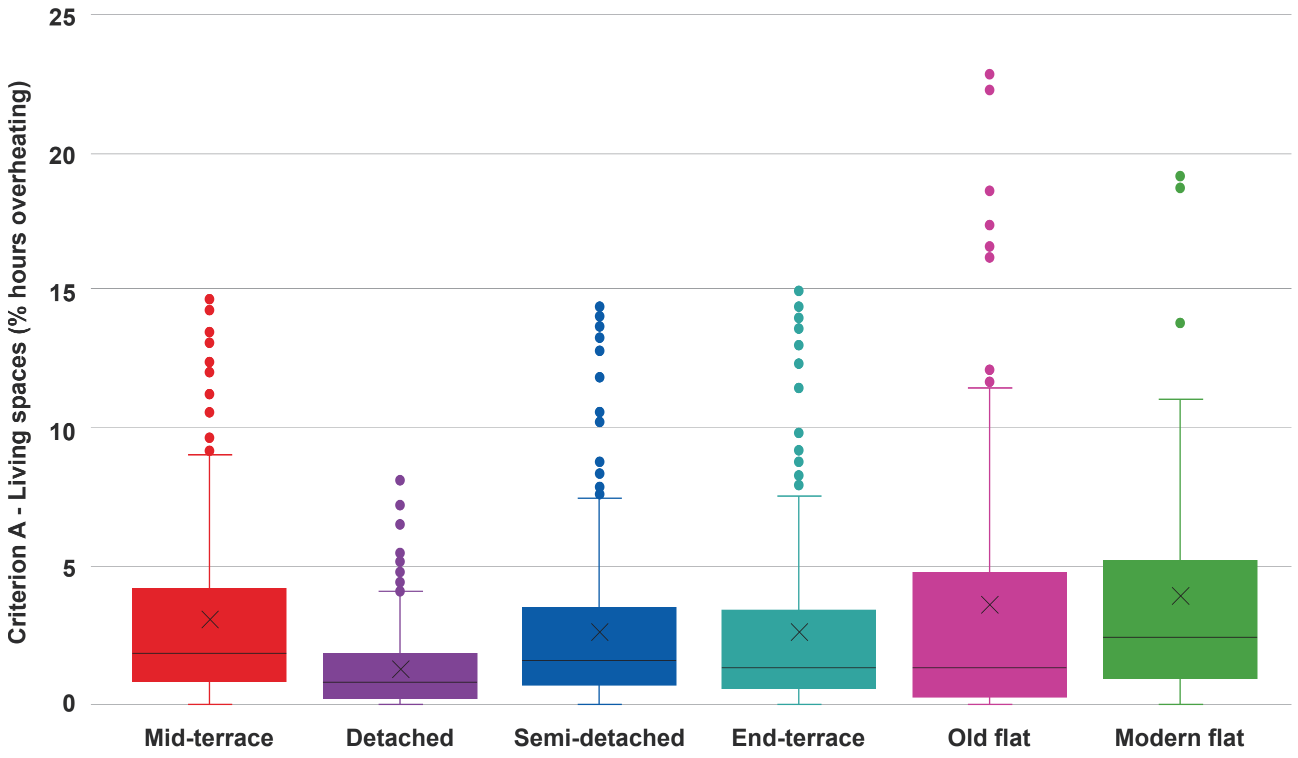

Figure 23: Box and whisker plot showing the distribution of the TM59 Criterion A in living spaces categorised by archetype – all weather scenarios

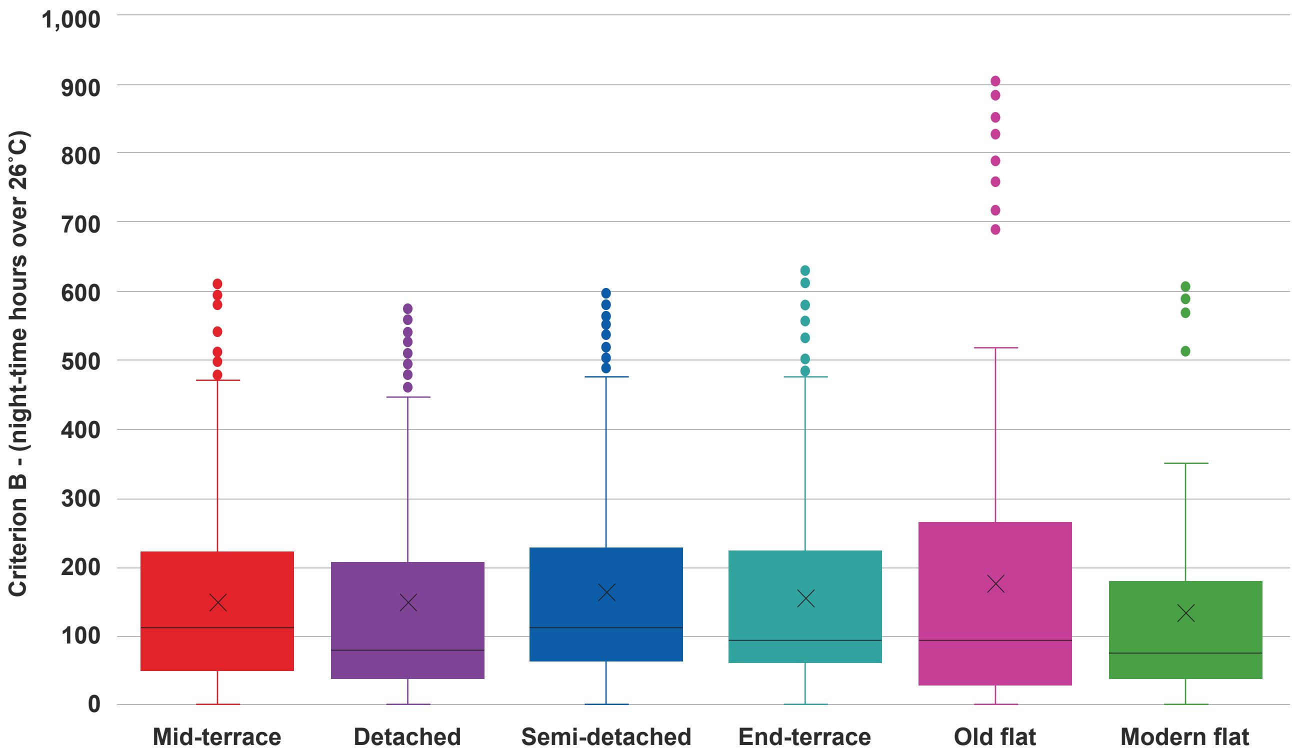

Figure 24: Box and whisker plot showing the distribution of the TM59 Criterion B categorised by archetype – all weather scenarios

3.3.6 Standard vs vulnerable users

Looking at the results for standard and vulnerable users, it could be noted that a higher number of dwellings failed Criterion A when vulnerable users were considered. However, as demonstrated in Figure 13, the dominant cause of TM59 failure is Criterion B (which is the same for standard and vulnerable users). All buildings passing Criterion B also passed Criterion A under both standard and vulnerable users limits. Due to these considerations and considering that the building stock does not include any information about the type of occupant in each dwelling, the type of occupant was excluded from the next steps of the analysis.

3.3.7 Comparison between results from current study and EFUS 2017

Confidence in the simulation results can be obtained by comparing them with the prevalence of overheating measured, or reported, by households in the EFUS 2017 study. Such a comparison can only be qualitative because the EFUS analysis used a binary (overheated/not overheated) assessment of each of the 616 living rooms and 591 bedrooms which yielded usable data and was influenced by the behaviour of the household, which can have a substantial impact on the risk of overheating. In contrast in the simulations, occupant behaviours are univocally defined. Both studies used Criterion A of TM59 for assessing both bedrooms and living rooms while EFUS did not consider Criterion B.

The simulations show that the likelihood of experiencing elevated temperatures is greater in London than in the other three cities, with the percentage of hours of overheating in bedrooms increasing the further south in the UK the dwelling is. The EFUS study revealed a similar trend: bedrooms and living rooms overheated more in London (28% living room, 32% bedroom) than in all other regions combined (13% living room, 17% bedroom), but the results were only significant at the 5% level.

The simulations indicate that roof insulation has a positive impact in reducing the overheating risk in bedrooms and, although the signal is less strong, in living rooms, while there is little, if any, correlation between wall insulation and overheating risk, either in cavities or onto solid walls. Likewise, the EFUS 2017 analysis showed that there were no significant differences in the measured prevalence of overheating in either the living rooms or the bedrooms for any of the energy efficiency related measures examined, i.e. wall insulation, glazing type (either single or double), depth of loft insulation or the number of energy efficiency measures applied. However, households living in dwellings with the least loft insulation (<50 mm) were significantly more likely to report overheating in the living room than those households living in dwellings with greater levels of loft insulation (Lomas, et al., 2021).

Further parallelisms between the simulated results and the outcome from the EFUS 2017 study could not be made due to some substantial differences in the sample that each analysis considered. In fact, while the EFUS study was based on monitored data within real buildings, which bring along all the different home configurations, orientations, occupant behaviours, etc, this study was based on a simplified homes sample and some univocally fixed parameters such as the absence of external overshading elements, the orientation of the buildings, the geometry and layout of the dwellings, etc.

3.4 Determination of representative building groups

Task 1 aimed to produce a large-scale and broad understanding of the risk of overheating in UK dwellings and to understand the major influences of overheating risk from different building characteristics. This information was then used to select a smaller sample of representative buildings onto which different mitigation packages could be applied.

Based on the analysis of different locations and weather scenarios, it was determined that Scotland can be excluded from the full mitigation modelling conducted in Task 3 due to the reduced overheating risk in that region. It was deemed unnecessary to model every mitigation package in every climate scenario for Scottish dwellings. Despite passing Criterion A for all weather scenarios, a minority of dwellings in Scotland were shown to moderately fail Criterion B in the 2°C warming scenario and the majority failed Criterion B in the 4°C weather scenario. Therefore, the lowest level mitigation packages will be applied to the representative Scottish dwellings until a TM59 pass has been achieved.

The overheating risk in the North of England and Northern Ireland (Manchester weather file) was shown to be very similar to the Midlands and Wales (Birmingham weather file). Therefore, it was deemed appropriate that the Birmingham weather file was used to represent also Northern England and Northern Ireland.

The external wall construction showed limited correlation with the overheating results; further investigation and sensitivity analysis of this was carried out and is described in section 3.6. The UK government's Heat and Building Strategy (HM Government, 2021) references the need to improve energy efficiency through a fabric-first approach, such as wall insulation, to make heating more cost effective and resilient. Given the need to improve insulation across the UK housing stock and the predominance of cavity wall across the building stock (as shown in Figure 25), it was considered appropriate that the main wall type used in the representative buildings was cavity insulated walls.

Roof insulation did have a significant influence on the overheating severity in bedrooms. Most dwellings performed poorly against Criterion B, so the two roof insulation options remained in the representative buildings as separate options.

Categorisation and differentiation based on orientation could be misleading in the context of this study as it is only measured from the perspective of the main living space. The overheating outcomes recorded may relate to spaces that do not face in that direction. Furthermore, the housing stock information does not record orientation of dwellings so it would not be possible to extrapolate simulation results if they were sub-divided by orientation. Therefore, variable orientation was not considered in the representative building groups. All representative buildings are assumed to have their main living space facing south which represents a balance between the highest overheating when facing West and the lowest overheating when facing North.

The resulting 30 representative buildings and related TM59 results are given in Table 11. In the current weather conditions, all buildings passed Criterion A, although several showed a high degree of overheating using Criterion B. When future climate scenarios are applied, the overheating becomes much more severe for both Criteria A and B.

Once a list of mitigation measures was selected in Task 2, the selected representative buildings were used to test the effect of various mitigation packages to these representative buildings to address the overheating challenge.

3.5 Extrapolation of results to building stock model

3.5.1 Extrapolation methodology

To extrapolate the results of the parametric modelling across the UK housing stock, it was important to understand how common each archetype is in different parts of the UK. National statistics of housing were analysed for each nation. The housing stock model of England produced by Parity Projects was used to forecast the numbers of each run within each region of England. This used data from the English Housing Survey, as described in Section 1.4.1, to create a representative dataset of homes. The number of homes within the stock model meeting the criteria of each building in terms of building archetype, wall type, roof insulation and region were counted. These were the attributes identified as being the key parameters for impacting overheating risk.

Similar surveys to the EHS exist for the other nations of the UK. These are:

- The Scottish House Conditions Survey (SHCS);
- The Welsh Housing Conditions Survey (WHCS);
- The Northern Ireland House Condition Survey (NIHCS).

It was not possible to perform the same detailed analysis of raw data for each of these data sources due to data availability. Instead, the headline results in each nation were used, as summarised by the BRE's report 'The housing stock of the United Kingdom' (BRE, 2020). From this report the total number of households in each nation and the proportion of homes by age, property type and wall type categories were extracted. Then, the proportion of homes meeting each of the criteria were drawn out from the EHS, but for these other nations. Data on loft insulation levels was not available, so an assumption was made that these proportions were the same as England across the UK.

These proportions were then combined to predict the number of homes in each archetype category required. For example, to find the number of detached homes in Scotland with insulated cavity walls and loft insulation, the product of the following was used:

- The proportion of detached homes in Scotland;
- The proportion of homes with insulated cavity walls in Scotland;
- The proportion of homes with loft insulation in England (due to the lack of data for Scotland);
- The total number of homes in Scotland.

Figure 25 shows the distribution of homes between different categories post-extrapolation of the numbers to the whole UK housing stock.

This method assumes that there is no correlation between the different attributes. It is recognised that this is not accurate, for example modern homes will almost certainly have insulated cavity walls and loft insulation. It is unlikely that the same proportion of solid walled homes and insulated cavity homes have loft insulation, for example. This simplification may lead to over-estimating the number of homes in categories that are unlikely combinations and to under-estimating homes in more typical categories. However, it was a necessary simplification due to not being able to assess the detailed data for the nations of the UK other than England, which reports the interactions between the factors of interest.

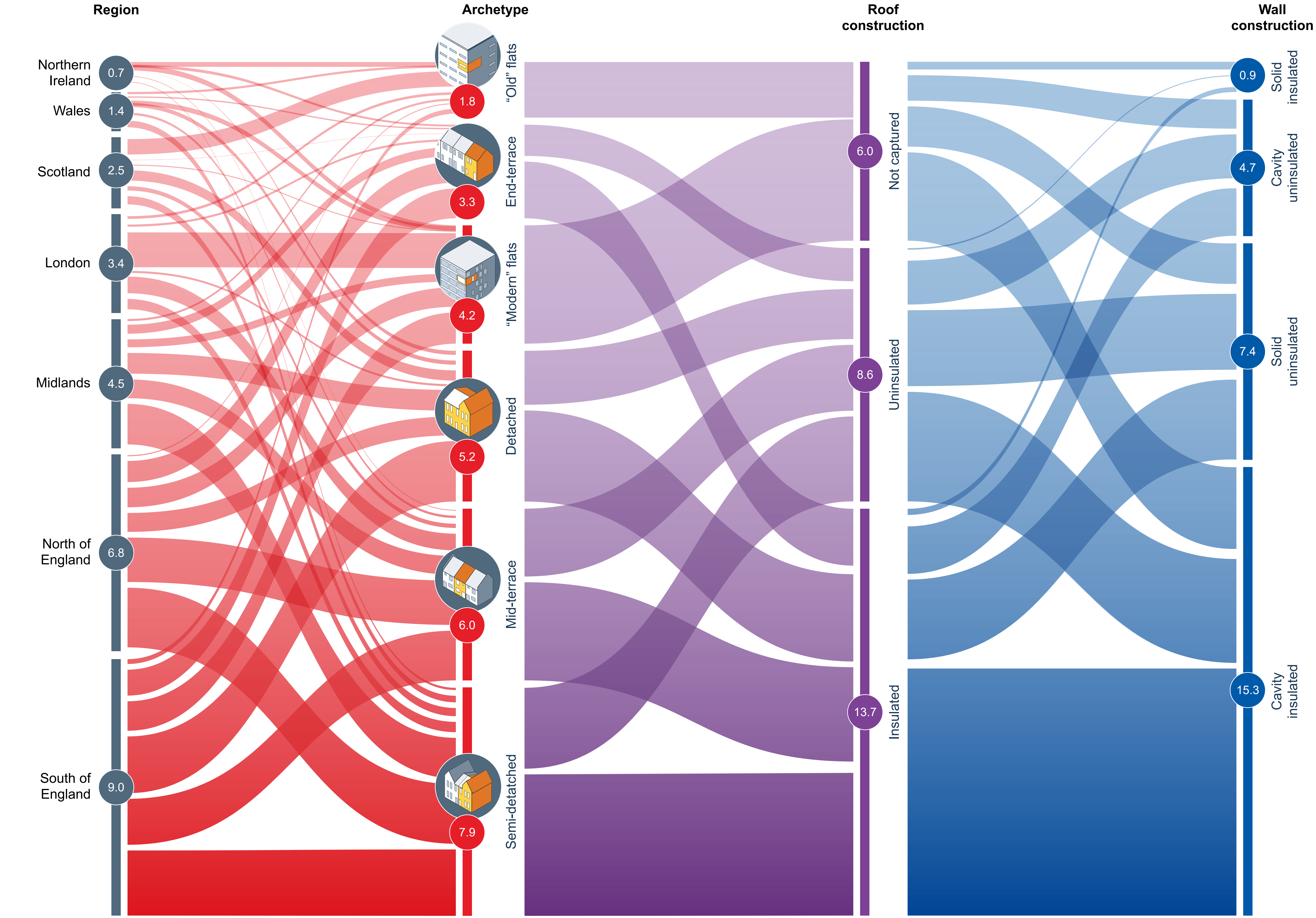

Figure 25: Distribution of UK homes based on different characteristics

3.5.2 Overheating results for the baseline at national scale

In subsequent tables displaying TM59 results, colour coding was used to give the reader a quick impression of the severity of overheating. For Criterion A and B, this was scaled based on the pass value of each criterion. The colour coding was based on the following:

- TM59 pass condition: Criterion A 0-3%, Criterion B 0-32 hours
- TM59 moderate fail: Criterion A 3-6%, Criterion B 32-64 hours
- TM59 severe fail: Criterion A 6-15%, Criterion B 64-160 hours
- TM59 extreme fail: Criterion A over 15%, Criterion B over 160 hours

Table 11 shows a total of 25.8 million dwellings within the UK which were included in the representative building groups discussed in Section 3.4. A further circa 2.5 million dwellings in Scotland were not included in this table due to the relatively lower risk of overheating and will be assessed in isolation.

In the current weather scenario, all representative buildings passed Criterion A, however, the majority of representative buildings failed Criterion B which collectively represented 55% of the UK housing stock. The overheating risk was more acute in the South of England and London, whereas using the Birmingham weather file only produced moderate failure of Criterion B. Buildings with uninsulated roofs showed a much greater degree of overheating compared to their insulated counterparts. In a current weather scenario, circa 12.6 million dwellings will not require any mitigation packages as they pass both Criterion A and Criterion B.

In the 2°C global warming scenario, none of the representative buildings outside Scotland passed TM59 as they all failed Criterion B. In addition, several archetypes, mainly in London, started to fail Criterion A. All simulations based in London showed an extreme failure of Criterion B whereas simulations using the Birmingham weather file only moderately failed Criterion B. Across the entire UK housing stock, 2.4 million dwellings would not require intervention, 21.1 million dwellings failed only Criterion B, and 4.8 million dwellings failed both criteria.

In a 4°C global warming scenario, all dwellings will need some type of intervention to mitigate against overheating. Almost all selected representative buildings showed an extreme failure of Criterion B, an order of magnitude above the determined acceptable level of overheating. This climate scenario also showed significant overheating in Criterion A in almost all buildings outside of Scotland. All UK dwellings would require intervention to mitigate against overheating, 4.8 million dwellings failed Criterion B, and 23.5 million dwellings failed both criteria.

Figure 26 shows how dwellings perform against CIBSE TM59 Criteria A and B across the UK based on the baseline models.

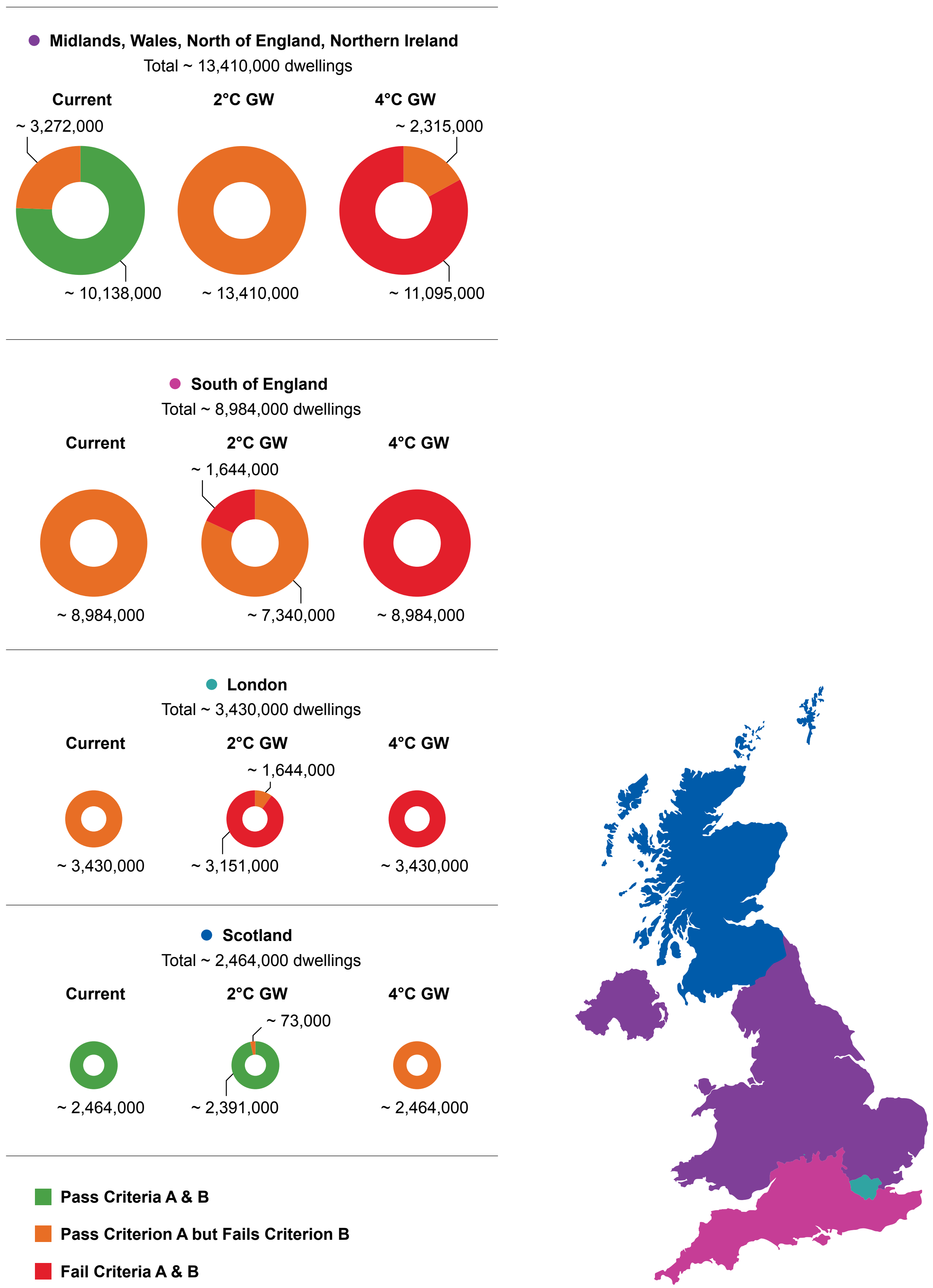

Figure 26: Dwelling overheating figures across the UK (excluding Scotland)

Archetype	Location	Roof Construction	Current Weather			2 Degrees GW			4 Degrees GW			No. Homes Represented
			Criterion A: Kitchen & Living %	Criterion A: Bedrooms %	Criterion B: Bedrooms (no. of hours)	Criterion A: Kitchen & Living %	Criterion A: Bedrooms %	Criterion B: Bedrooms (no. of hours)	Criterion A: Kitchen & Living %	Criterion A: Bedrooms %	Criterion B: Bedrooms (no. of hours)	
Mid-terrace	Birmingham	Uninsulated	1.1	0.9	50.2	2.2	1.9	106.5	6.3	4.6	226.0	1,118,591
Mid-terrace	Swindon	Uninsulated	1.4	1.4	78.3	2.9	2.5	138.8	6.4	5.6	297.0	844,459
Mid-terrace	London	Uninsulated	1.8	1.5	147.2	4.8	3.9	316.7	12.4	9.2	535.5	392,155
Mid-terrace	Birmingham	Insulated	1.1	0.6	27.7	2.2	1.4	63.3	6.2	3.4	155.5	1,929,387
Mid-terrace	Swindon	Insulated	1.4	0.9	50.2	2.8	1.6	99.5	6.3	3.6	219.5	949,026
Mid-terrace	London	Insulated	1.7	0.9	89.8	4.6	2.3	214.3	12.2	6.8	459.2	384,447
Semi-detached	Birmingham	Uninsulated	0.3	0.6	50.2	1.7	1.5	88.5	4.9	3.7	224.3	1,551,620
Semi-detached	Swindon	Uninsulated	0.9	1.1	76.7	2.2	2.2	132.5	5.3	5.1	331.7	912,108
Semi-detached	London	Uninsulated	1.3	1.2	168.3	3.1	3.1	315.2	10.6	8.9	499.0	302,191
Semi-detached	Birmingham	Insulated	0.2	0.5	21.8	1.7	1.3	58.8	4.9	3.0	160.7	2,971,163
Semi-detached	Swindon	Insulated	0.9	0.7	55.7	2.1	1.5	89.2	5.2	3.3	235.3	1,427,098
Semi-detached	London	Insulated	1.3	0.9	73.8	3.0	2.4	223.2	10.5	7.0	435.0	253,078
Detached	Birmingham	Uninsulated	0.0	0.2	26.0	0.5	0.6	56.8	2.2	2.4	157.7	775,870
Detached	Swindon	Uninsulated	0.3	0.6	53.8	0.9	1.2	101.7	3.5	3.3	269.8	882,053
Detached	London	Uninsulated	0.3	0.6	124.2	1.0	1.4	280.0	3.6	5.0	499.5	63,169
Detached	Birmingham	Insulated	0.0	0.1	23.0	0.5	0.5	45.7	2.0	1.8	123.0	1,539,511
Detached	Swindon	Insulated	0.2	0.5	37.7	0.9	0.9	86.3	3.4	2.7	234.8	1,285,712
Detached	London	Insulated	0.3	0.5	81.7	1.0	1.0	215.0	3.2	3.4	464.8	64,144
End-terrace	Birmingham	Uninsulated	0.9	0.3	56.8	2.4	0.6	93.0	5.8	2.7	260.3	601,589
End-terrace	Swindon	Uninsulated	1.3	0.6	81.5	3.1	1.3	142.5	6.4	4.0	325.3	423,218
End-terrace	London	Uninsulated	1.6	0.7	159.8	4.5	1.4	335.2	12.5	5.3	537.3	121,463
End-terrace	Birmingham	Insulated	0.4	0.1	30.2	1.2	0.3	58.3	3.8	1.3	166.7	1,089,839
End-terrace	Swindon	Insulated	0.9	0.3	49.3	1.5	0.6	93.5	4.7	2.3	217.3	674,794
End-terrace	London	Insulated	1.0	0.3	66.2	1.9	0.7	214.0	7.5	2.3	445.5	151,583
Old flat	Birmingham	NA	0.2	0.0	23.2	1.5	0.0	56.3	6.4	1.0	264.5	446,537
Old flat	Swindon	NA	1.0	0.2	47.0	2.4	0.4	154.0	11.2	2.3	492.0	365,011
Old flat	London	NA	1.1	0.1	182.7	6.3	0.5	420.5	18.8	6.7	895.8	289,689
Modern flat	Birmingham	NA	0.6	0.3	25.0	1.9	1.1	53.3	5.0	3.0	151.8	1,386,506
Modern flat	Swindon	NA	1.1	0.5	39.7	3.0	1.7	91.0	7.1	4.3	230.0	1,220,874
Modern flat	London	NA	1.2	1.1	109.8	4.1	2.7	287.2	13.9	9.4	569.0	1,407,746

TM59 pass condition: Criterion A 0-3%, Criterion B 0-32 hours

TM59 moderate fail: Criterion A 3-6%, Criterion B 32-64 hours

TM59 severe fail: Criterion A 6-15%, Criterion B 64-160 hours

TM59 extreme fail: Criterion A over 15%, Criterion B over 160 hours

Table 11: Selected representative buildings and their overheating scores in each climate scenario

3.6 Sensitivity analyses

The current analysis was based on a specific set of assumptions that were selected to represent the majority of existing homes based on the information available; these are described in section 3.2.

However, for certain parameters – as described below – there was no certain information on what the typical homes would present and some of these assumptions can have a significant impact on overheating risk. For these cases, assumptions were made based on technical experience from Arup and Loughborough University, and sensitivity analyses were conducted to further explore the impacts of varying some of these onto the overheating risk.

3.6.1 Impact of wall insulation on overheating risk

The results from Task 1 showed no or little correlation between the external wall U values and overheating risk; however, more investigation was needed to understand the reasons behind this and what other factors would influence the results in combination with wall insulation.

Wall insulation is known to be an effective measure to reduce heating demand in winter. However, the impact of insulation in summer is controversial. In the literature, it is often stated that insulation could worsen the overheating if the heat gains are poorly managed. To properly understand the impact of wall insulation in summer, several sensitivity analyses were conducted, including:

- The impact of wall insulation coupled to roof insulation;
- The impact of wall insulation in different archetypes;
- The impact of wall insulation in different weather conditions;
- The impact of wall insulation in different locations;
- The impact of external vs internal solid insulation;
- The impact of wall insulation coupled with the opening of windows for natural ventilation.

For the sake of simplification, the results for the detached house and double sided flat are reported which represent the two extreme configurations in terms of geometry and wall to floor area ratio.

One of the main conclusions of the sensitivity analyses is that the wall insulation has a positive impact on reducing the overheating risk for homes that have significant exterior walls area such as the detached, end-terrace and semi-detached. The analysis shows that the overheating risk was reduced for both living areas (Criterion A) and for bedrooms (Criterion B). The analysis also showed that the presence of wall insulation did not have a significant influence on the overheating risk for flats or for mid-terrace house which have limited wall area compared to the floor area as shown in Figure 27.

Another major conclusion is that the impact of insulation is subject to weather conditions and location of the building; for instance, the wall insulation is more effective in the Manchester region than in the London region, and this could be explained by the higher solar gains in London that counter-effects the impact of wall insulation. Similarly, the effectiveness of wall insulation decreases when the buildings are simulated in future weather conditions of 2°C and 4°C GW (see Appendix A).

Other factors play a key role in the effectiveness of wall insulation, such as the ventilation of the building. For houses with big openable windows and good cross-ventilation, wall insulation is beneficial, but the positive impact is considerably less significant if poorer ventilation is simulated. For the flats, wall insulation has minimal influence in the original conditions but becomes counter effective in the case of poor ventilation worsening the overheating risk as shown in Figure 28.

Due to the smaller floor area of the old flat, the density of the internal heat gains is higher. Therefore, the ability to release those heat gains via air exchange with outdoors is the main mechanism to reduce temperature. The detached house shows an increase in overheating with poor ventilation but to a much lesser extent than the old flat as the detached house loses more heat via conduction through the external fabric.

More details on these analyses are included in Appendix A.

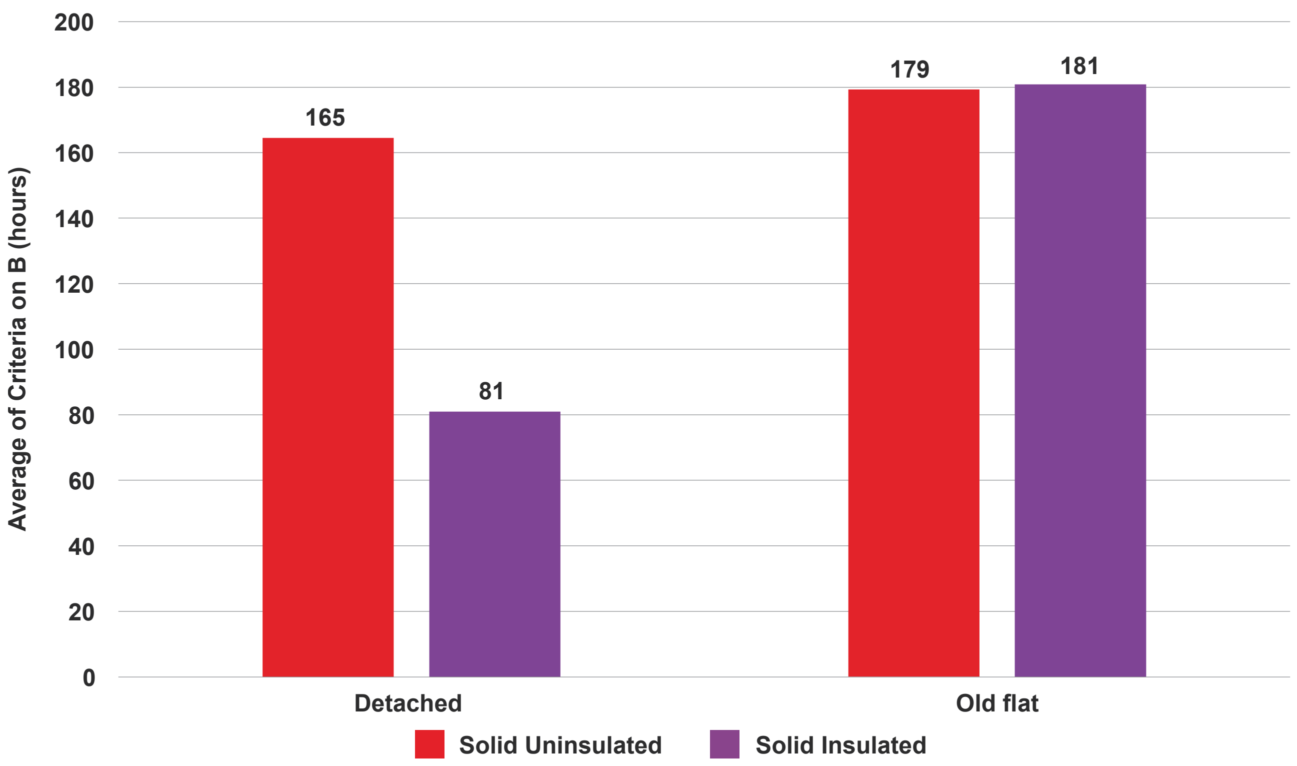

Figure 27: Impact of solid insulation in different archetypes – Criterion B for London

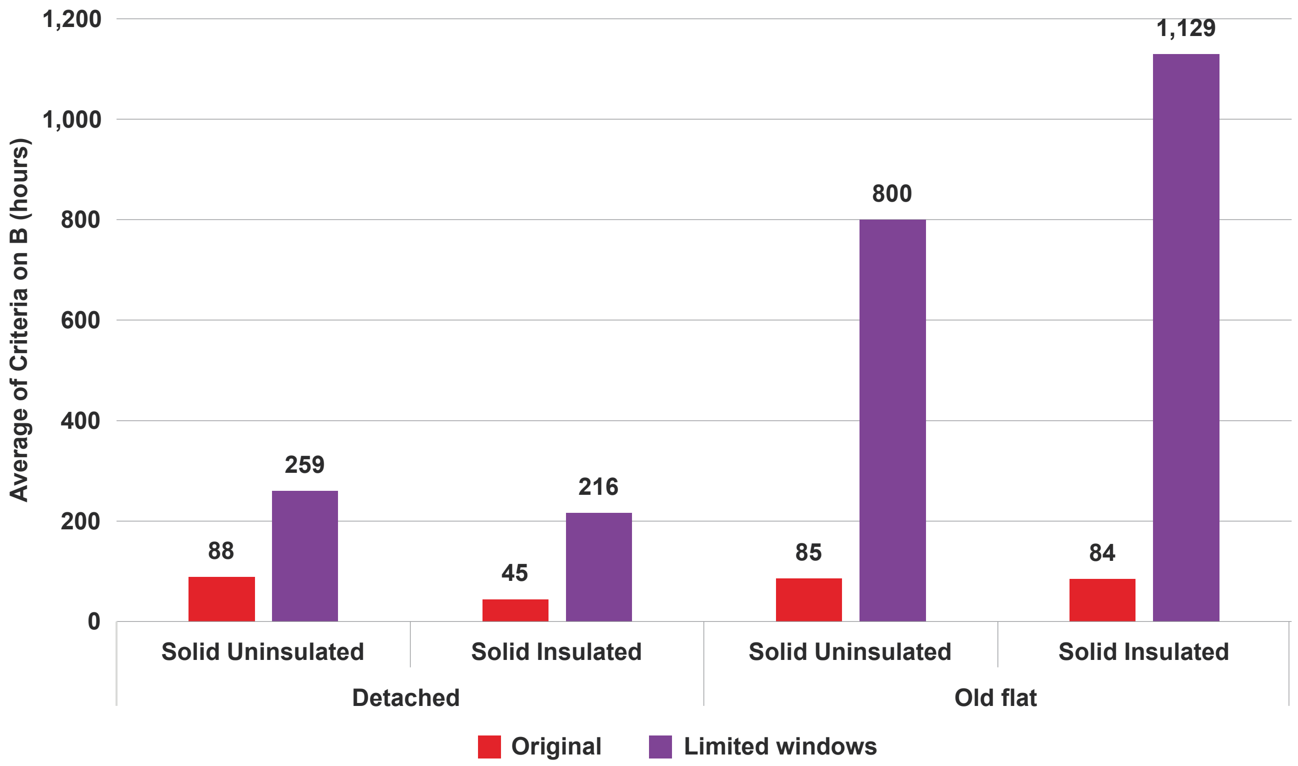

Figure 28: Impact of wall insulation averaged for all locations in the case of poor ventilation

3.6.2 Additional factors that can impact overheating

The key objective of this study was to estimate the overheating risk of existing UK homes and the effect of possible mitigation measures at scale. For this reason, a number of assumptions and simplifications were made including the definition of standard conditions on which to base the modelling exercise.

However, it is recognised that several additional factors can influence, and substantially, the risk of overheating in homes which could not be considered in the current quantitative assessment due to multiple reasons, such as lack of data at a stock level, impossibility to estimate unique modelling settings or predict very subjective behaviours. These include the following:

- The size and openable area of the windows in the selected archetypes was based on the information from the selected case studies, however in reality each home will have different window types and sizes which would lead to different air flow achievable through natural ventilation.
- Another assumption was that occupants could operate openings freely; however, this is not always case in instances with significant noise, pollution or security constraints. A restricted openability of the windows would produce much higher risk of overheating in all conditions, as demonstrated in Figure 28.
- The behaviour of the occupants has a significant influence on the risk of overheating. Some occupants may take positive actions to minimise the risk of overheating such as closing blinds in advance of warm weather, closing windows when the outside temperature is higher than the indoor temperature, purging the warm air during the night and encouraging cross-flow ventilation where possible. However, these actions are unlikely to be representative of the whole public and therefore not included in the modelling of this study.
- Similarly, some other occupants may have a less positive behaviour than what has been modelled in this study. Particularly, vulnerable users may be less inclined or unable to take action when needed. These occupants would experience higher discomfort. However, this is partially captured in the vulnerable user criterion in TM59.
- Occupant density and internal gains were assumed as per TM59 which represent a worst case scenario. In reality, the heat gain density and times of operation would vary dwelling by dwelling. Homes with higher occupancy density or internal gains would experience higher overheating than what was modelled and homes with lower occupancy and other internal gains would experience a lower risk.
- Thermal mass can influence the risk of overheating; buildings with larger exposed thermal mass can absorb heat during the day and release it at night if appropriate night-time purge ventilation is possible. Thermal mass was not considered in this study since there is no information on thermal mass properties at stock level; thermal mass would also be very challenging to retrofit and would have to be managed correctly by occupants (e.g. night purging).
- No contextual shading from other buildings or vegetation was modelled in this study. This feature is a highly localised variable that could not be estimated at a stock level. The modelled buildings with no shading represents a worst case scenario, thus it is expected that many buildings would experience lower levels of overheating in real conditions.
- Flats were modelled as mid-floor to represent the vast majority of flats at stock level. However, overheating risk for top-floor flats would be higher, especially when no or limited roof insulation is included.

- Single weather files were selected to represent the conditions of a wide geographic area. Within these regions, there are likely to be variances due to local microclimates. For example, dwellings close to the coast are likely to experience reduced overheating whereas dwellings in larger inner cities are likely to experience increased overheating as a result of the urban heat island effect. This was captured to an extent by including London as its own weather scenario.
- CIBSE TM59 recommends considering additional heat gains for communal pipework for distribution of domestic hot water. The flat case studies were assumed to have independent heating generation systems, as representative of the majority of the cases in the UK existing stock, and therefore these gains were not considered. Overheating risk is expected to be higher in those flats with a communal heating system due to the heat losses from badly insulated DHW pipework and heat interface units.
- Other building characteristics such as adjacency with particularly warm spaces (e.g. above a restaurant kitchen or plantroom) were not considered and are expected to impact the overheating risk of specific dwellings.

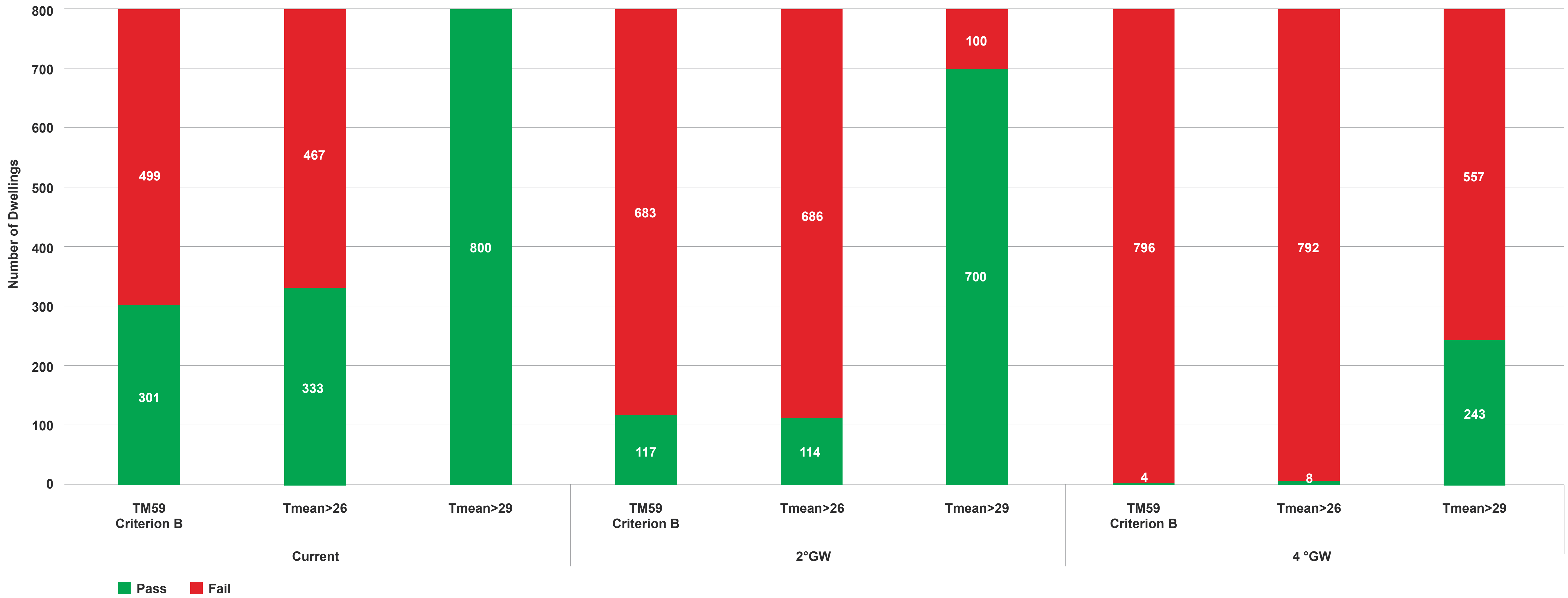

Figure 29: Comparison of bedroom results under alternative criteria

3.6.3 Bedroom comfort under alternative approaches

The effect of alternative criteria to assess night-time comfort were investigated, based on the initial findings from on-going research that is being conducted by Loughborough University (Lomas, et al., 2022) summarised in section 3.1.3.2. The initial research findings showed that:

– Night-time comfort has a stricter correlation to mean night-time temperature than peak temperature;

– Different mean night-time temperatures have different effects on sleep quality and productivity, with mean temperatures above 29°C showing effects on health other than wellbeing.

For the purpose of this sensitivity analysis and based on this research, two possible alternative criteria for night-time comfort were investigated

– Number of nights with mean temperature above 26°C;

– Number of nights with mean temperature above 29°C;

In absence of a definite criterion on what the maximum number above threshold should be, the limit was identified as the number of nights corresponding to 32 hours, as per TM59 Criterion B limit, which equates to three nights per year.

Figure 29 below shows overall number of dwellings that pass or fail TM59 Criterion B and the two alternative criteria tested. It can be seen that results are very similar when using TM59 Criterion B and the mean temperature limit of 26°C, while a much higher number of dwellings would pass the assessment if a mean temperature limit of 29°C was considered, roughly 66% more compared to Criterion B.

Breaking this down into each climate scenario; every dwelling modelled would pass if the mean temperature limit was 29°C and only 100 modelled scenarios failed under a 2°C global warming scenario.

Considering that Criterion B was the criterion driving the pass/fail results for most cases tested and that the vast majority of cases would pass the adaptive comfort for both living areas and bedrooms, these results show that if a less stringent criterion was deemed more appropriate and was used to assess the night-time overheating risk, the extent of mitigation measures needed could be drastically reduced.

Section 4

Task 2: Assessing the options to reduce overheating risks in existing properties

4.1	Qualitative assessment of mitigation measures	65
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The analysis of overheating risk within current existing homes based on CIBSE TM59 criteria shows significant evidence that some mitigation measures for parts of the UK housing stock would be required, especially in future weather scenarios (see results from Section 3). The analysis highlighted that the overheating risk varies by the type of dwelling meaning that some require greater interventions than others. The focus of Task 2, reported in this section, was to define possible mitigation measures to reduce the risk and perform qualitative and quantitative assessments of each one. A long list of mitigations was compiled, assessed qualitatively and quantitatively (as described in the following paragraphs) and modelled to create multiple mitigation packages which could be deployed depending on the archetype and severity of overheating risk.

4.1 Qualitative assessment of mitigation measures

4.1.1 Long list of mitigation options

A list was created with all mitigation measures which could potentially reduce the overheating risk in dwellings. These were split into four groups of measures that provided mitigation in one of the following ways:

- reducing solar heats gains;
- reducing heat gains through conduction via the building envelope;
- increasing natural ventilation of homes
- adopting mechanical systems.

A qualitative assessment of the mitigation measures was conducted based on the following criteria:

- Cost of implementation;
- Ease of implementation on existing homes;
- Cultural limitations (how likely a measure would be acceptable to most people);
- Fire safety (ensuring measures are not creating safety risks in homes).

Table 13 summarises the qualitative assessment conducted on the mitigation measures.

4.1.2 Fire safety considerations

Each mitigation measure within the long list was assessed to highlight any potential issues which may need to be addressed to ensure they would not increase the building's fire risk. The findings are summarised in Table 12.

Mitigation Measure	Fire considerations
Internal blinds and curtains	Need to comply with BS 5867-2:2008, Fabrics for curtains, drapes and window blinds – Part 2: Flammability requirements – Specification. No direct impact on fire strategy.
External shading and external shutters	External solar shadings need to comply with combustibility requirements of Regulation 7 where the building exceeds 18m in height (11m in draft BS 9991). Requirement is for materials to achieve Euro Class A1-s1,d0 when tested to BS EN 13501-1.
Internal shutters	No fire impact unless integrated into the external wall system.
Increase window openable area	Need to be aware of any façade fire rating requirements for external fire spread purposes (defined by fire engineer) as if fire rated glazing is used to achieve this the window cannot be openable in the fire rated zone.
Solar reflective wall paint	Reaction to fire performance requirements for the external surface of walls need to be met as outlined in Approved Document B.
Building over 18m in height - Euro Class A2-s1,d0	May be a feature within a room
Building under 18m in height - No requirement	Effective all year round
Building under 18m in height where external wall is within 1m of the site boundary/relevant boundary - Euro Class B-s3,d2.	Improved ventilation and indoor air quality
Solar reflective roofs	Needs to meet roof finish fire requirements based on proximity to the relevant boundaries.

Table 12: Summary of fire safety considerations for mitigation measures

Viable mitigation measures (short list)

Following a qualitative assessment of all mitigation measures the following were chosen to not be modelled as part of this assessment:

- External natural shading
  - Difficult to predict the geometry of natural shading elements
  - Not all dwellings have enough space to add trees or vegetation around perimeter
- Mechanical Ventilation with Heat Recovery (MVHR)
  - Part of a whole dwelling retrofit strategy and not a mitigation which would be applied in isolation
  - Only effective when outdoor air temperature is lower than indoor air temperature

The final list of mitigation considered in the analysis were the following:

- Internal Blinds;
- Curtains;
- External shading on south, east and west orientated windows;
- External shutters;
- Internal shutters;
- Replacement of windows with low g-value glazing;
- Low g-value window film;
- Replacement of windows with an increased openable area;
- Solar reflective coating to walls;
- Solar reflective coating to roofs;
- Roof insulation;
- Ceiling fans;
- Active cooling (Air Conditioning).

Whilst many homes already have some of the mitigation in place such as blinds and curtains, there is no information available on the number of homes that have these already. Thus, these features were not considered in the baseline models and were modelled as mitigation measures in order to show their effectiveness in reducing overheating risk.

For the representative buildings that already had roof insulation, this was not considered as a mitigation measure.

Mitigation measure	Benefits of measure	Possible trade-offs and disadvantages	Cultural Limitations
Internal blinds or curtains	Easy to install, easy to operate	Can obstruct airflow from windows and limit daylight	None, common in many UK homes currently
External shading	Limited interference with natural ventilation. Most effective at reducing solar gains before they enter a building	Impacts appearance and are harder to retrofit. Not viable for listed buildings or in conservation areas. Can have high embodied carbon impact depending on material	Although common in Mediterranean countries, the appearance may not appeal to those in the UK
External natural shading (vegetation, trees etc)	Improves air quality, improved biodiversity and offsets carbon emissions	Can limit natural daylight, impact hard to predict in time	None acknowledged
External and internal shutters	Reduce solar gains in summer	Can obstruct airflow through windows and limit daylight which reduces winter heat gains. External shutters are not compatible with outward opening windows.	Although common across Europe and Mediterranean countries, the appearance may not appeal to those in the UK.
Solar reflective walls and roofs (application of solar reflective white or silver paint to walls and roofs)	Easy to install	Impacts appearance, not applicable to all wall and roof types and might need planning permission for heritage buildings. May require reapplication after a few years as degradation of paint would impact effectiveness.	None acknowledged
Low g-value glazing	Reduce solar gains in summer. Improve energy efficiency	Limits daylight and reduces winter heat gains, high Capex and high embodied carbon	None acknowledged
Low g-value film (Plastic film which can be applied to windows to reduce the solar transmittance)	Reduce solar gains in summer. Improve energy efficiency	May impact visual appearance if film is not applied evenly. May require reapplication after a few years as degradation of film would impact effectiveness.	None acknowledged
Increase window openable area	Improved indoor air quality if in a non-polluted area	Additional noise from outdoors, high Capex and high embodied carbon	None acknowledged
Ceiling fans	May be a feature within a room	Additional noise and energy consumption	Although common in Asian countries, the appearance may not appeal to those in the UK
Air conditioning	Effective all year round	High capex and high energy consumption	None acknowledged
MVHR (Mechanically ventilated heat recovery unit replacing indoor air with fresh outdoor air)	Improved ventilation and indoor air quality	High capex and high energy consumption	None acknowledged

Table 13: Qualitative assessment of mitigation measures

4.2 High-level cost assessment of mitigation measures

4.2.1 Methodology

The initial costing task involved measuring each archetype 1 to 6, as described in Section 3.1.1, and obtaining elemental unit cost rates for each mitigation measure. Due to the differences in the construction and design, each archetype required a specific cost build-up for each mitigation measure. All the mitigation costs selected in the shortlist above were built up using typical unit rates extracted from Spon's Price Books, past project data and market benchmarks, and applied to the construction information obtained from each individual archetype.

Baseline costs for each mitigation were initially built-up based on Outer London rates. An industry recognised source, BCIS (BCIS, 2022), was then employed to obtain a blended location factor for the modelled locations (see Table 14). These location factors were then applied as a multiple to the base estimate for each mitigation and archetype, as shown in the tables in Appendix C.

Typically, where the design is less developed the approach to costing would align accordingly, with functional unit and metre squared (of Gross Internal Floor Area (GIFA)) rates used. However, to reflect the archetype differences and to capture the nuances of the modelled scenarios, it was determined that a more detailed costing exercise was necessary. Indicative design solutions and likely installation requirements were developed by the cost and engineering teams to allow each intervention and archetype to be individually measured and costed using elemental unit rates, improving the accuracy and more clearly defining the commercial differences between them.

Weather file location	Area represented	Factor Used
London	London	1.21
Birmingham	Midlands and Wales	0.98
Manchester	North of England and Ireland *	0.94
Glasgow	Scotland	0.91
Swindon	South England	1.08

Table 14: Location factor table

* Note: The Northern Ireland location factor is excluded from the 'North of England and Ireland' region as it was not representative of all areas in the region.

In the original longlist of interventions, the MVHR unit costs were built up using data from Arup's partner, Parity Projects, who have captured market rates for the supply and installation of these units. Parity Projects' costs include the supply and installation of the MVHR unit as well as a 'per site' preliminary cost, plus an additional 'per number of liveable' room cost, which was measured accurately based on each archetype's specific requirement and provides a complete cost for implementing this mitigation measure. The MVHR mitigation was not shortlisted, or used in the packages, but this costing methodology is included here for completeness.

During the elemental cost estimate formation, several key assumptions and exclusions were made for the costing work in general and for the mitigations themselves. The general assumptions and exclusions are included in Appendix B. Each mitigation also required specific assumptions to select the most suitable elemental unit rate. These mitigation assumptions are shown in Appendix B.

Following cost estimation, a summary cost table for each location was produced (see Appendix C). This shows the cost in total for the mitigation and per square metre of the GIFA of the archetype.

The table for each location includes the costs for each mitigation for that archetype, with descriptions and assumptions of the mitigation listed in Appendix B. For the flats, three key assumptions were made prior to costing:

1. The roof and all mitigations involving the roof would not feature as a cost on a flat-by-flat mitigation basis.
2. The flat is assumed to be on the third floor of the building. Therefore, where scaffolding or access equipment is required, the access equipment rates are based on an elevation / façade area measured by calculating the width of all building elevations and a height to the third floor, only.
3. No natural shading (tree shading) is possible for the flats, as this mitigation would only help ground level flats due to the maximum reach and height of the trees, and the flat modelled is on the third floor, above the height where shade is offered from planted trees.

The costs for the mitigation options are summarised by archetype in the chart below (Figure 30). Similar summaries are available for the other Task 2 region locations, in table form, see Appendix C.

4.2.2 Factors affecting cost

Certain patterns and potential cost saving opportunities emerged from reviewing the cost outputs:

– Some shared costs could be exploited by implementing multiple mitigation solutions on the same construction element at the same time such as a lower g value and increased openable area when replacing windows; this could ease the cost impact of the works packages as some of the builder's work and cost would be accounted for once and therefore have a lower impact on the cost of the single mitigation measure;

– Some mitigation combinations may be able to share access costs as well, for example shared scaffolding with concurrent external works to one archetype would reduce the impact of scaffolding on the single mitigation cost;

– The procurement of two or three packages through one installer could reduce the cost of the packaged works; for example, should the external wall insulation installer have the capacity and capability to install solar reflective roof paint, the costs for the works combined may be lower than if the works were procured through two separate contractors; this is over and above the shared access (scaffolding) costs, and would reflect shared programme, project management and preliminary costs. The counter argument could be made however, where an uncompetitive cost was agreed with a contractor who then went on to undertake multiple packages of work; the cost impact of these scenarios are outside of this costing exercise. Simply put, the procurement route chosen and the ability to combine packages has the potential for cost saving for the homeowner;

– Some packages are mutually exclusive, for example new blinds, curtains and internal shutters are unlikely to be procured by the same household; it is here that the cost impact and the thermal benefits of the impact must be weighed-up and the most suitable measure for the archetype and location selected;

– Some packages are easier to install, and this is reflected in the price, so this may come into the selection criteria; however arguably, some packages may cost less in reality to that estimated due to the homeowners' ability to 'DIY' install.

– The cost of some overheating measures can be shared with those that also improve energy efficiency; these include the costs to replace windows with improved performance, the costs to install curtains (thermal insulation), and the costs to insulate the external walls and roof which reduce heating costs in winter too;

– The costs for works have been considered to be carried out and procured on one single dwelling in isolation. However, it is right to assume there might be savings when procuring packages of work for multiple dwellings, e.g. a block of flats or rows of houses or grouping works to similar areas of the building. If costs for certain items were to be shared, such as scaffolding, certain assumptions and time restrictions would then apply.

4.2.3 Considerations for cost of mitigation packages

The costs for works in this task were considered for each mitigation to be installed in isolation. When considering the cost of a combined mitigation package (as follows in Task 3), some of the costs (e.g. scaffolding) will be considered shared among multiple measures and therefore the total cost of a package will be lower than the sum of the single mitigation costs.

Each package combination for Task 3 will require examination of the potentially shared costs, or some parts of each cost, such as Builders Work in Connection or Making Good , which could potentially be shared by parallel works.

Additionally, works 'packages' that then employ access costs could enable combined access equipment costs. However, caution should be employed when reviewing packaged costs as by modelling this cost efficiency it was assumed that the scaffolding or access equipment will be used by all contractors and works will be procured consecutively, meaning programme accuracy will impact cost, if not maintained, or reflected in the actual works.

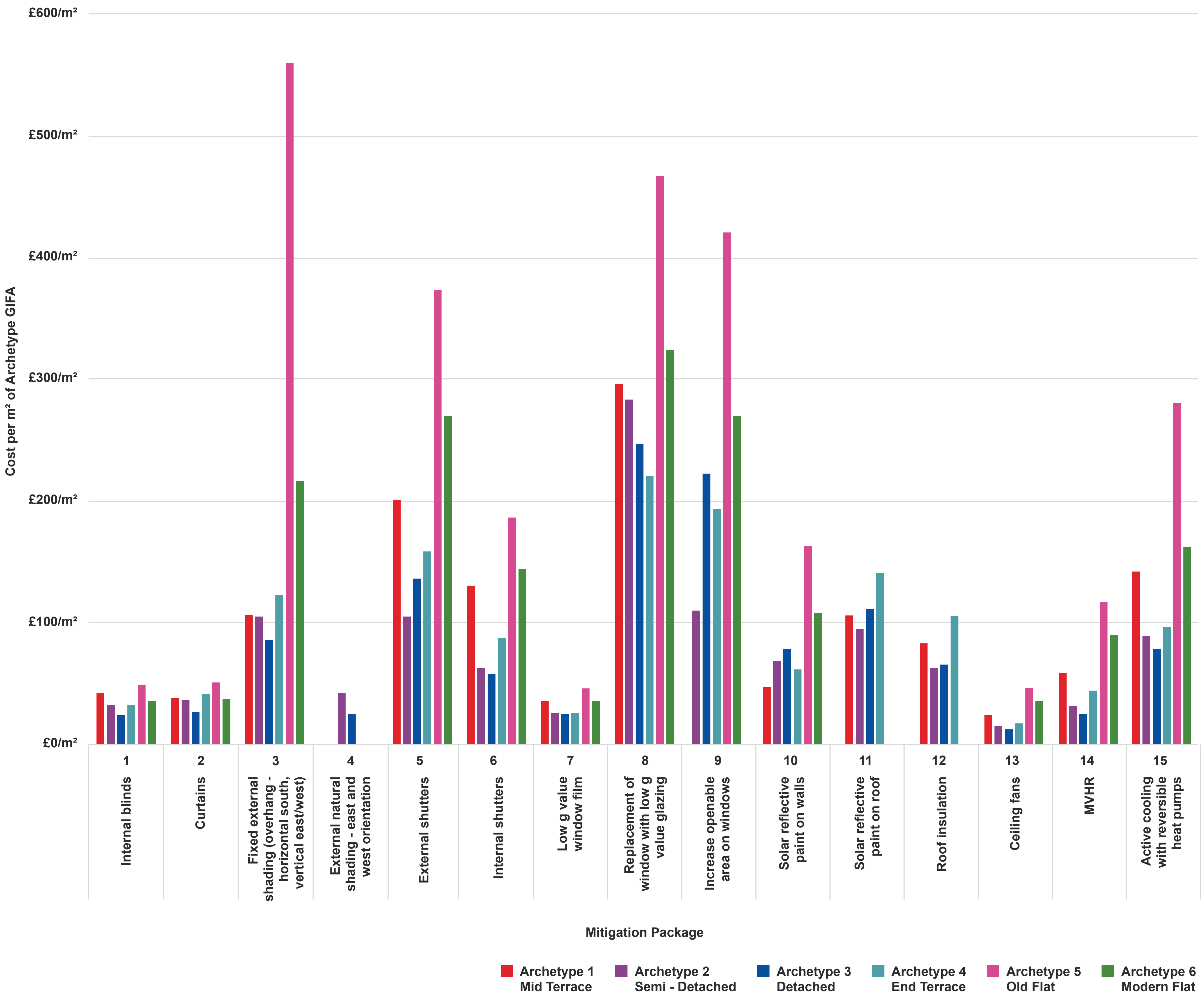

Figure 30: Baseline cost of single mitigation measures per archetype (£ per sqm GIFA, London baseline)

4.3 Thermal assessment of mitigation measures

4.3.1 Modelling assumptions for mitigation measures

A full list of assumptions on mitigation measures is included in Appendix A.

It is worth noting that some of the mitigation measures provide a fixed or unvarying impact on solar heat gain or ventilation quantity. For example, fixed external shading does not need to be opened or closed and isn't switched on or off; its impact only varies by the time of the day and the angle of the sun.

The effect of other measures will vary depending on how people use them in their homes. For example, the effectiveness of blinds will vary depending on when people open and close them. Because of this, it was necessary to define how to model the operation of some mitigation measures to best represent how the average person might interact and use them in reality. In order to define this specific investigation was undertaken to test the sensitivity of the results to the assumptions around different interventions' performance and operation. Details on this sensitivity analysis are reported in Appendix A.

The materials below have been selected to represent commonly available domestic products with accessible prices which comply with fire safety consideration stated previously in Section 4.1.2.

Internal blinds

Based on the sensitivity analysis reported in Appendix A, the following settings were considered for internal blinds:

- Shade roller, medium opaque type with a solar reflectance of 0.35;
- Blinds are closed when solar radiation is above 200 W/m².

External shutters and internal shutters

- The external shutters are modelled as aluminium louvres with a solar reflectance of 0.4, with a solar radiation control.
- The internal shutters are modelled as wooden louvres with a solar reflectance of 0.22, with a solar radiation control.
- Internal and external shutters are closed when solar radiation is above 200 W/m².

Curtains

- Drape curtain with close weave medium with solar reflectance of 0.3;
- Curtains are closed when solar radiation is above 200 W/m².

The curtain type was selected from the DesignBuilder Library.

Fixed external shading

- The fixed external shading is modelled as overhang with a 1m projection.
- On south facing windows, the overhang is horizontally mounted above the window. On east and west facing windows, the fins are arranged vertically.

Low g-value window film

- The addition of a plastic solar reflective window film lowered the g-value to 0.54 from the original 0.69. The properties of the window film were based on the 3M Sun Control range.
- Modelling assumes condition when first applied and not consider any degradation of film and colour change over time.

Low g-value windows

- The replacement windows were modelled with a new lower g-value of 0.36. The properties of the glazing were based on the Pilkington Suncool range.

Increased openable area windows

- The baseline window opening area was determined from the as-built drawings of the selected building archetypes. Any window which had an original openable area of less than 50% was assumed to be replaced with a new window with an openable area of 90%.

Solar reflective coatings on walls and roofs

- An additional material layer with a solar absorptance of 0.2 and a reflectivity of 0.8 was added to the outside surface of the wall and window construction.
- Modelling assumes condition when first applied and does not consider any degradation of paint colour.

Ceiling fans

Increasing the air velocity in a space is known to provide a cooling effect in warm conditions. This is supported by CIBSE, ASHRAE and BS EN 15251 (British Standards, 2007). In this study, the ceiling fan was modelled to turn on at operative temperatures above 26°C and turn off when the operative temperature then fell below 24°C. When operating, the ceiling fan was assumed to reduce the perceived temperature by 1.2°C based on an assumed 0.6m/s air velocity as given in BSEN15251. Each ceiling fan was modelled to emit 50W of heat gain when turned on..

These values are based on typical dimensions of a domestic ceiling-mounted fan. Similar effects on reducing overheating are expected if using smaller, free-standing fans. However, the effectiveness of these would vary depending on the size, power capacity, location and distance from the occupant. These have not been included in this study.

Active cooling

- Active cooling was modelled within each occupied space with a cooling set point of 26°C to eliminate any overheating risk.

Active cooling was considered as a last option in case all other passive and low-energy measures did not suffice to mitigate overheating.

4.3.2 Effectiveness in mitigating overheating risk

Each mitigation measure was applied in isolation to two of the building archetypes to gauge their effectiveness. They were applied to the detached house and old flat to test these on the two most different archetypes considered.

The pattern of which mitigation is most effective is consistent across each climate scenario. However, the percentage reduction in both criteria broadly decreases as warmer weather scenarios are applied.

The shading mitigation measures tend to be effective to reduce Criterion A overheating in living spaces. Of these measures, external shutters are the most effective, followed by blinds and internal shutters. The effectiveness of these measures for Criterion B compliance is much lower since overheating at night is minorly impacted by solar gains.

Low g-value glazing is also effective at reducing the Criterion A overheating and reasonably effective at reducing Criterion B. The low g-value window film is much less effective for both criteria than a full window replacement (since the g-value achieved is higher than when installing a brand new unit) but is much cheaper and less disruptive to install.

In general, mitigations that reduce solar gain through windows were found to be more effective when applied to the old flat compared to the detached house. This was likely a result of the greater window to wall ratio in the old flat and the reduced external wall to floor area ratio meaning that solar gains have a proportionally greater impact on likelihood of overheating in the old flat.

Changing the windows to allow a greater openable area was the only measure that consistently reduced Criterion B more than it reduced Criterion A. The ability to achieve a larger exchange of air was effective at reducing night-time bedroom temperatures. This was particularly effective when applied to the old flat archetype due to the relatively limited openable areas in the original model.

Solar reflective paint applied to the walls of the detached house gave a moderate reduction in overheating but was the least effective measure when applied to old flat. This is due to the substantially smaller external wall-to-floor area ratio in the old flat compared to the detached house. The solar reflective roof on the detached house was much less effective than the solar reflective walls.

The ceiling fan is one of the most effective measures in both archetypes and in both criteria. Although not a truly passive measure due to the increased electrical consumption, this can be considered a low-energy measure compared to installing active cooling and the increased airflow provided a relatively simple and inexpensive method of reducing occupants' perception of overheating.

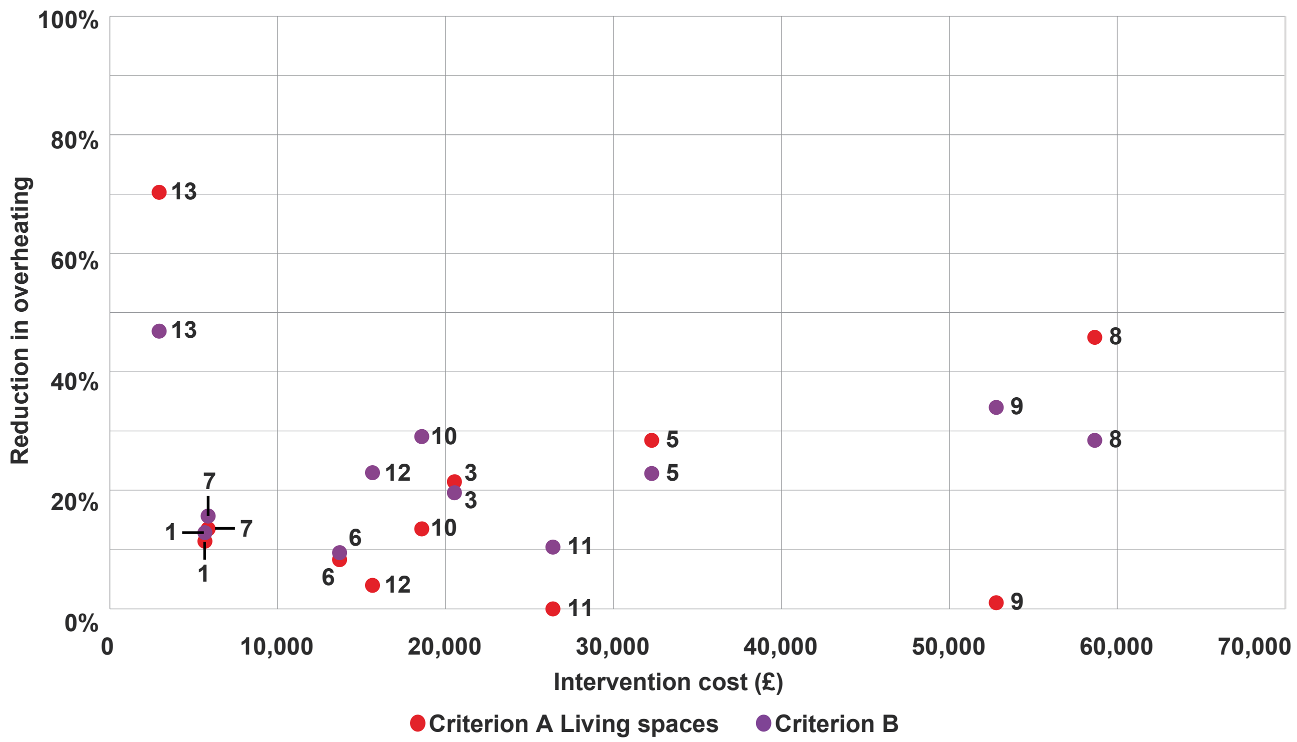

Figure 31: The effect and cost of each mitigation package applied to the detached house archetype – London weather with 2°C global warming

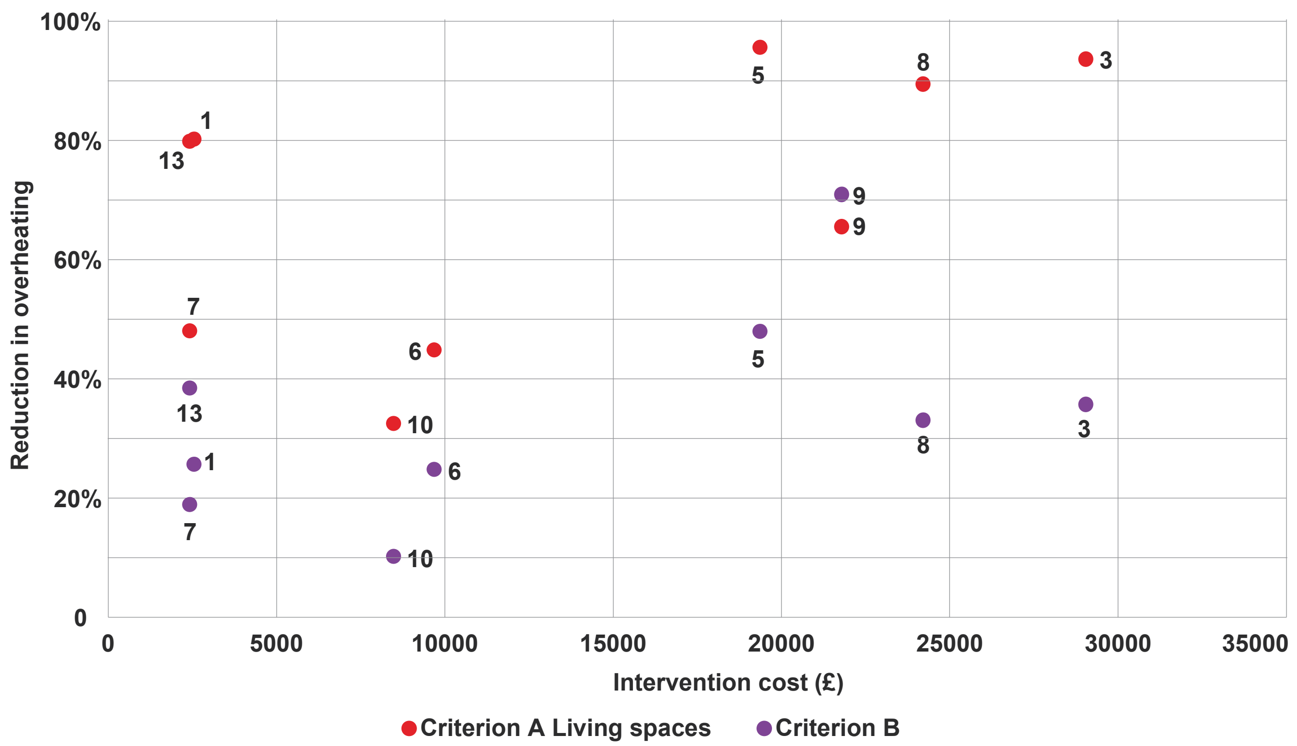

Figure 32: The effect and cost of each mitigation package applied to the old flat archetype – London weather with 2°C global warming

1. Internal blinds
2. Curtains
3. Fixed external shading (overhang - horizontal south, vertical east/west)
4. External natural shading - east and west orientation
5. External shutters
6. Internal shutters
7. Low g value window film
8. Replacement of window with low g value glazing
9. Increase openable area on windows
10. Solar reflective paint on walls
11. Solar reflective paint on roof
12. Roof insulation
13. Ceiling fans
14. MVHR
15. Active cooling with reversible heat pumps

4.4 Comparison and selection of mitigation packages

The selected mitigation measures were combined in a series of packages that can be implemented simultaneously and are likely to reduce overheating risk in different scenarios. The definition of these packages was based on a variety of quantitative and qualitative measures including:

– Effectiveness in reducing overheating;

– Cost of installation;

– Compatibility with other mitigation measures;

– Disruption to the occupants.

The packages have been compiled in such a way that the initial packages are lower cost, lower disruption but inevitably less effective. Priority has been given to passive strategies (or low energy, for ceiling fans) in order to minimise the impact on operational energy consumption and, therefore, carbon emissions. Package 4 is the final passive mitigation package and aims to combine the most effective mitigations regardless of cost and disruption. Package 5 resorts to active cooling in the event that the overheating cannot be mitigated through passive or low-energy measures.

Table 15 provides the full details of each mitigation package. The packages have been split into those applied to houses and those applied to flats. The minor differences between the packages applied to houses and flats reflect the varying applicability and effectiveness of the mitigation measures. For example, reflective walls do not feature in any of the flat packages.

Archetype	Package 1	Package 2	Package 3	Package 4	Package 5
Houses	Blinds, roof insulation (where not present in baseline), low g-value window film.	External shutters instead of blinds, roof insulation (where not present in baseline), low g-value window film, ceiling fan.	Package 2 + solar reflective walls	Package 3 + window replacement (low g-value and openable)	Package 1 + active cooling
Flats	Blinds, low g-value window film.	Package 1 + ceiling fan	External shutters instead of blinds, low g-value window film, ceiling fan.	Package 3 + window replacement (low g-value and openable)	Package 1 + active cooling

Table 15: Mitigation packages to be applied in Task 3

Mitigation packages for houses

Figure 33: Package 1 for houses

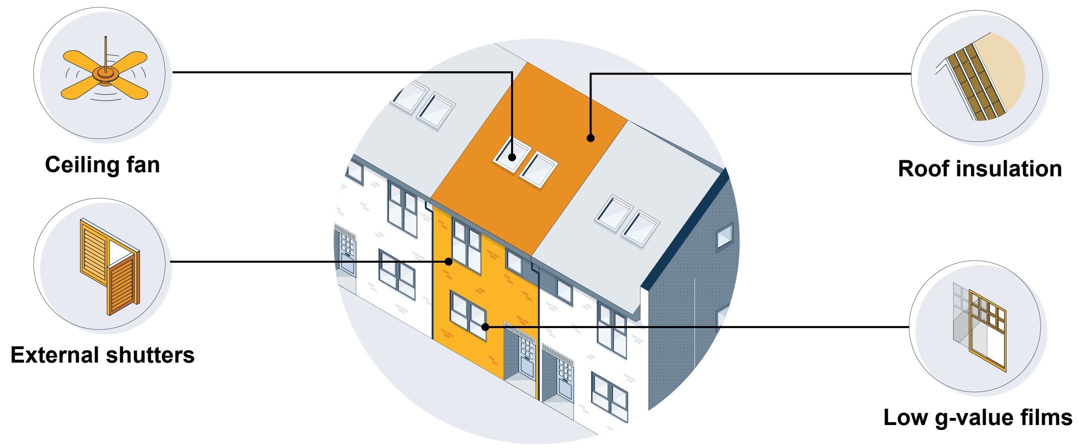

Figure 34: Package 2 for houses

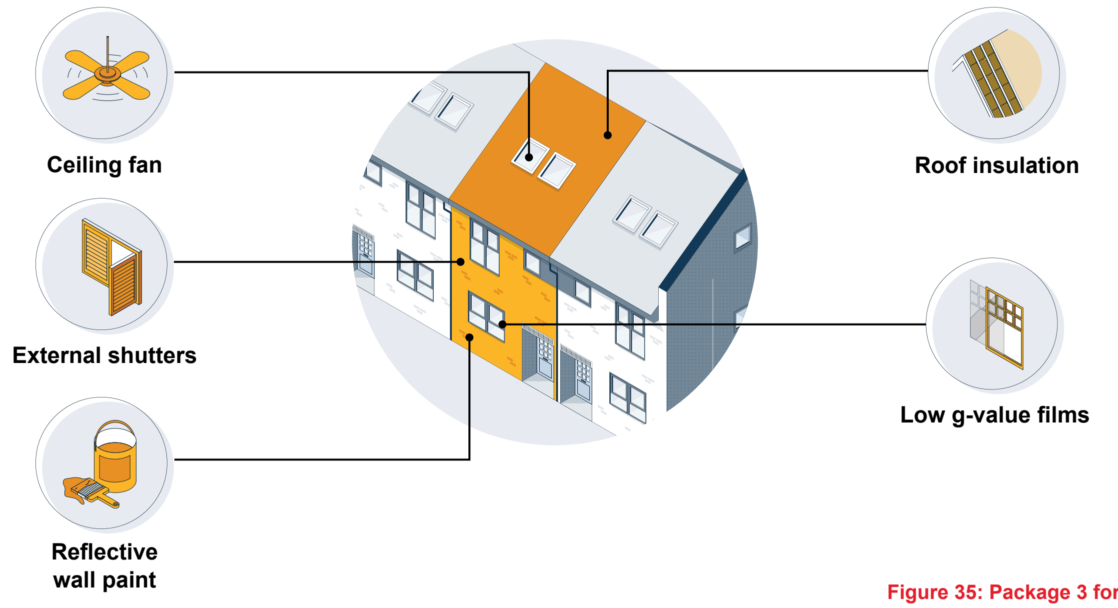

Figure 35: Package 3 for houses

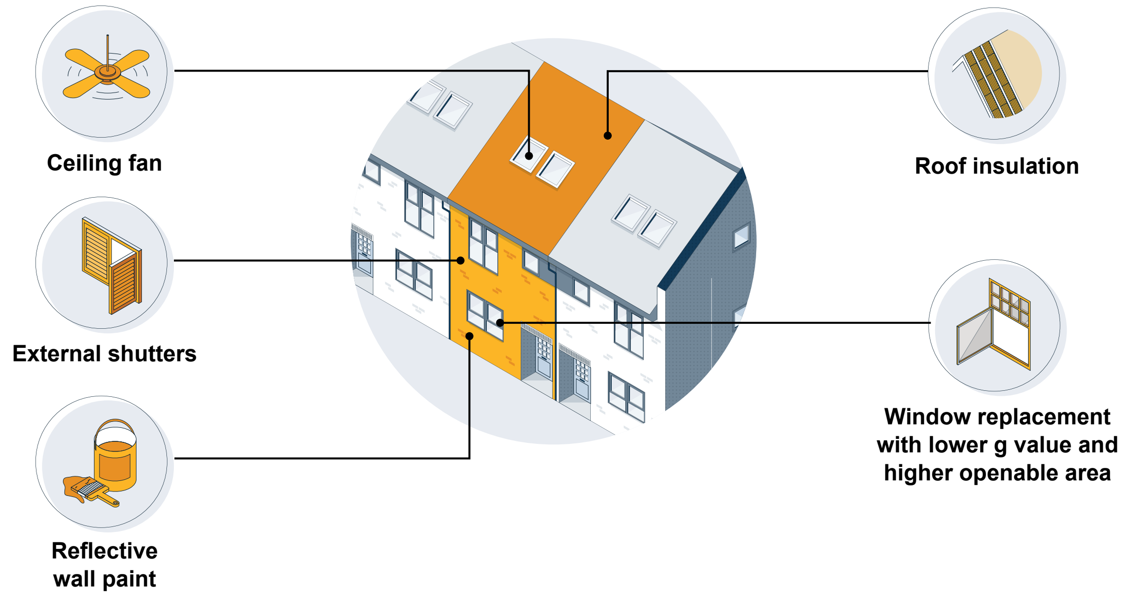

Figure 36: Package 4 for houses

Figure 37: Package 5 for houses

Mitigation packages for flats

Figure 38: Package 1 for flats

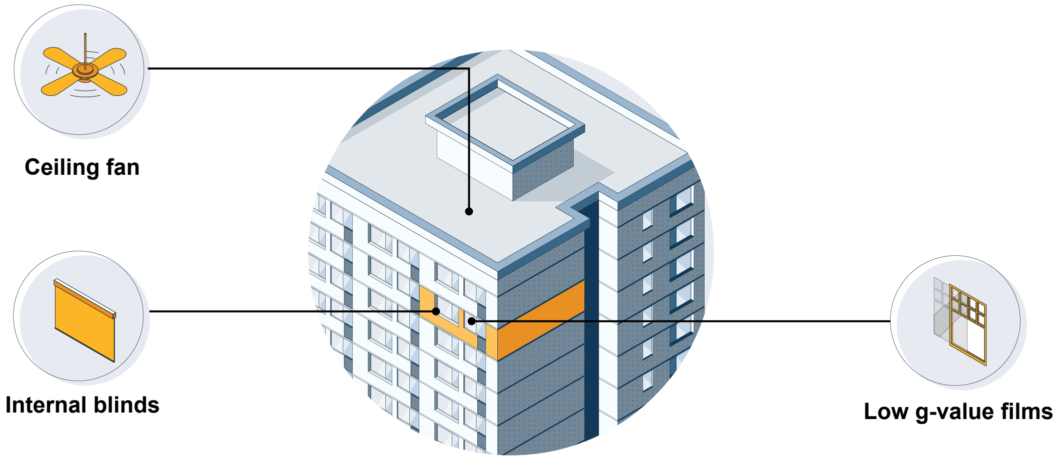

Figure 39: Package 2 for flats

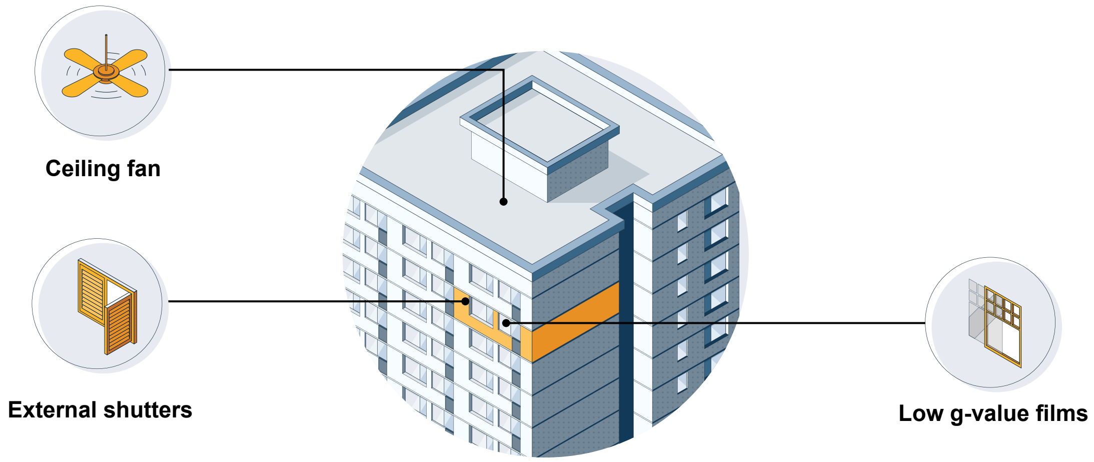

Figure 40: Package 3 for flats

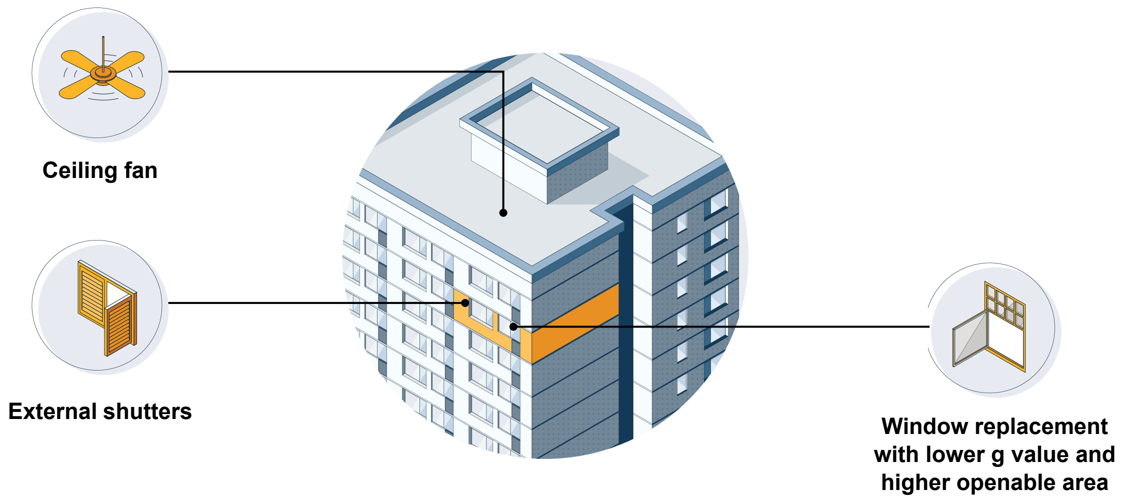

Figure 41: Package 4 for flats

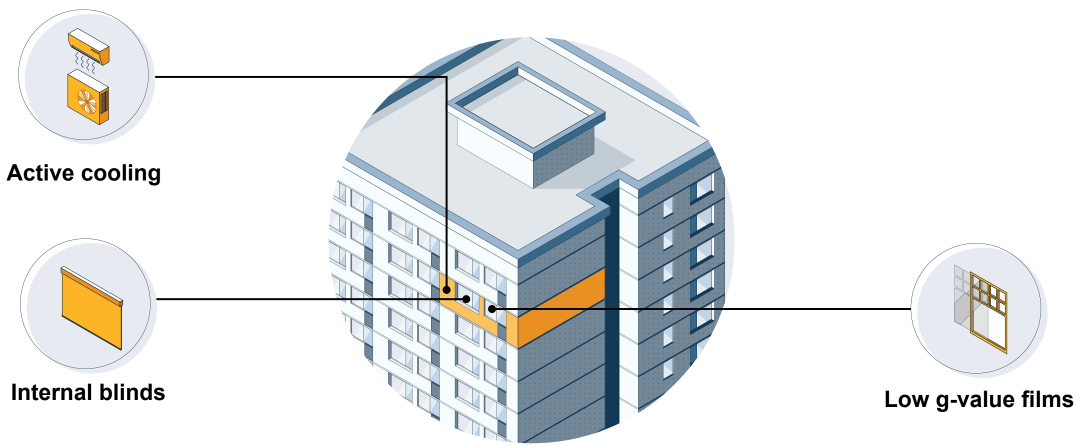

Figure 42: Package 5 for flats

Task 3: Assessing the level of deployment of mitigation measures at country scale

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Task 1 modelled and quantified the extent of the overheating risk in the UK housing stock. Task 2 then detailed and costed a series of passive mitigation measures to limit the risk of overheating and developed five discrete packages to be applied to the representative buildings.

Task 3 aimed to apply each of these mitigation packages to the representative buildings under the three climate scenarios considered to understand the appropriate mitigation that would have to be applied to reduce the risk of overheating under TM59 threshold and to estimate the cost of such intervention. Effective mitigation packages and their cost were then extrapolated at UK level to estimate the level of investment needed at scale for a full overheating adaptation strategy at scale.

5.1 Technical assessment of applied mitigation packages on representative buildings

The selected mitigation packages were tested on the representative buildings defined in Section 3.4. Table 16 to Table 18 present the results of the CIBSE TM59 assessment.

As a reminder, the colour coding was based on the following:

- TM59 pass condition: Criterion A 0-3%, Criterion B 0-32 hours
- TM59 moderate fail: Criterion A 3-6%, Criterion B 32-64 hours
- TM59 severe fail: Criterion A 6-15%, Criterion B 64-160 hours
- TM59 extreme fail: Criterion A over 15%, Criterion B over 160 hours

Note that the overheating results for Package 5 are not shown as active cooling with a setpoint of 26°C or lower would eliminate overheating as measured by TM59.

5.1.1 Overheating risk assessment of selected mitigation packages – Current weather scenario

When the current weather scenario was applied, as shown in Table 16, the following could be observed:

- None of the representative buildings failed Criterion A in the bedrooms or living spaces. All representative buildings with well insulated roofs using the Birmingham weather file also pass Criterion B and therefore require no mitigation package to reduce the overheating risk.
- When Package 1 was applied, the extreme overheating is eliminated entirely, and the severe overheating is limited to the two flat archetypes in London. Half of the representative buildings passed Criterion B when Package 1 was applied and hence require no further mitigation.
- Package 2 eliminates all severe overheating and leaves only the two flat archetypes with moderate night-time overheating in bedrooms. All buildings outside London only require the Package 2 mitigations, at most, to limit overheating in the current weather scenario.
- Package 3 was able to eliminate the moderate overheating in the old flat but did not make enough of an improvement to the London modern flat which still suffered from moderate bedroom overheating.
- Even Package 4 was unable to completely remedy the overheating in the London modern flat although it was extremely close to being within the acceptable threshold.

5.1.2 Overheating risk assessment of selected mitigation packages – 2°C GW scenario

In the 2°C global warming scenario, as shown in Table 17, the following was observed:

- None of the representative buildings pass both TM59 criteria when no mitigations are applied. Unlike the current weather scenario, some of the baseline models also failed Criterion A.
- With Package 1 applied, all representative buildings passed Criterion A. Whilst Package 1 reduced the Criterion B outcomes, the majority did not change category. Improving the roof insulation had a much greater impact on Criterion B than the addition of blinds and low g-value window film.
- Package 2 has a significant impact on the overheating risk. The extreme Criterion B scores are eliminated with the exception of the old flat in London. All models using the Birmingham weather file passed both criteria with Package 2 applied. All models using the Swindon weather file moved from severe bedroom overheating to moderate overheating at worst. Representative buildings in London remained a challenge.
- Package 3 added the solar reflective walls to the houses which had a limited effect on the mid-terrace but a good reduction in overheating when applied to the other houses. The addition of shutters produced a large reduction in Criterion B for the old flat but had a lesser effect on the modern flat due to the smaller windows and the balcony that already provided some solar shading.
- Package 4 was unable to eliminate severe overheating in two London archetypes, the mid-terrace and the modern flat. All London archetypes fail to pass Criterion B with the exception of the old flat. The old flat has a large area of glazing which originally had a small openable percentage. For this reason, increasing the openable area for the old flat resulted in a very large increase in natural ventilation rates and hence a reduction in overheating. Overheating challenges in the South of England can largely be mitigated by passive measures excluding the modern flat and mid-terrace archetypes.

5.1.3 Overheating risk assessment of selected mitigation packages – 4°C GW scenario

In the 4°C GW scenario, shown in Table 18, the following was observed:

- The baseline representative buildings with no mitigations applied showed extreme overheating challenges in almost all instances and the challenges were not limited to just Criterion B but also demonstrated severe overheating in living spaces.
- Package 1 was effective at reducing the Criterion A risk and removing severe overheating in all the houses. Flats in London retained severe overheating in living spaces. Package 1 had a very limited impact on bedroom overheating with most representative buildings recording an extreme fail on Criterion B.
- Package 2 was able to eliminate almost all Criterion A failures. Dwellings simulated in London still failed Criterion B by an extreme margin although other locations demonstrated good reductions in their Criterion B outcomes.
- Package 3 produced only one change in category, the semi-detached in Birmingham moving from a severe to moderate fail. As shown in the previous climate scenarios, Package 3 had a small effect on reducing the Criterion B results compared to Package 2.
- Package 4 resulted in only one representative building passing both Criteria A and B, the old flat simulated with Birmingham weather. Most archetypes failed moderately when using the Birmingham weather file. However, the Swindon weather file showed severe night-time overheating in bedrooms and the London weather file presented extreme failures of Criterion B.
- With the 4°C GW climate scenario, active cooling would be required in the majority of UK dwellings to eliminate the risk of overheating.

The following tables show the effect of installing each package on the representative buildings under the three weather scenarios considered.

Archetype	Location	Roof Construction	Baseline			Package 1			Package 2			Package 3			Package 4		
			Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)
Mid-terrace	Birmingham	Uninsulated	1.1	0.9	50.2	0.1	0.1	14.7	0.0	0.0	3.3	0.0	0.0	3.2	0.0	0.0	3.2
Mid-terrace	Swindon	Uninsulated	1.4	1.4	78.3	0.6	0.4	37.7	0.0	0.0	11.8	0.0	0.0	10.3	0.0	0.0	8.7
Mid-terrace	London	Uninsulated	1.8	1.5	147.2	0.6	0.5	57.8	0.0	0.1	30.2	0.0	0.1	28.5	0.0	0.1	28.2
Mid-terrace	Birmingham	Insulated	1.1	0.6	27.7	0.1	0.1	14.7	0.0	0.0	3.3	0.0	0.0	3.2	0.0	0.0	3.2
Mid-terrace	Swindon	Insulated	1.4	0.9	50.2	0.6	0.4	37.7	0.0	0.0	11.8	0.0	0.0	10.3	0.0	0.0	8.7
Mid-terrace	London	Insulated	1.7	0.9	89.8	0.6	0.5	57.8	0.0	0.1	30.2	0.0	0.1	28.5	0.0	0.1	28.2
Semi-detached	Birmingham	Uninsulated	0.3	0.6	50.2	0.0	0.1	16.0	0.0	0.0	1.0	0.0	0.0	0.7	0.0	0.0	0.5
Semi-detached	Swindon	Uninsulated	0.9	1.1	76.7	0.1	0.3	44.5	0.0	0.0	11.2	0.0	0.0	3.8	0.0	0.0	2.7
Semi-detached	London	Uninsulated	1.3	1.2	168.3	0.4	0.4	57.5	0.0	0.1	31.2	0.0	0.1	26.5	0.0	0.1	22.5
Semi-detached	Birmingham	Insulated	0.2	0.5	21.8	0.0	0.1	16.0	0.0	0.0	1.0	0.0	0.0	0.7	0.0	0.0	0.5
Semi-detached	Swindon	Insulated	0.9	0.7	55.7	0.1	0.3	44.5	0.0	0.0	11.2	0.0	0.0	3.8	0.0	0.0	2.7
Semi-detached	London	Insulated	1.3	0.9	73.8	0.4	0.4	57.5	0.0	0.1	31.2	0.0	0.1	26.5	0.0	0.1	22.5
Detached	Birmingham	Uninsulated	0.0	0.2	26.0	0.0	0.1	18.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Detached	Swindon	Uninsulated	0.3	0.6	53.8	0.0	0.3	26.7	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Detached	London	Uninsulated	0.3	0.6	124.2	0.2	0.3	62.0	0.0	0.0	24.7	0.0	0.0	22.0	0.0	0.0	11.8
Detached	Birmingham	Insulated	0.0	0.1	23.0	0.0	0.1	18.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Detached	Swindon	Insulated	0.2	0.5	37.7	0.0	0.3	26.7	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Detached	London	Insulated	0.3	0.5	81.7	0.2	0.3	62.0	0.0	0.0	24.7	0.0	0.0	22.0	0.0	0.0	11.8
End-terrace	Birmingham	Uninsulated	0.9	0.3	56.8	0.0	0.1	18.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
End-terrace	Swindon	Uninsulated	1.3	0.6	81.5	0.6	0.2	35.8	0.0	0.0	3.0	0.0	0.0	0.7	0.0	0.0	0.2
End-terrace	London	Uninsulated	1.6	0.7	159.8	0.5	0.2	49.7	0.0	0.0	28.8	0.0	0.0	25.7	0.0	0.0	23.5
End-terrace	Birmingham	Insulated	0.4	0.1	30.2	0.0	0.1	18.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
End-terrace	Swindon	Insulated	0.9	0.3	49.3	0.6	0.2	35.8	0.0	0.0	3.0	0.0	0.0	0.7	0.0	0.0	0.2
End-terrace	London	Insulated	1.0	0.3	66.2	0.5	0.2	49.7	0.0	0.0	28.8	0.0	0.0	25.7	0.0	0.0	23.5
Old flat	Birmingham	NA	0.2	0.0	23.2	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Old flat	Swindon	NA	1.0	0.2	47.0	0.6	0.0	21.7	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Old flat	London	NA	1.1	0.1	182.7	0.2	0.0	107.2	0.0	0.0	42.3	0.0	0.0	22.8	0.0	0.0	5.2
Modern flat	Birmingham	NA	0.6	0.3	25.0	0.2	0.1	19.2	0.0	0.0	7.0	0.0	0.0	3.3	0.0	0.0	2.5
Modern flat	Swindon	NA	1.1	0.5	39.7	0.6	0.2	30.2	0.0	0.0	12.0	0.0	0.0	6.8	0.0	0.0	3.0
Modern flat	London	NA	1.2	1.1	109.8	0.9	0.6	84.0	0.4	0.3	47.5	0.3	0.0	39.3	0.1	0.0	33.3

TM59 pass condition: Criterion A 0-3%, Criterion B 0-32 hours

TM59 moderate fail: Criterion A 3-6%, Criterion B 32-64 hours

TM59 severe fail: Criterion A 6-15%, Criterion B 64-160 hours

TM59 extreme fail: Criterion A over 15%, Criterion B over 160 hours

Table 16: TM59 overheating results with mitigation packages applied to the represenative buildings under current weather

Archetype	Location	Roof Construction	Baseline			Package 1			Package 2			Package 3			Package 4		
			Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)
Mid-terrace	Birmingham	Uninsulated	2.2	1.9	106.5	0.6	0.5	49.3	0.0	0.0	24.8	0.0	0.0	24.2	0.0	0.0	23.7
Mid-terrace	Swindon	Uninsulated	2.9	2.5	138.8	1.1	0.6	74.8	0.0	0.2	47.8	0.0	0.2	45.8	0.0	0.1	45.5
Mid-terrace	London	Uninsulated	4.8	3.9	316.7	1.2	0.9	179.0	0.2	0.3	76.7	0.1	0.3	75.2	0.1	0.3	72.7
Mid-terrace	Birmingham	Insulated	2.2	1.4	63.3	0.6	0.5	49.3	0.0	0.0	24.8	0.0	0.0	24.2	0.0	0.0	23.7
Mid-terrace	Swindon	Insulated	2.8	1.6	99.5	1.1	0.6	74.8	0.0	0.2	47.8	0.0	0.2	45.8	0.0	0.1	45.5
Mid-terrace	London	Insulated	4.6	2.3	214.3	1.2	0.9	179.0	0.2	0.3	76.7	0.1	0.3	75.2	0.1	0.3	72.7
Semi-detached	Birmingham	Uninsulated	1.7	1.5	88.5	0.2	0.4	52.2	0.0	0.1	22.5	0.0	0.1	16.0	0.0	0.0	11.5
Semi-detached	Swindon	Uninsulated	2.2	2.2	132.5	0.7	0.6	83.3	0.0	0.2	53.3	0.0	0.2	40.7	0.0	0.1	28.5
Semi-detached	London	Uninsulated	3.1	3.1	315.2	1.2	0.9	188.3	0.1	0.3	69.0	0.0	0.2	57.8	0.0	0.2	51.3
Semi-detached	Birmingham	Insulated	1.7	1.3	58.8	0.2	0.4	52.2	0.0	0.1	22.5	0.0	0.1	16.0	0.0	0.0	11.5
Semi-detached	Swindon	Insulated	2.1	1.5	89.2	0.7	0.6	83.3	0.0	0.2	53.3	0.0	0.2	40.7	0.0	0.1	28.5
Semi-detached	London	Insulated	3.0	2.4	223.2	1.2	0.9	188.3	0.1	0.3	69.0	0.0	0.2	57.8	0.0	0.2	51.3
Detached	Birmingham	Uninsulated	0.5	0.6	56.8	0.1	0.3	36.8	0.0	0.0	20.3	0.0	0.0	13.0	0.0	0.0	5.5
Detached	Swindon	Uninsulated	0.9	1.2	101.7	0.6	0.6	72.5	0.0	0.1	31.3	0.0	0.0	18.0	0.0	0.0	8.3
Detached	London	Uninsulated	1.0	1.4	280.0	0.7	0.7	171.7	0.0	0.2	69.3	0.0	0.2	51.8	0.0	0.2	34.5
Detached	Birmingham	Insulated	0.5	0.5	45.7	0.1	0.3	36.8	0.0	0.0	20.3	0.0	0.0	13.0	0.0	0.0	5.5
Detached	Swindon	Insulated	0.9	0.9	86.3	0.6	0.6	72.5	0.0	0.1	31.3	0.0	0.0	18.0	0.0	0.0	8.3
Detached	London	Insulated	1.0	1.0	215.0	0.7	0.7	171.7	0.0	0.2	69.3	0.0	0.2	51.8	0.0	0.2	34.5
End-terrace	Birmingham	Uninsulated	2.4	0.6	93.0	0.6	0.2	54.5	0.0	0.0	20.0	0.0	0.0	13.3	0.0	0.0	6.8
End-terrace	Swindon	Uninsulated	3.1	1.3	142.5	1.0	0.5	82.0	0.0	0.0	38.0	0.0	0.0	25.8	0.1	0.0	17.2
End-terrace	London	Uninsulated	4.5	1.4	335.2	1.1	0.6	173.0	0.2	0.2	63.5	0.2	0.2	48.7	0.2	0.2	42.3
End-terrace	Birmingham	Insulated	1.2	0.3	58.3	0.6	0.2	54.5	0.0	0.0	20.0	0.0	0.0	13.3	0.0	0.0	6.8
End-terrace	Swindon	Insulated	1.5	0.6	93.5	1.0	0.5	82.0	0.0	0.0	38.0	0.0	0.0	25.8	0.1	0.0	17.2
End-terrace	London	Insulated	1.9	0.7	214.0	1.1	0.6	173.0	0.2	0.2	63.5	0.2	0.2	48.7	0.2	0.2	42.3
Old flat	Birmingham	NA	1.5	0.0	56.3	0.1	0.0	38.7	0.0	0.0	14.5	0.0	0.0	5.3	0.0	0.0	0.2
Old flat	Swindon	NA	2.4	0.4	154.0	0.8	0.2	92.8	0.4	0.0	38.8	0.1	0.0	15.2	0.0	0.0	0.7
Old flat	London	NA	6.3	0.5	420.5	1.1	0.1	289.2	0.2	0.0	173.8	0.0	0.0	114.3	0.0	0.0	26.5
Modern flat	Birmingham	NA	1.9	1.1	53.3	1.2	0.4	46.0	0.2	0.1	28.7	0.1	0.0	23.7	0.1	0.0	20.7
Modern flat	Swindon	NA	3.0	1.7	91.0	2.0	0.7	72.2	0.4	0.1	46.7	0.3	0.0	41.7	0.3	0.0	35.7
Modern flat	London	NA	4.1	2.7	287.2	2.2	1.3	233.3	0.9	0.6	126.3	0.8	0.4	107.8	0.6	0.3	87.0

TM59 pass condition: Criterion A 0-3%, Criterion B 0-32 hours

TM59 moderate fail: Criterion A 3-6%, Criterion B 32-64 hours

TM59 severe fail: Criterion A 6-15%, Criterion B 64-160 hours

TM59 extreme fail: Criterion A over 15%, Criterion B over 160 hours

Table 17: TM59 overheating results with mitigation packages applied to the represenative buildings under the 2°C GW scenario

Archetype	Location	Roof Construction	Baseline			Package 1			Package 2			Package 3			Package 4		
			Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)
Mid-terrace	Birmingham	Uninsulated	6.3	4.6	226.0	2.7	1.8	118.0	0.4	0.3	69.2	0.4	0.3	68.2	0.4	0.3	66.0
Mid-terrace	Swindon	Uninsulated	6.4	5.6	297.0	3.6	2.4	185.7	0.8	0.8	140.7	0.7	0.8	137.0	0.7	0.7	134.5
Mid-terrace	London	Uninsulated	12.4	9.2	535.5	3.9	2.9	422.2	0.6	0.7	283.5	0.6	0.6	277.8	0.6	0.6	269.3
Mid-terrace	Birmingham	Insulated	6.2	3.4	155.5	2.7	1.8	118.0	0.4	0.3	69.2	0.4	0.3	68.2	0.4	0.3	66.0
Mid-terrace	Swindon	Insulated	6.3	3.6	219.5	3.6	2.4	185.7	0.8	0.8	140.7	0.7	0.8	137.0	0.7	0.7	134.5
Mid-terrace	London	Insulated	12.2	6.8	459.2	3.9	2.9	422.2	0.6	0.7	283.5	0.6	0.6	277.8	0.6	0.6	269.3
Semi-detached	Birmingham	Uninsulated	4.9	3.7	224.3	2.5	1.7	133.0	0.2	0.5	65.5	0.1	0.4	60.0	0.0	0.3	56.5
Semi-detached	Swindon	Uninsulated	5.3	5.1	331.7	3.4	2.5	208.2	0.5	1.0	129.3	0.3	0.8	115.3	0.5	0.7	102.8
Semi-detached	London	Uninsulated	10.6	8.9	499.0	3.7	3.1	409.0	0.4	1.0	282.7	0.4	0.8	253.3	0.5	0.6	211.8
Semi-detached	Birmingham	Insulated	4.9	3.0	160.7	2.5	1.7	133.0	0.2	0.5	65.5	0.1	0.4	60.0	0.0	0.3	56.5
Semi-detached	Swindon	Insulated	5.2	3.3	235.3	3.4	2.5	208.2	0.5	1.0	129.3	0.3	0.8	115.3	0.5	0.7	102.8
Semi-detached	London	Insulated	10.5	7.0	435.0	3.7	3.1	409.0	0.4	1.0	282.7	0.4	0.8	253.3	0.5	0.6	211.8
Detached	Birmingham	Uninsulated	2.2	2.4	157.7	1.3	1.3	104.2	0.2	0.3	53.3	0.1	0.2	46.2	0.1	0.2	34.3
Detached	Swindon	Uninsulated	3.5	3.3	269.8	2.3	2.2	204.7	0.5	0.8	123.0	0.2	0.5	95.0	0.6	0.5	66.0
Detached	London	Uninsulated	3.6	5.0	499.5	2.2	2.3	424.8	0.4	0.6	259.3	0.4	0.3	185.5	0.4	0.3	147.8
Detached	Birmingham	Insulated	2.0	1.8	123.0	1.3	1.3	104.2	0.2	0.3	53.3	0.1	0.2	46.2	0.1	0.2	34.3
Detached	Swindon	Insulated	3.4	2.7	234.8	2.3	2.2	204.7	0.5	0.8	123.0	0.2	0.5	95.0	0.6	0.5	66.0
Detached	London	Insulated	3.2	3.4	464.8	2.2	2.3	424.8	0.4	0.6	259.3	0.4	0.3	185.5	0.4	0.3	147.8
End-terrace	Birmingham	Uninsulated	5.8	2.7	260.3	2.4	1.0	133.7	0.3	0.2	61.2	0.2	0.2	58.3	0.2	0.2	55.0
End-terrace	Swindon	Uninsulated	6.4	4.0	325.3	3.5	1.9	194.2	0.8	0.5	119.5	0.7	0.5	111.0	0.8	0.5	95.3
End-terrace	London	Uninsulated	12.5	5.3	537.3	4.1	1.8	409.8	0.6	0.3	249.7	0.5	0.3	220.8	0.7	0.3	185.8
End-terrace	Birmingham	Insulated	3.8	1.3	166.7	2.4	1.0	133.7	0.3	0.2	61.2	0.2	0.2	58.3	0.2	0.2	55.0
End-terrace	Swindon	Insulated	4.7	2.3	217.3	3.5	1.9	194.2	0.8	0.5	119.5	0.7	0.5	111.0	0.8	0.5	95.3
End-terrace	London	Insulated	7.5	2.3	445.5	4.1	1.8	409.8	0.6	0.3	249.7	0.5	0.3	220.8	0.7	0.3	185.8
Old flat	Birmingham	NA	6.4	1.0	264.5	3.3	0.3	177.2	0.5	0.0	94.2	0.0	0.0	64.2	0.0	0.0	20.5
Old flat	Swindon	NA	11.2	2.3	492.0	4.9	0.8	390.7	1.3	0.3	250.7	0.6	0.1	190.5	0.6	0.1	44.8
Old flat	London	NA	18.8	6.7	895.8	10.5	3.3	728.2	3.4	0.5	550.3	0.4	0.1	429.0	0.4	0.1	170.5
Modern flat	Birmingham	NA	5.0	3.0	151.8	3.6	1.9	121.8	2.0	1.1	77.5	1.6	0.4	67.5	0.9	0.3	59.7
Modern flat	Swindon	NA	7.1	4.3	230.0	5.0	2.8	199.5	3.3	1.9	150.5	3.1	1.0	138.7	1.8	0.7	119.8
Modern flat	London	NA	13.9	9.4	569.0	10.0	5.2	523.2	3.2	2.0	386.2	2.5	0.9	341.7	1.4	0.6	297.3

TM59 pass condition: Criterion A 0-3%, Criterion B 0-32 hours

TM59 moderate fail: Criterion A 3-6%, Criterion B 32-64 hours

TM59 severe fail: Criterion A 6-15%, Criterion B 64-160 hours

TM59 extreme fail: Criterion A over 15%, Criterion B over 160 hours

Table 18: TM59 overheating results with mitigation packages applied to the representative buildings under the 4°C GW scenario

5.1.4 Assuming perfect occupant behaviour

Throughout this study, the occupants were assumed to behave identically to allow meaningful comparison between individual simulations. However, informed occupants could take positive actions to limit the effect of overheating within their homes. This sensitivity aimed to simulate the actions of the perfect occupant, purely focussed on minimising summer overheating. The actions they were assumed to take are given below.

– Windows were closed when the outdoor temperature exceeded the indoor temperature.

– Windows were fully opened when the indoor temperature exceeded 22°C as opposed to the proportional approach used in the baseline assumption and recommended in Part O.

– Bedroom window operation was still based on the indoor temperature at 11pm. If that temperature exceeded 23°C, the windows were opened fully (50% in baseline) and remained open all night regardless of how low the indoor temperature falls.

– Night-time purge ventilations was enabled by opening living space windows fully all night if the indoor temperature at 11pm was above 23°C even though these spaces were unoccupied.

– With Package 1 applied, blinds were closed when a solar setpoint of 100 W/m^2 was reached in contrast to a setpoint of 200 W/m^2 in the baseline. This represents a more pre-emptive user that closes blinds before large solar gains occur.

Note that these are not actions expected from the majority of the public, and hence were not assumed during the original simulations discussed in Section 3.3. Some actions are also subject to sufficient security measures being present to allow window openings at night. The results of this sensitivity aimed to show the upper bound of what a well-informed, active occupant could potentially achieve rather than what is realistic from every occupant.

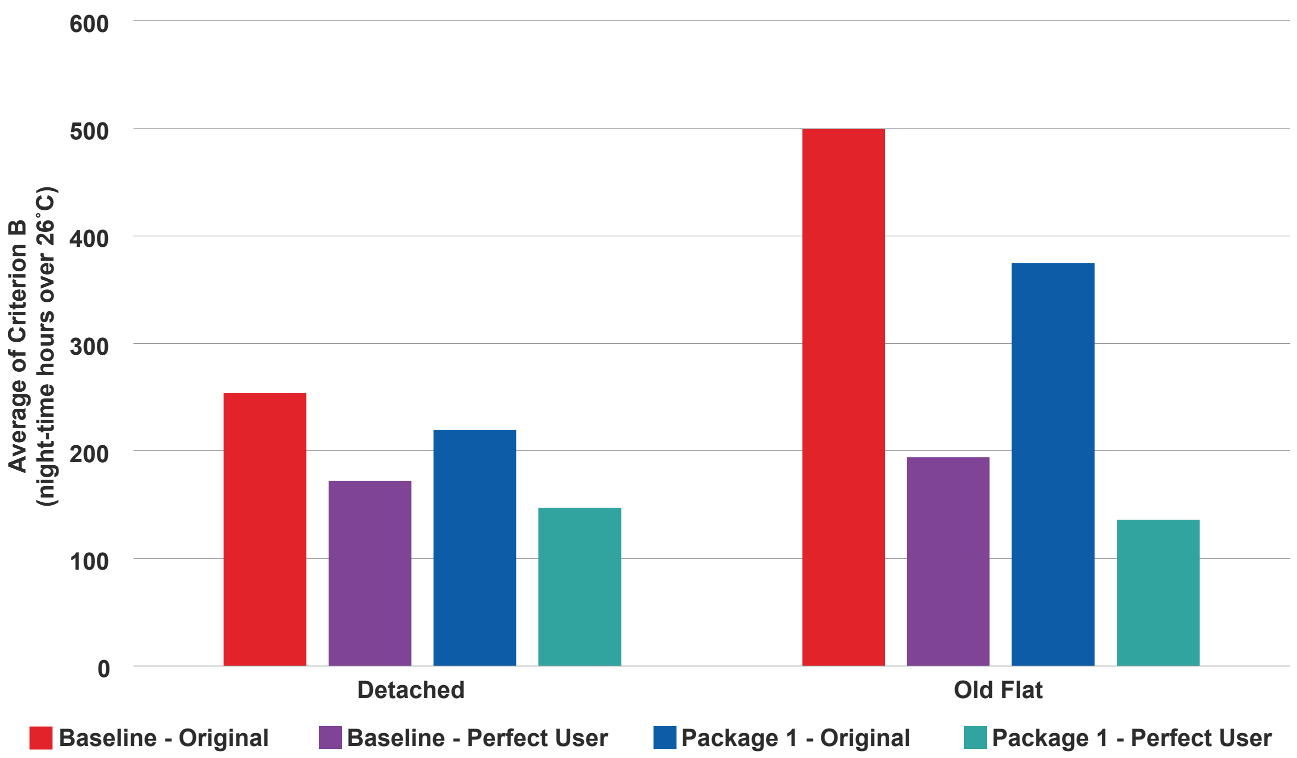

Figure 43: Average Criterion B overheating in London comparing simulations with original behaviour and the perfect user

The perfect user operation was applied to the detached and old flat archetypes using the Birmingham, Swindon and London weather files in all climate scenarios. For the sake of clarity, only the average Criterion B results for London across all climate scenarios are given in Figure 43.

This demonstrates a significant reduction in overheating by taking the actions described above. This was particularly pronounced in the old flat archetype where the perfect user only experienced around 38% of the bedroom night-time overheating hours compared to the original simulation. Whereas the detached house experienced around 67% of the overheating hours compared to the original simulation. Assuming windows can be opened securely, this reduction in overheating is achieved without any additional capital expenditure or physical alterations to the property.

As already evidenced in Section 3.6.1, the overheating risk in the old flat was far more sensitive to changes to the natural ventilation rates than the detached house. Therefore, the actions of the perfect occupant, which focus largely on the control of natural ventilation, had a greater reduction in overheating compared to the detached house which is driven to a larger extent by conduction through the greater external wall area.

5.2 Selection of mitigation packages

Based on the results shown in Table 16, Table 17 and Table 18, the effective package to reduce overheating under TM59 limits were selected for each archetype and weather scenario. Table 19 below shows the final selection of packages.

None	Package 3
Package 1	Package 4
Package 2	Package 5

Archetype	Location	Roof Construction	Current weather	2°C GW	4°C GW
Detached	Birmingham	Insulated	None	2	5
Detached	Birmingham	Uninsulated	None	2	5
Detached	Glasgow	Insulated	None	None	1
Detached	Glasgow	Uninsulated	None	None	1
Detached	London	Insulated	2	5	5
Detached	London	Uninsulated	2	5	5
Detached	Swindon	Insulated	1	2	5
Detached	Swindon	Uninsulated	1	2	5
End-terrace	Birmingham	Insulated	None	2	5
End-terrace	Birmingham	Uninsulated	1	2	5
End-terrace	Glasgow	Insulated	None	None	2
End-terrace	Glasgow	Uninsulated	None	1	2
End-terrace	London	Insulated	2	5	5
End-terrace	London	Uninsulated	2	5	5
End-terrace	Swindon	Insulated	2	3	5
End-terrace	Swindon	Uninsulated	2	3	5
Mid-terrace	Birmingham	Insulated	None	2	5
Mid-terrace	Birmingham	Uninsulated	1	2	5
Mid-terrace	Glasgow	Insulated	None	None	1
Mid-terrace	Glasgow	Uninsulated	None	None	1
Mid-terrace	London	Insulated	2	5	5
Mid-terrace	London	Uninsulated	2	5	5
Mid-terrace	Swindon	Insulated	2	5	5
Mid-terrace	Swindon	Uninsulated	2	5	5
Modern flat	Birmingham	NA	None	2	5
Modern flat	Glasgow	NA	None	None	2
Modern flat	London	NA	5	5	5
Modern flat	Swindon	NA	1	5	5
Old flat	Birmingham	NA	None	2	4
Old flat	Glasgow	NA	None	None	1
Old flat	London	NA	3	4	5
Old flat	Swindon	NA	1	3	5
Semi-detached	Birmingham	Insulated	None	2	5
Semi-detached	Birmingham	Uninsulated	1	2	5
Semi-detached	Glasgow	Insulated	None	None	2
Semi-detached	Glasgow	Uninsulated	None	None	2
Semi-detached	London	Insulated	2	5	5
Semi-detached	London	Uninsulated	2	5	5
Semi-detached	Swindon	Insulated	2	4	5
Semi-detached	Swindon	Uninsulated	2	4	5

Table 19: Selected packages for each representative building and weather scenario

Archetype	Location	Weather scenario	Roof Construction	Criterion A Living & Kitchen (%)	Criterion A Bedrooms (%)	Criterion B (hours)
End-terrace	Glasgow	2°C GW	Uninsulated	0.40	0.04	35.7
Mid-terrace	Glasgow	4°C GW	Uninsulated	1.39	0.89	67.0
Mid-terrace	Glasgow	4°C GW	Insulated	1.36	0.73	41.5
Semi-detached	Glasgow	4°C GW	Uninsulated	1.01	0.86	75.3
Semi-detached	Glasgow	4°C GW	Insulated	0.80	0.68	47.8
Detached	Glasgow	4°C GW	Uninsulated	0.00	0.19	53.2
Detached	Glasgow	4°C GW	Insulated	0.00	0.10	39.2
End-terrace	Glasgow	4°C GW	Uninsulated	1.23	0.36	79.5
End-terrace	Glasgow	4°C GW	Insulated	0.65	0.04	51.7
Old flat	Glasgow	4°C GW	Uninsulated	0.27	0.00	43.3
Modern flat	Glasgow	4°C GW	Insulated	1.04	0.77	46.0

Table 20: Scottish case studies requiring mitigation measures to pass Criterion B

TM59 pass condition: Criterion A 0-3%, Criterion B 0-32 hours	TM59 severe fail: Criterion A 6-15%, Criterion B 64-160 hours
TM59 moderate fail: Criterion A 3-6%, Criterion B 32-64 hours	TM59 extreme fail: Criterion A over 15%, Criterion B over 160 hours

5.2.1 Selection of mitigation packages for Scottish dwellings

As demonstrated in Section 3.3, the overheating risk is Scotland was significantly lower than the rest of the UK. Nevertheless, mitigation packages needed to be selected to reduce the Criterion B overheating in a small number of cases, shown in Table 20.

As the Criterion B failures predominantly occur in the 4°C climate scenario and even then, the majority only moderately fail, it was deemed unnecessary to simulate every mitigation package in all climate scenarios. Instead, the mitigation packages were applied to the cases listed in Table 20 in order until a TM59 pass was achieved. The resulting mitigation packages required for Scottish representative building are given in Table 21.

Archetype	Location	Roof Construction	Current weather	2°C GW	4°C GW
Mid-terrace	Glasgow	Uninsulated	None	None	1
Mid-terrace	Glasgow	Insulated	None	None	1
Semi-detached	Glasgow	Uninsulated	None	None	2
Semi-detached	Glasgow	Insulated	None	None	2
Detached	Glasgow	Uninsulated	None	None	1
Detached	Glasgow	Insulated	None	None	1
End-terrace	Glasgow	Uninsulated	None	1	2
End-terrace	Glasgow	Insulated	None	None	2
Old flat	Glasgow	NA	None	None	1
Modern flat	Glasgow	NA	None	None	2
Detached	Glasgow	Uninsulated	None	None	1
Detached	Glasgow	Insulated	None	None	1
End-terrace	Glasgow	Uninsulated	None	1	2
End-terrace	Glasgow	Insulated	None	None	2
Old flat	Glasgow	NA	None	None	1
Modern flat	Glasgow	NA	None	None	2

Table 21: Mitigation packages applied to Scottish representative buildings

None
Package 1
Package 2
Package 3
Package 4
Package 5

5.3 High-level cost assessment of selected mitigation packages

The five packages of mitigations were costed for each of the six archetypes in a similar way to the costing exercise in Task 2. The costs were built up including facilitating works, supply and installation costs (using elemental unit rates), preliminaries, and overheads and profits for the contractor. The costs for the packages, per archetype, were combined into a table, with no location factorisation (so the location was assumed as Outer London, factor of 1). For the purpose of this costing exercise, all window mitigations were considered to be applied to all windows and roof lights.

A key consideration for the package costing exercise is the assumption that the packaged works will be procured in a complimentary, consecutive or even parallel programme with all the components of the package, with no large time gaps in the works taking place. Furthermore, this was assumed to enable a shared scaffolding cost for works that required access. Where multiple works required access costs to be included, an additional 20% was added for each additional set of works using the scaffolding, allowing for increased time on site but no new set up and dismantling costs.

For the flats it was assumed the archetype example was on the third floor (as in Task 2) and the scaffolding and access costs are for that individual flat alone. This is unlikely to occur in a real-life situation but for a comparative costing exercise it is important to identify the cost of the mitigations to that specific dwelling and allow for an 'average' storey height for flats. A grouped procurement of the works for multiple flats (such as the whole building) would reduce the individual access costs considerably. To put this in perspective, for example, if all three of the flats below the third-floor modelled flat were to procure the same package of works, the total cost of the access within the single flat package, would cover access to the flats below completely and these costs could be split four ways. It is therefore advised that the flat archetype package costs are used solely for comparison with the house archetypes and are individually tested in a full costing exercise, when the building to be modified by flat type and number of storeys is known.

Following production of package costs it was suggested we identify which costs relate to thermal overheating mitigations only and which costs are related to other factors such as home renovations or general energy saving mitigations. Four categories were developed and the mitigations grouped as shown:

Pure mitigation - overheating only (Pure)

These are costs that are solely related to overheating mitigation and are not typically shared with other retrofit purposes:

– Low G film

– External Shutters

– Ceiling fans

– Solar reflective walls

– Active cooling

Extra over upgrade costs (Extra)

These are the uplift cost related to selecting specific overheating mitigation related features compared to the cost of a like-for-like replacement of an element at the end of its useful life:

– Low G value windows

– Openable windows

Complimentary measures (Complimentary)

These are costs that can be shared with other retrofit works, such as improvement of energy efficiency:

– Roof insulation

Generally existing measures (Existing)

These are the costs for measures that are potentially already present in a large portion of the housing stock and could therefore be lower than estimated at scale.

– Blinds

These mitigation category splits (Pure, Extra, Complimentary and Existing) were applied to the different mitigation packages, to achieve a breakdown of the costs for each package, for each archetype.

The spread of costs (and the split of costs into categories) per archetype for each of the packages is shown in the graphs below. Note that the insulated and uninsulated versions of each archetype are shown, because this dictates whether a complimentary cost is incurred in the package. Full cost tables are presented in Appendix C.

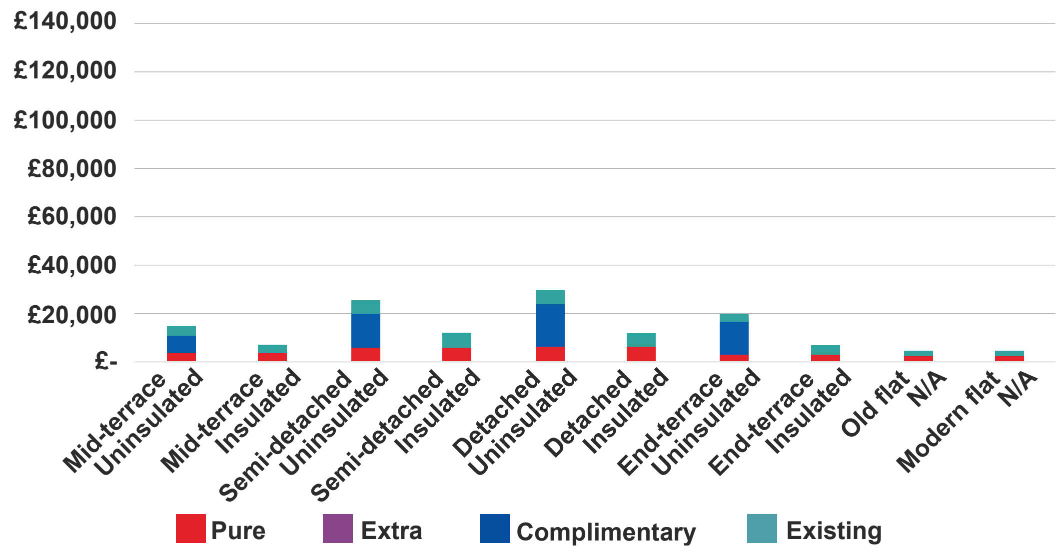

Figure 44: Package 1 costs, showing splits, for all archetypes in Outer London location (base costs) - Scottish representative buildings

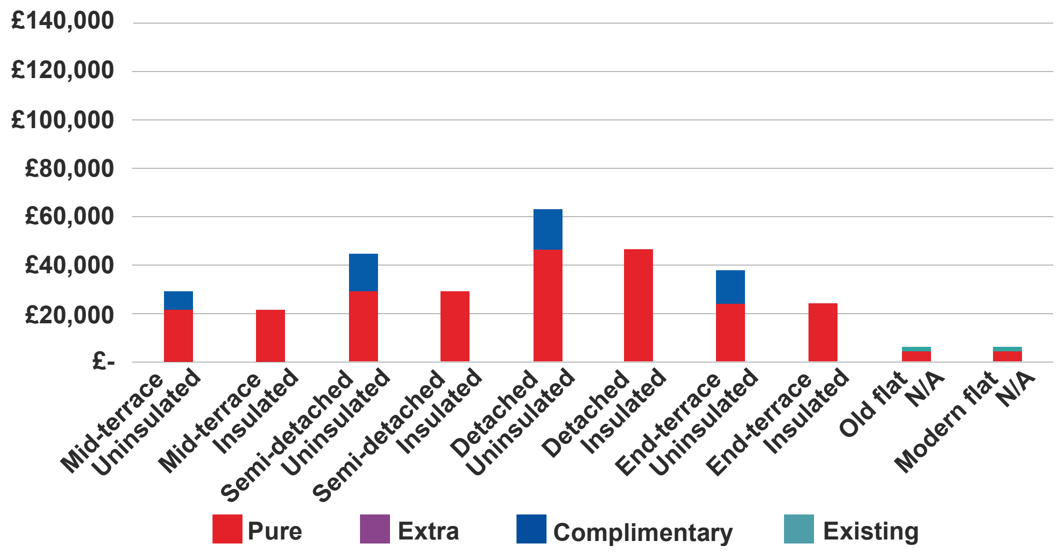

Figure 45: Package 2 costs, showing splits, for all archetypes in Outer London location (base costs)

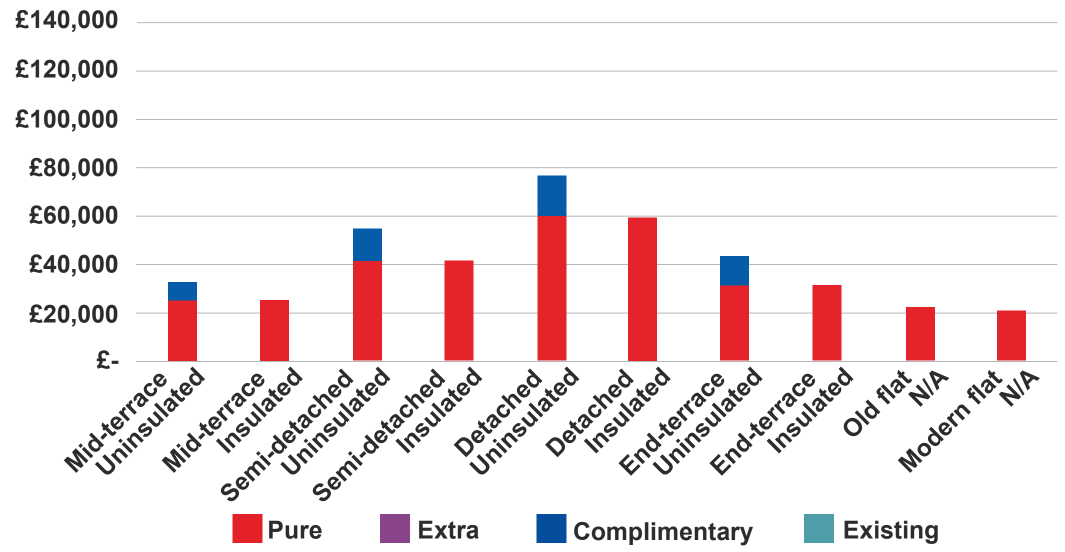

Figure 46: Package 3 costs, showing splits, for all archetypes in Outer London location (base costs)

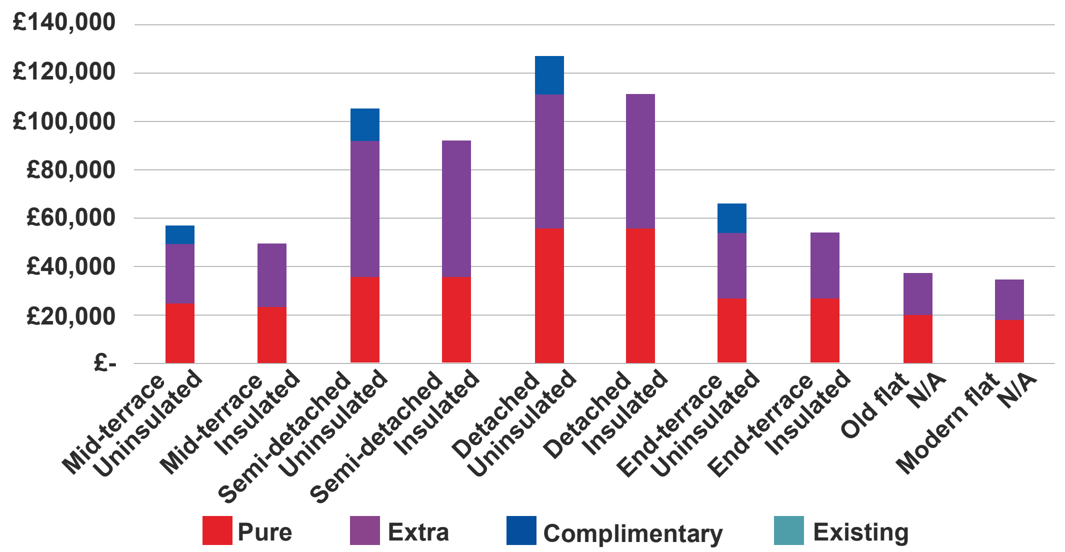

Figure 47: Package 4 costs, showing splits, for all archetypes in Outer London location (base costs)

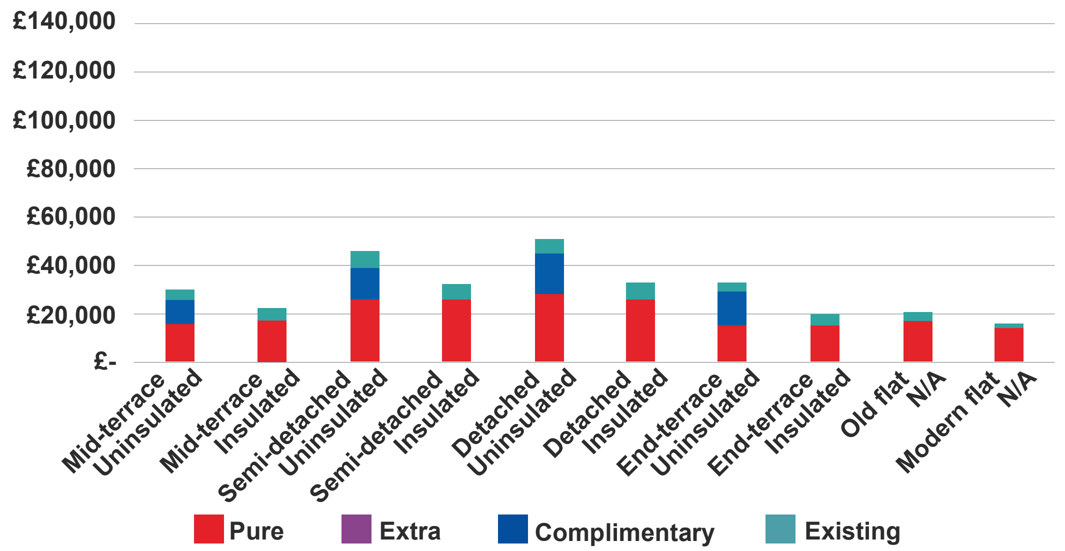

Figure 48: Package 5 costs, showing splits, for all archetypes in Outer London location (base costs)

5.4 Assessment of deployment of mitigation packages at scale

5.4.1 Assessment of mitigation packages applied at scale

Table 19 showed the packages considered for each representative building. Each one of these buildings was representative of a larger group of simulations in Task 1, as described in Section 3.4. Based on this, the selected packages were then applied to the remaining of the 2,400 case studies modelled in Task 1 and, consequently, the number of homes in each nation and in the UK overall that would require a certain package was estimated for each weather scenario.

Looking at the results by nation, the following key points can be deduced:

- Scotland was found to have negligible overheating issues and therefore no overheating mitigation packages are expected to be required in the current weather scenario. However, a small number of homes require Package 1 in the 2°C warming scenario and a combination of package 1 and 2 is required for all Scottish homes in the 4°C GW scenario.
- Package 2 was sufficient to overcome overheating issues in a 2°C GW scenario in Wales and Northern Ireland, while Southern England required greater levels of intervention.
- In England, Wales and Northern Ireland, the majority of dwellings require active cooling (Package 5) to mitigate overheating in a 4°C GW scenario.

These figures have been used to estimate the cost of intervention at scale for each weather scenario.

Table 22 shows the total number of homes in the UK requiring each mitigation package in each weather scenario in order to pass the CIBSE TM59 assessment. Figure 49 shows the expected level of intervention under each weather scenario in terms of number of homes by nation.

Mitigation Package	Climate Scenario		
	Current	2°C GW	4°C GW
None	12,602,811	2,391,322	0
1	7,025,450	72,679	1,630,357
2	6,962,933	15,578,378	833,641
3	289,689	1,463,023	0
4	0	2,628,895	446,537
5	1,407,746	6,154,335	25,378,094

Table 22: Total number of UK homes requiring mitigations in each climate scenario

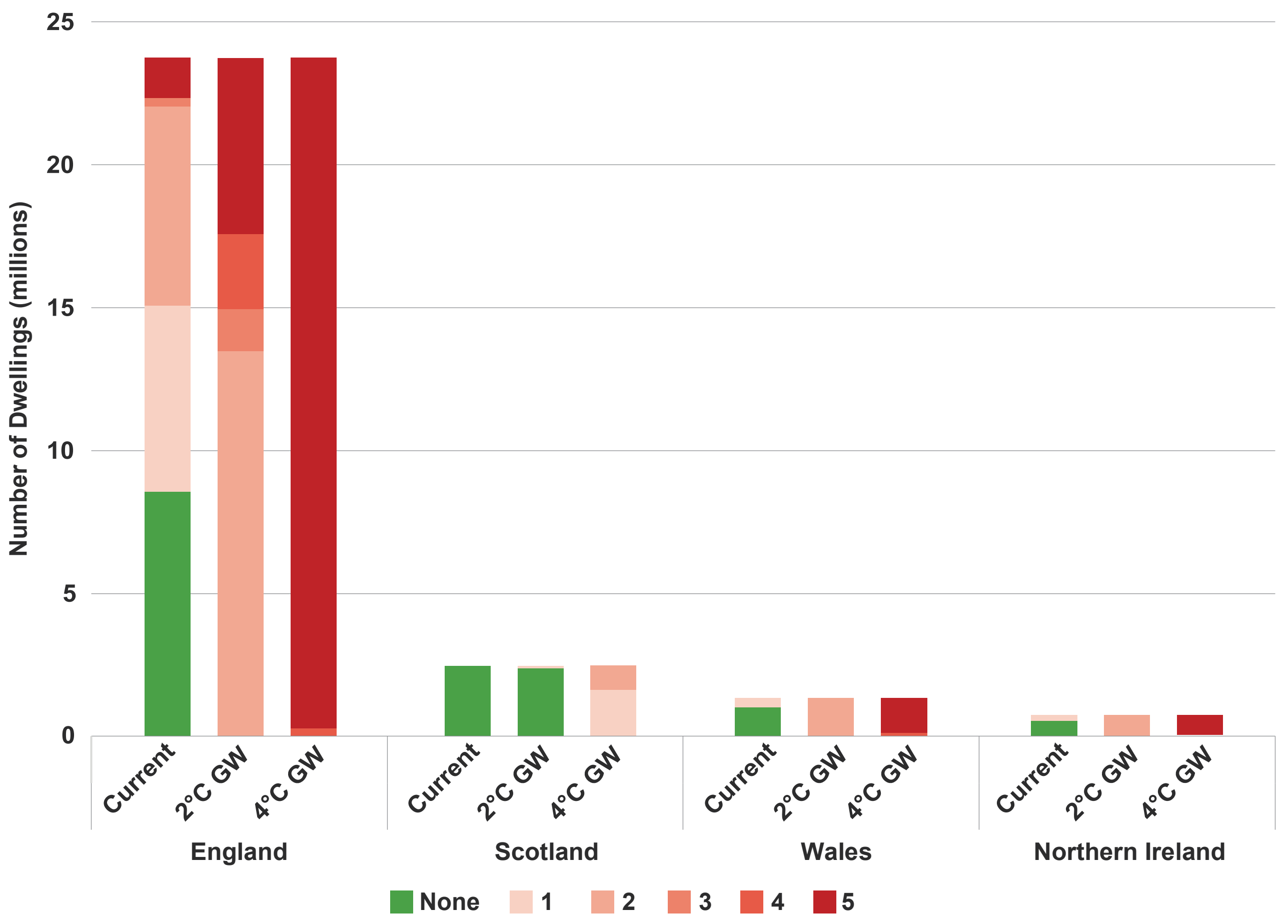

Figure 49: Mitigation packages required for each nation across the UK

Area Represented	Weather File Location	Area Represented	Factor to Use
London	London	London	1.21
Midlands	Birmingham	Midlands	0.99
Wales	Birmingham	Wales	0.93
North England	Manchester	North England	0.94
Northern Ireland	Manchester	Northern Ireland	0.56
Scotland	Glasgow	Scotland	0.91
South of England	Swindon	South of England	1.08

Table 23: Location factors with nations differentiated for Task 3

5.4.2 Estimated cost of overheating mitigation strategy at scale

Section 5.4.1 presented the number of homes to which each package was applied under each weather scenario. These figures were used to define, at a high-level of approximation, the investment needed for each nation to overcome the overheating issues in each weather scenario, based on CIBSE TM59 criteria.

Following the costing of each of the packages for each archetype (including those with insulated or uninsulated roof), the factors for the final modelled housing data were determined. The housing data produced by Parity Projects offered more granularity than the anticipated location factors from Task 2 and the location factors were updated to allow for the nuances between the Midlands housing stock set in England and Wales, and the North England set in England and Northern Ireland. Capturing the difference in these location factors enabled the factor for each of the housing (archetype) numbers in the modelled data to be accurately represented. For this reason an expanded set of factors was used, as shown below in the Task 3 location factor table. This was used when applying costs at scale on the housing stock data for the UK.

The location factors were used within the total cost calculation. The calculation process was then carried out in the following way:

1. Building archetypes per location numbers were supplied by Parity Projects' stock model;
2. Selected archetypes were allocated three packages, one per each weather scenario;
3. The costs for each selected package for each archetype were allocated;
4. The costs were then factored by location, including the nation factor allowance;
5. The costs were then multiplied by housing stock data for that archetype in that location;
6. These costs were then summed according to the data selection for the modelling study.

The grouped 'weather scenario' packaged mitigation costs for the whole of the UK housing stock were calculated. However, following this, it was determined that the modelled archetypes were generally larger than the average UK home and each archetype GIFA was mapped against the average, to achieve a factor by which our costings should be adjusted, to be more representative of UK housing stock size. The factors used are shown in Table 24, with the national level costings shown in Table 25.

The national-scale cost of mitigating against domestic overheating in the three climate scenarios are also shown in Figure 50. This figure also breaks down those costs into the four cost categories; pure, extra, complimentary and existing.

Archetype Number	Archetype	No. of matches	Mean floor area	Modelled area (m² GIFA)	Factor to Use
1	Mid-terrace	5,161,721	84.98	102.32	0.83
2	Semi-Detached	6,770,494	94.84	230.21	0.41
3	Detached	4,067,609	148.43	293.84	0.51
4	End-terrace	2,813,727	87.62	137.45	0.64
5	Double sided flat	943,553	61.71	51.82	1.19
6	Single sided flat	3,975,531	60.51	67.15	0.90

Table 24: Modelled versus average archetype area to generate factor

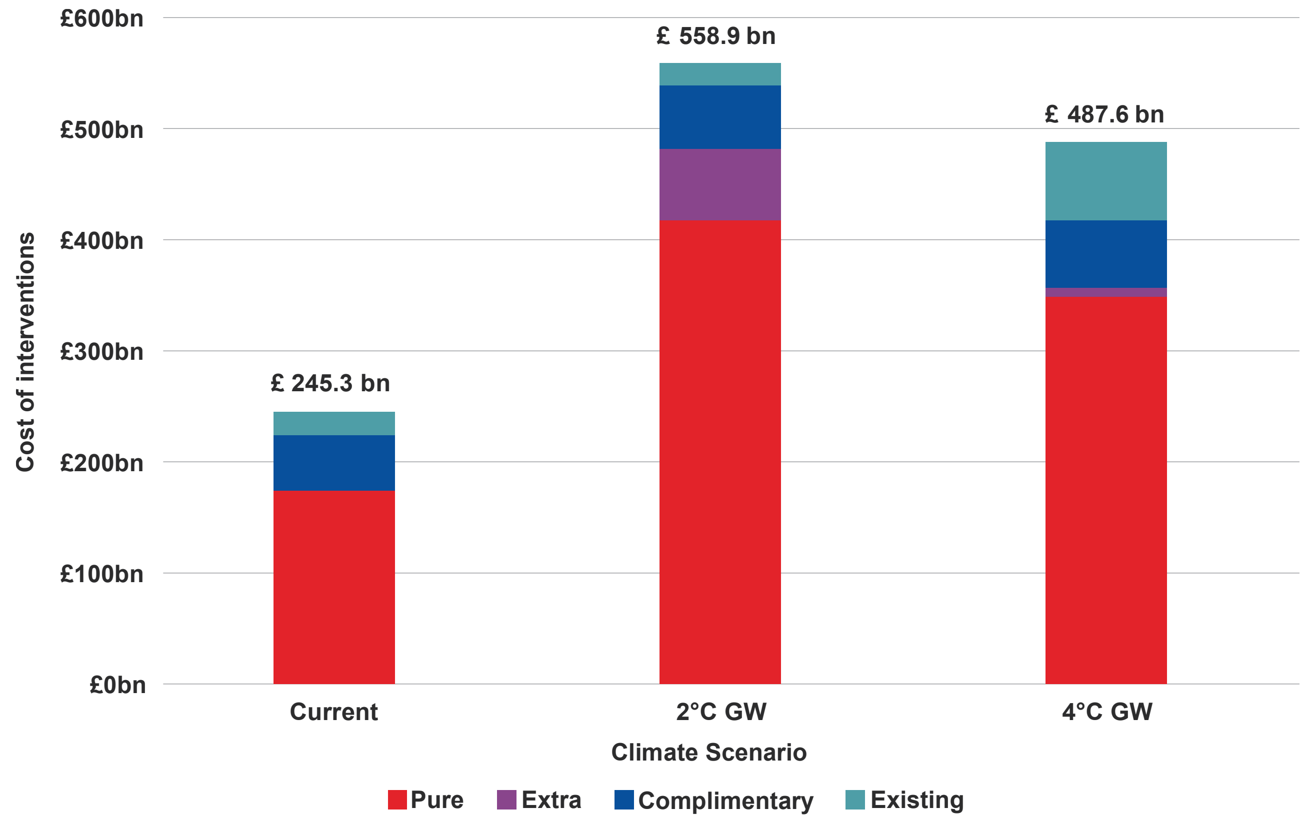

Figure 50: Total cost to implement the mitigations for each weather scenario using average house areas (showing package cost splits)

The costs across the whole UK housing stock are high and demonstrate a number of things:

– Even considering 'current' climatic conditions in the UK, significant investment in mitigation measures is required to address an existing overheating challenge.

– Over 70% or more of the costs at each weather scenario are pure measures (and relate only to mitigating overheating); this demonstrates the significant investment needed to address the existing and future overheating challenge.

– The costs associated with 2°C and 4°C warming scenarios are considerably higher.

– The costs do not capture the costs of running the technology (especially electricity costs for Package 5) or the maintenance required, and they do not capture other cost impacts such as the increased thermal heating costs if the solar gain is reduced.

– The useful life of the mitigations is also not captured in the cost assessment and a whole life cost should be considered when selecting a mitigation package in real scenarios, particularly for active cooling equipment.

– Furthermore, these costs do not capture the environmental impact of increased electricity use, carbon impact or refrigerant use in the Package 5 (seemingly lower cost) option.

– The 'higher' capital cost of Packages 2-4 are balanced by their lower operational costs and lower environmental impacts compared to the active cooling option in Package 5.

Weather Scenario	Total	Pure	Extra	Complimentary	Existing
Current	£245.3bn	£174.2bn	£0.0bn	£50.0bn	£21.1bn
2°C GW	£558.9bn	£417.4bn	£64.5bn	£56.8bn	£20.1bn
4°C GW	£487.6bn	£348.7bn	£8.5bn	£60.3bn	£70.1bn

Table 25: Split package costs, at scale, for each weather scenario

Weather Scenario	Pure	Extra	Complimentary	Existing
Current	71.04%	-	20.37%	8.59%
2°C GW	74.70%	11.54%	10.17%	3.59%
4°C GW	71.50%	1.75%	12.36%	14.38%

Table 26: Percentages of Pure, Extra, Complimentary, and Existing measures, within the at scale costs, for each weather scenario

5.5 Impact of overheating mitigations on operational energy consumption, carbon emissions and cost

Energy consumption

Whilst the main aim of this study was to assess the risk of overheating in UK homes and the impact of mitigation strategies on reducing it, it was considered important to assess the impact of overheating mitigation solutions on the buildings' overall energy consumption. This was estimated in the dynamic simulation modelling which assessed the increase or decrease in heating demand and energy consumption for each mitigation measure and package.

Several of the mitigations had knock on impacts on the heating energy demand as they reduced the solar heat gain during the heating season as well as the overheating period. Mitigation packages including the ceiling fan adds an additional electrical demand, and Package 5 introduces a cooling demand and related energy consumption to eliminate the risk of overheating.

For the sake of clarity, only the annual energy consumption of one archetype (mid-terrace) and one location (London) is shown in Figure 51, however, the trends discussed were similar across all representative buildings and the full results are given in Appendix E. It should be noted that the annual energy values are expressed in terms of demand and therefore do not account for the efficiency of the equipment fulfilling that demand.

The key findings were as below:

– There was a 20-25% reduction in heating demand between the poorly insulated and well insulated roof baselines. Insulating the roof was shown to be beneficial from an energy and overheating perspective and this was the driver behind including roof insulation in all mitigation packages if not already installed.

– Packages 1, 2, 3 and 5 all introduced the low g-value window film which caused a small 3-6% increase in heat demand compared to the insulated roof baseline. Package 4 changed the windows entirely to a very low g-value pane and caused a 12-14% increase in heating demand.

– Ceiling fans were introduced in packages 2, 3 and 4. The energy consumption resulting from these fans is proportional to their operational time which is linked to the room temperatures. Therefore, the ceiling fan energy consumption increases in the warmer weather scenario but decreases slightly as improved packages are applied.

– Active cooling demand remains a small proportion of the household energy demand in the current weather scenario. In the 2°C warming scenario the cooling demand rises significantly to be equal to the heating demand. Finally, in the 4°C weather scenario, the cooling demand becomes very large, far exceeding the energy demands required for heating and operation of the ceiling fan.

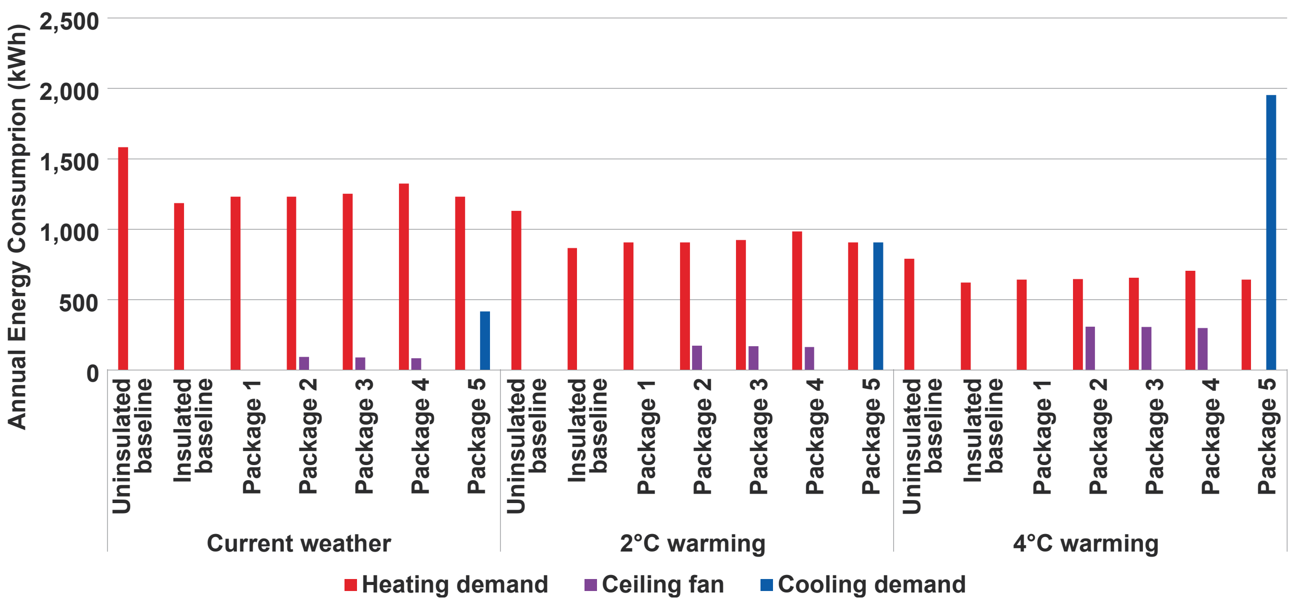

Figure 51: Annual energy demand of the London mid-terrace house for the insulated and uninsulated roof baselines and the 5 mitigation packages

Energy cost and operational carbon emissions

The change in annual operation energy demand would lead to changes on annual energy cost and carbon emissions. A high-level assessment of these was undertaken based on the assumptions in Table 27.

Two scenarios were considered, one where heating was provided through traditional gas-fired boilers – more realistic for current weather scenario – and one where it was generated through an Air Source Heat Pump (ASHP) – potentially more representative for future weather scenarios if zero carbon strategies are put in place. In reality, the housing stock will present a mix of solutions in each scenario, but the two scenarios can be interpreted as limits of a range in which the carbon and cost savings or increases would fall.

Figure 52 and Figure 53 present the effects that the mitigation packages produce on annual energy cost and carbon emissions on the mid-terrace house in London with a gas boiler, as an example.

The figures show that, when looking at the case studies assumed to have insulated roof as a baseline (violet in the graph), all mitigation packages produce an increase in energy cost compared to the baseline. This is due to the increased heating demand generated by the measures that reduce solar gains throughout the year, plus the additional energy for fan operation in Package 2-4 and active cooling in Package 5. When applied to the uninsulated roof baseline (red in the graph), a similar pattern between mitigations is evident, however the costs are lower due to the reduction in heat demand from the added roof insulation; also, Package 1 results in an overall cost saving in all three weather scenarios as well as Package 2 and 3 in the current.

Package 5 did not lead to large operational cost increases in the current or 2°C global warming weather scenario since the number of hours in which cooling is needed and the capacity needed to achieve comfort conditions are lower than in warmer conditions; however, the increment in cost under the 4°C GW scenario is considerable due to the increase in cooling demand.

Looking at carbon emissions (Figure 53), all mitigation packages produce an increase compared to the baseline when considering the insulated roof baseline. This is, again, due to the increase in heating demand related to the reduced solar gains. However, when looking at the uninsulated baseline, the inclusion of roof insulation in all packages produces a decrease in heating demand, more significant in the current weather scenario which involves lower temperatures throughout the year, including winter.

The difference in trend between cost and carbon emissions is due to the cost of gas being very low compared to electricity, while the two carbon factors being very close. This means that, when balancing energy reduction for heating (gas) with energy increase for ceiling fans and cooling (electricity), a smaller heating reduction can be sufficient to offset carbon emissions but not to offset the additional cost for electricity.

Item	Assumption	Source
Gas-boiler efficiency	91%	Minimum BR Part L requirements
ASHP CoP	2.4	Project experience
Active cooling SEER	3	Project experience
Electricity unit price	0.28 £/kWh	OFGEM Price Caps (OFGEM, 2022)
Gas unit price	0.07 £/kWh	OFGEM Price Caps (OFGEM, 2022)
Electricity carbon intensity factor	0.191 $kgCO_2e/kWh$	BEIS Conversion factors 2022 (BEIS, 2022)
Gas carbon intensity factor	0.183 $kgCO_2e/kWh$	BEIS Conversion factors 2022 (BEIS, 2022)

Table 27: Assumptions for the high-level operational cost and carbon assessment

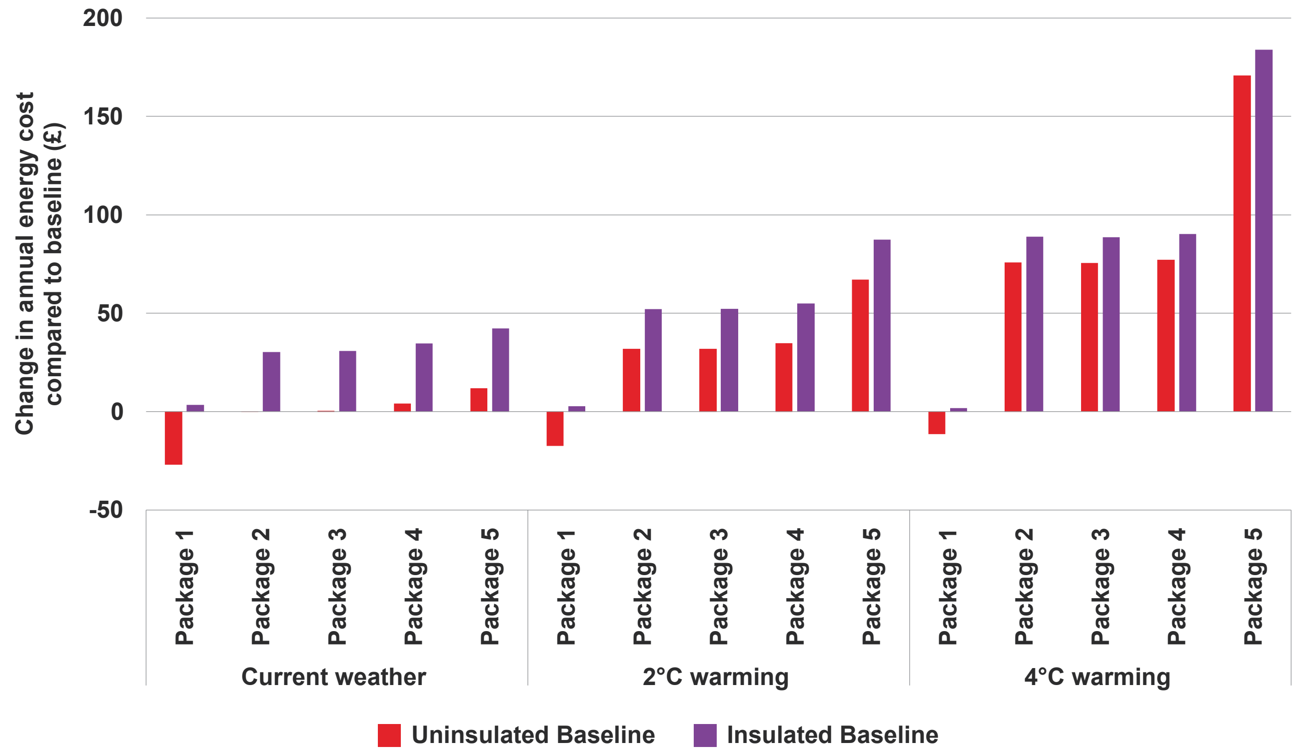

Figure 52: The effect on annual energy cost of mitigation packages applied to the mid-terrace house in London

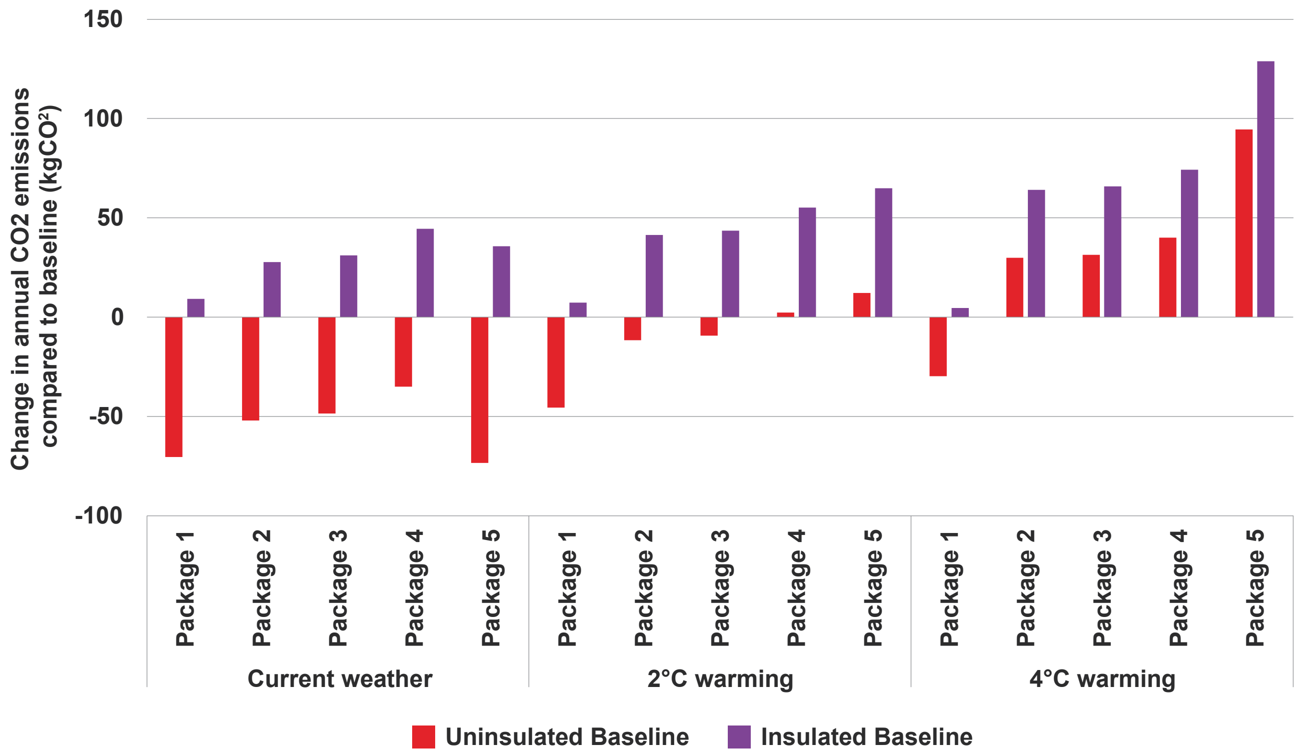

Figure 53: The effect on annual carbon emissions of mitigation packages applied to the mid-terrace house in London

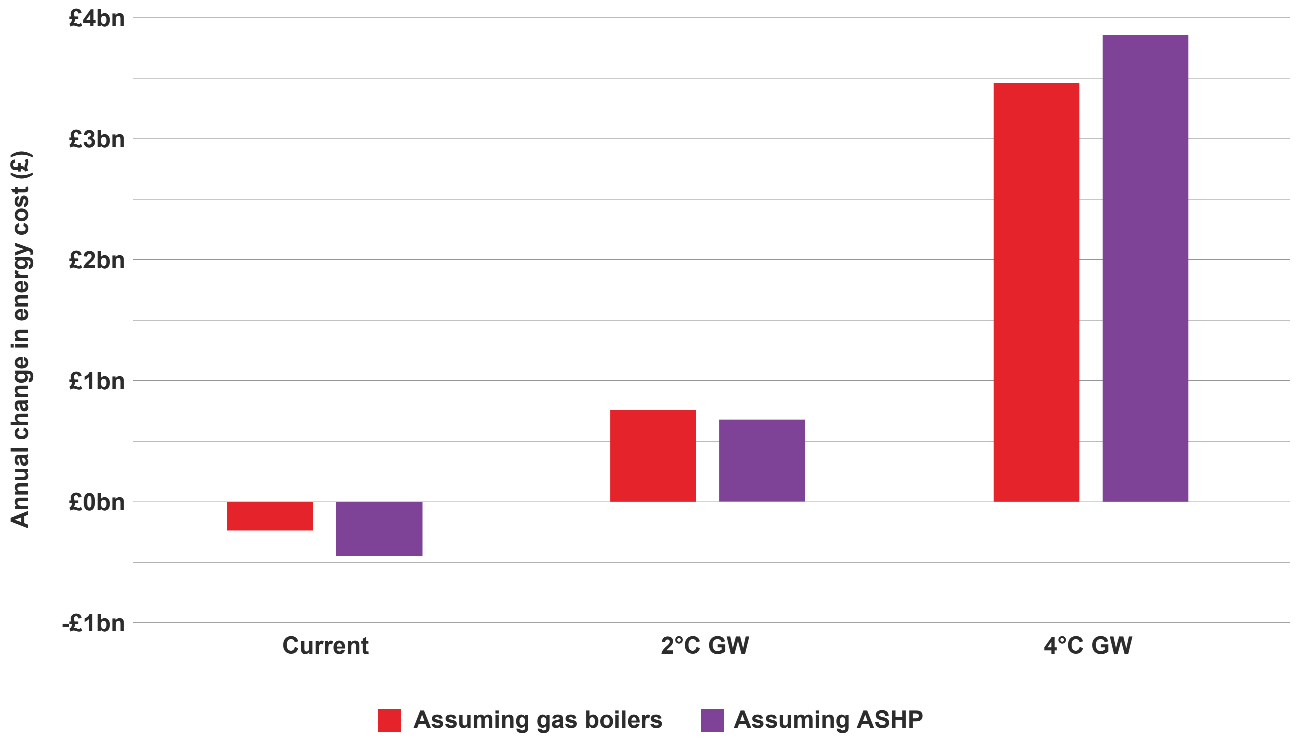

Figure 54: Changes in annual energy costs at UK stock level as a result of applied mitigation packages by weather scenario

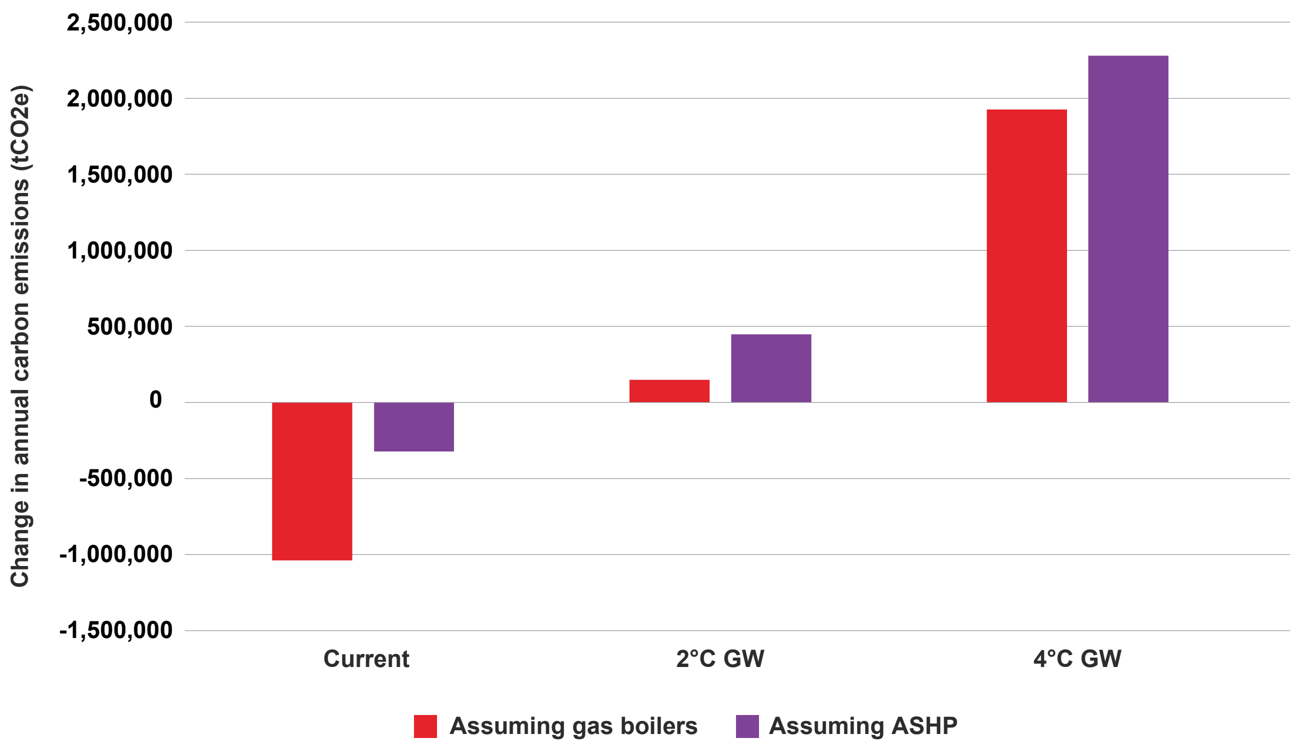

Figure 55: Changes in carbon emissions at UK stock level as a result of applied mitigation packages by weather scenario

Considerations at stock level

Figure 54 and Figure 55 show the estimated changes in annual energy cost and carbon emissions at UK stock level. In all cases, the energy consumption and carbon emissions are compared to the relevant baseline consumption in the same climate scenario. The following key points were observed:

- In the current weather scenario, the majority of homes required Package 1 or 2 to achieve comfort conditions under TM59 criteria, therefore the overall energy consumption is lower than in the stock baseline (and consequently both cost and carbon emissions are lower). In addition to this, many dwellings were upgraded to include additional roof insulation which saved significant amounts of energy and carbon emissions for heating.
- In the 2°C GW scenario, the vast majority of homes would require a package between 2 and 5 to mitigate the overheating risk, which – as explained in the previous section – generate an overall increase in energy demand under this weather scenario. In these cases, a high proportion of dwellings require ceiling fans or active cooling which resulted in an increase electricity consumption, higher than the energyin savings related to insulating many of the roofs.
- In the 4°C GW scenario, similar conditions apply, with an even higher number of dwellings requiring active cooling; and the scale of that active cooling demand was increased. This leads to the largest increase in energy cost and emissions.
- Cost and carbon emission estimates have been made assuming two different heating sources: a gas boiler and an ASHP. This aimed to produce a like for like comparison where the change in cost or emissions is relative to a baseline scenario with same heating technology installed and no mitigations applied. For example, Figure 54 shows the change in annual energy costs at a stock level. In the 2°C climate scenario when assuming all homes have gas boilers, the annual energy costs increase by £0.75bn when the mitigation packages are applied compared to a baseline scenario with no mitigation packages and the same heating technology.
- Looking at the differences between the gas-fired boiler scenario (in red) and the ASHP scenario (in violet), Figure 55 shows a larger relative increase in carbon emissions when assuming ASHP throughout the building stock. This is not suggesting greater overall emissions when assuming ASHP, just a greater relative change when overheating mitigations are applied. This may seem counter-intuitive but is explained by the fact that the emissions from heating demand are lower in the ASHP baseline with no overheating mitigations. Therefore, the emission reduction when applying roof insulation is relatively less compared to the gas boiler assumption. The increases in electrical consumption from ceiling fans and cooling is the same for both gas boiler and ASHP assumptions.
- In reality, the housing stock will remain split between predominantly gas boiler and ASHP for many years. Therefore, the cost and emissions impact of applying the mitigations under the different climate scenarios would fall between the red and violet bars in each climate scenario.

A whole-life-cycle (WLC) cost and carbon analysis was not included in the scope of this report as it would involve a substantial number of assumptions which would, anyway, lead to unreliable results. However, the qualitative considerations expressed in this section give an understanding of the importance of looking at the whole life cycle of a building to define what the most energy, cost and carbon-effective solutions are to achieve optimal designs.

5.6 Additional impacts not quantified in this study

The variation in operational energy, and consequent cost and carbon emissions, is only one of the aspects that should, when retrofitting real buildings, influence the selection of the optimal retrofit strategy overall.

Other factors that should be considered (but were not in the scope of this study) are:

– Embodied carbon and whole life carbon savings generated: each retrofit measure will generate so called 'embodied carbon emissions', namely emissions related to the construction, installation, maintenance and end-of-life of the element. The savings in carbon emissions generated in operation thanks to reduction in energy consumption and the additional embodied carbon should be estimated for the whole life cycle of the element to assess whether the intervention is worthwhile. Additionally, some measures may produce similar operational savings but have very different embodied carbon (and additional environmental impacts) which should be considered when selecting a strategy; for example, active cooling systems typically involve the use of refrigerant which is associated to very high embodied carbon.

– Environmental impacts and contribution on global warming: refrigerants, if leaking, can also have devastating impacts on the environment and contribute to the global warming and are, in fact, categorised based on their Global Warming Potential (GWP). If active cooling is installed, low GWP refrigerants should be selected to minimise the related environmental impacts.

– Additionally, the installation of active cooling can impact the local microclimate and increase the risk for overheating. In fact, the heat rejection from cooling systems, especially if installed on multiple buildings in a densely built area, can produce an increase in the local air temperature which would make the challenge of reducing the indoor overheating progressively more challenging, with consequent reduction in the system efficiencies and increase in the energy consumption to deliver comfort conditions.

Section 6

Conclusions

This section summarises the key findings and recommendations.

6.1 Summary of results

This section summarises the key findings from each task within the study.

Task 1

- In the current weather, the majority of representative buildings failed the bedroom overheating criterion, representing around 55% of the UK housing stock (15.7 million homes). The remaining 45% of dwellings (circa 12.6 million) do not require any mitigation packages as they pass both overheating risk criteria for living areas and bedrooms.
- In the 2°C GW scenario, none of the representative buildings outside Scotland passed the overheating risk assessment as they all failed the bedroom criterion. Several archetypes, mainly in London, also failed in the living areas. Across the entire UK housing stock, 2.4 million dwellings (around 8%) would not require intervention, 21.1 million dwellings failed only the bedroom criterion (roughly 75%) and 4.8 million dwellings failed both criteria (the remaining 17%).
- In the 4°C GW scenario, all dwellings will need some type of intervention to mitigate against overheating and almost all selected representative buildings showed an extreme failure of the bedroom criterion, an order of magnitude above the determined acceptable level of overheating. At the UK scale, 4.8 million dwellings failed the bedroom criterion only (17%) and 23.5 million dwellings failed both criteria (83%).
- Under the current weather conditions, half of the UK homes suffer from overheating risk, based on TM59 criteria. The risk is particularly high in the south of England, with London being the hottest spot in the country, and a moderate problem is present in the Midlands and Wales under current weather conditions. Northern England, Northern Ireland and Scotland currently face a limited risk.
- Around 90% of the existing homes will overheat under a 2°C GW scenario and the totality of the UK will face overheating risks in a 4°C GW scenarios.
- Smaller houses and flats are generally at more risk of overheating than larger homes.
- Smaller bedrooms and loft rooms are more prone to overheating than other rooms, particularly where loft insulation is not present.
- Even under current weather conditions, a majority of homes did not pass TM59 Criterion B (night-time bedroom comfort).
- The impact of insulation on overheating risk is very dependent on other correlated factors; while roof insulation produced a reduction in overheating risk in the majority of modelled cases, the insulation of walls can produce variable effects. Particularly, additional wall insulation would increase the overheating risk in homes with limited windows openability where natural ventilation was not effective in expelling heat gains from the space and the insulation would contribute to trapping the heat inside; on the other hand, in cases where enough ventilation was provided and especially where cross ventilation was present, the addition of wall insulation was beneficial and contributed to further reducing overheating risk by reducing the heat gains through the walls. This shows that measures undertaken to improve homes' energy efficiency can produce undesirable effects on overheating performance, if not properly designed and calibrated on the specific characteristics of the building.

Task 2

– The pattern of which mitigation measure is most effective is consistent across each climate scenario. However, as expected, the percentage reduction in both overheating criteria broadly decreases as warmer weather scenarios are applied.

– In general, measures that reduce solar gain into homes, such as shading and low g-value, are more impactful in flats than houses due to the higher ratio between window area and internal volume.

– Measures that increase the solar reflectivity of walls and roofs were found to be more effective on houses than flats due to the larger ratio between the surface area they would be applied onto versus internal volume.

– In living spaces, shading devices tend to be most effective in reducing overheating risk. Of these measures, external shutters have the highest impact since they stop the solar radiation from entering the building, followed by blinds and internal shutters. The effectiveness of shading measures is much lower for mitigating night-time overheating in bedrooms on which solar gains have a very limited impact.

– Low g-value glazing is effective at reducing overheating in both living rooms and bedrooms. The low g-value window film is much less effective for both criteria than a full window replacement but is much cheaper and less disruptive to install.

– Increasing the openable area of windows for natural ventilation has the greatest benefit on improving night-time ventilation in bedrooms. The ability to achieve a larger exchange of air was effective at reducing night-time bedroom temperatures.

– Ceiling fans are an effective mitigation measure and have a reasonably low installation cost. They don't reduce space temperatures but the increased air speed they create provides improved comfort. Their use results in some increased electricity costs.

– Some mitigation measures will be limited by regulations on fire safety; for example, some external shading measures may not be appropriate for taller buildings. Others may be restricted by external noise and pollution or security issues, such as windows openability, or by specific configurations of the existing buildings, for example external louvres could not be installed on windows opening outwards.

– Many of the measures considered in this study are common in warmer climates already and are often part of the fabric of homes. This is not the case in the UK which has had a cooler climate historically and where some measures could encounter cultural challenges in relation to the need of a change in the appearance of homes and occupants' behaviour.

– Costs of implementation of each measure vary by type of home they are applied to. In general, costs are higher for flats than they are for houses and this is generally because more expensive means of access are required to external areas of the home.

– Some shared costs could be reduced by implementing multiple mitigation solutions on the same construction element at the same time such as a lower g-values and increased openable area when replacing windows. This could ease the cost impact of the works packages as some of the builder's work and costs would be accounted for once and shared across measures, therefore having a lower impact on the cost of the single mitigation measure.

– Some combinations of measures may be carried out at the same time to share access costs, for example shared scaffolding with concurrent external works not related to overheating mitigation would reduce the impact of scaffolding on the single mitigation cost.

– The cost of some overheating measures can be shared with those that also improve energy efficiency; these include the costs to replace windows with improved performance, the costs to install curtains (thermal insulation), the costs to insulate the external walls and roof. There will therefore be overlap between overheating mitigation costs and costs for energy efficiency upgrades.

– The costs for works have been considered to be carried out and procured on one single dwelling in isolation. However, it is right to assume there might be savings when procuring packages of work for multiple dwellings, e.g. a block of flats or rows of houses, or grouping works to similar areas of the building.

Task 3

– Under current weather conditions, Package 1 can eliminate extreme overheating entirely and severe overheating is only evident within flats in London. Half of the representative buildings passed Criterion B when Package 1 was applied, meaning no further mitigation measures would be needed. Package 2 eliminates all severe overheating – only the flat archetypes in London have residual moderate overheating. When Package 2 is applied, all buildings outside London pass overheating criteria. Package 3 eliminates the overheating from the older flat archetype in London but only reduces overheating in the newer flat type. With Package 4 applied, the new flat archetype located in London still marginally fails but it is close enough to the acceptable threshold not to apply further measures. Some modern flats in London would need Package 5 to completely eliminate overheating risk based on TM59 criteria. This corresponds to approximately 5% of the UK building stock.

– In the 2°C GW scenario, all representative building archetypes pass Criterion A when Package 1 measures are applied; Criterion B failures are also reduced but not significantly. Package 2 delivers a significant improvement in overheating risk; extreme overheating is eliminated for all but London flat archetypes and other areas see significant improvements. Package 3 improved outcomes for houses, particularly the detached and semi-detached; no major improvement was seen on flats. Package 4 solves the majority of the overheating challenges in the South of England, however the modern flat and mid-terrace archetypes still see a significant risk. Active cooling measures are required to cope with overheating in approximately 22% of the UK housing stock.

– In the 4°C GW scenario, the application of Package 1 measures is effective for Criterion A compliance for all houses but had limited impact on reducing bedroom overheating with most representative buildings showing an extreme fail for Criterion B. Package 2 measures eliminate almost all Criterion A failures. In all locations outside London, these package measures also significantly improved Criterion B outcomes. Package 3 produced limited benefits above Package 2 with some small improvements in Criterion B compliance. Package 4 shows improvements across Midlands geographies, but southern regions still report severe night-time overheating. Active cooling measures are required under this scenario for almost all archetypes outside of Scotland to fully comply with CIBSE TM59 criteria.

– In the current climate scenario, the cost for upgrading all homes in the UK requiring some form of mitigation to meet TM59 criteria is circa £250 billion. Around £180 billion of this figure are 'pure' overheating mitigation measures only.

– Under the current climate scenario, the average capital cost per home is around £15,000 of which around £11,000 is for pure mitigation measures, e.g. not extra over/uplift costs or costs for complimentary measures.

– Significantly more investment is required in the 2°C and 4°C GW scenarios compared to the current weather conditions, circa £559 billion and £488 billion respectively. The 'pure' mitigation costs associated with the packages costs for these scenarios are circa £415 billion and £340 billion respectively.

– Under these warming scenarios, the total capital costs per household are around £22,000 for the 2°C GW scenario and £17,000 for the 4°C GW scenario. Of these totals, around £16,000 and £12,000 are for purely mitigation measures respectively.

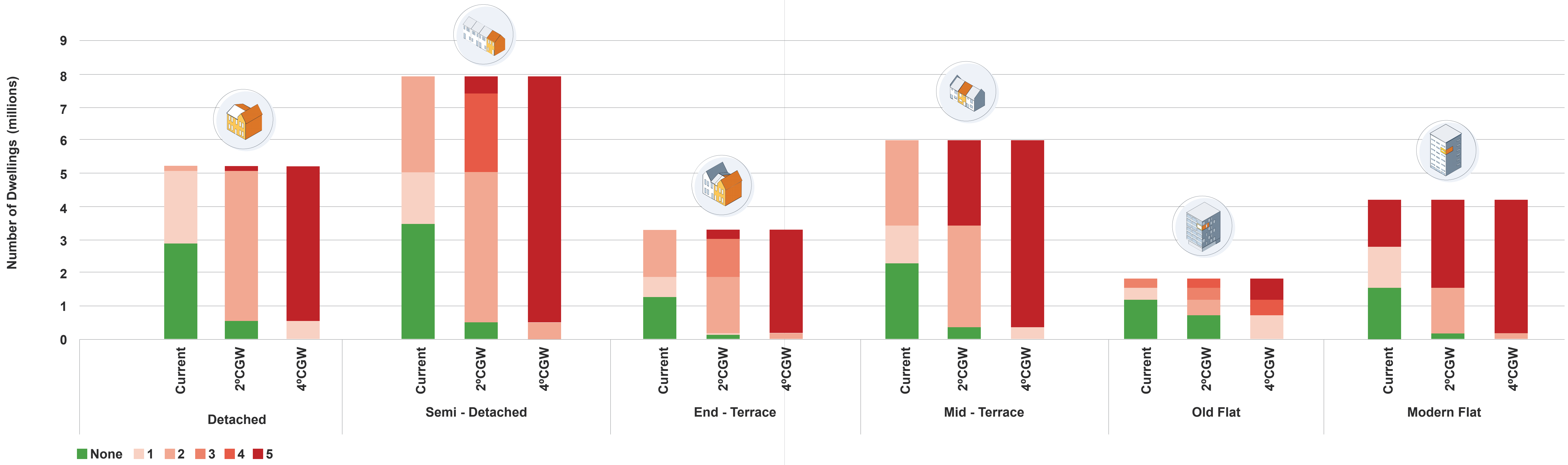

Figure 56: Distribution of mitigation packages by archetype

– In the warmest scenario, even the most effective (but expensive to install) passive measures are unable to fully mitigate overheating risk in the majority of dwellings, therefore active cooling (cheaper to install) is needed in a greater proportion of dwellings, and the capital cost for reducing overheating risk under TM59 thresholds becomes lower because passive packages are applied to a smaller proportion of the housing stock.

– However, it should be noted that the installation of active cooling would produce a large increase in electrical demand and operational energy cost, which would weigh on the occupants' energy bills. This was estimated to be around £200 per year for a typical house in a 4°C GW weather (considering a setpoint of 26°C) which equates to about £10,000 over a house's 50-year lifetime. This was based on current energy prices, but with rising energy costs the annual expense – and the cost over a home's lifetime – could quickly escalate.

– The estimated capital cost at scale are high but it should be acknowledged that these would likely be carried out over a long time given the extremely high number of houses under consideration in this analysis. Depending on the warming scenario, a programme of 30 years would mean works to around 800,000 homes on average every year.

– The study confirmed that all the mitigation packages increase energy consumption for homes to some extent and this needs to be considered alongside the capital expenditure required. The most significant impact is where active cooling is applied. While active cooling provides comfortable conditions, under a 4°C GW scenario applying this at scale would result in an additional £4 billion of energy costs per year across the housing stock relative to a 'no-intervention' baselines, and an additional 2 million tonnes of carbon emissions annually from operational energy alone. Active cooling systems would also have a greater impact on embodied carbon than passive measures.

– One sensitivity analysis conducted in this study looked at what impact behavioural change could have on overheating risk. Throughout the main study, the occupants were assumed to behave identically to allow meaningful comparison between individual simulations, mostly based on TM59 settings; however, informed occupants could take positive actions to limit the effect of overheating within their homes. This sensitivity test aimed to simulate the actions of the 'perfect occupant', purely focussed on minimising summer overheating. Behavioural change simulated included how users control window openings and how blinds/curtains are deployed in an optimal way.

– The study showed that the behaviour of a more informed (almost 'perfect') occupant can have a significant reduction in overheating risk. This was particularly pronounced in the old flat archetype where the 'perfect user' operation only experienced around 38% of the bedroom night-time overheating hours compared to the original simulation, whereas the detached house experienced around 67% of the overheating hours compared to the original simulation. Assuming windows can be opened securely, this reduction in overheating is achieved without any additional capital expenditure or physical alterations to the property, meaning that improving how people open and close windows can have a significant improvement in overheating mitigation.

– The study was not able to quantify how air quality, noise, security concerns or urban greening could impact overheating results. Both noise and air quality in urban areas are factors which can limit the effectiveness of passive mitigation strategies, but data is not available at scale to determine what impact this may have in quantitative terms. Similarly, studies show that measures such as 'cool roofs' and green spaces within cities can provide local benefits to the microclimate that would positively influence overheating risk by reducing the local air temperature, but these are hard to quantify as well.

6.2 Key recommendations

The study suggests that a lot of retrofit works are required across the housing stock to mitigate the risk of overheating up to a 4°C global warming scenario which, this study shows, presents real challenges for the UK housing stock. Mitigation packages for global warming scenarios come with a high cost, and simple capacity limits within the construction industry mean it is not feasible to carry out this volume of building upgrades to all dwellings, all at once. This section provides some general next steps and recommendation measures that are considered appropriate to help to reduce the global warming risk and in turn reduce the overheating risk on the basis of the outcomes of this study.

Policy Makers

– The study showed that typical energy saving measures such as improved insulation are mutually beneficial in mitigating overheating if the home has good natural ventilation. However, these may produce a negative impact on overheating risk where ventilation is restricted or not sufficient. It is key that retrofit strategies and policies promote a holistic approach to improving dwellings' performance throughout the whole year to limit these countereffects.

– The study demonstrates that deployment of blinds, curtains and the opening/closing of windows at the right time of day can be important in mitigating overheating effectively. Investing in public information campaigns which encourage behavioural change on how to operate windows and curtains/ blinds would prevent the need for immediate high capital cost changes.

– Higher temperatures are commonplace in warmer climates and a large majority of people generally find this acceptable without the need for active cooling. Regulations should be introduced to govern the installation and use of domestic air conditioning, ensuring that passive measures are prioritised and energy consumption for cooling is limited.

– There are questions around the definition of overheating given the challenges presented by climate change. CIBSE TM59 is a stringent assessment method and the results show that the principal reason homes fail in current and future scenarios to fully meet TM59 criteria is because they do not pass the Criterion B which governs night-time bedroom overheating. Ongoing academic research (Lomas, et al., 2021) shows concerns in relation to the lack of experimental evidence to support Criterion B and suggests a need to validate it with further experimentation. Investing in academic studies which look at night-time bedroom comfort would be a sensible next step. Further research leading to a revised night-time comfort criterion could show a lower risk of overheating for bedrooms and therefore a lower number of dwellings at high risk, which could result in a smaller financial investment across the UK housing stock than this study suggests.

Urban Planners

– Importance should be given to measures which limit and reduce the impact of the built environment on global warming and overheating risk. Planners should demand for more greenery and cool roofs and set lower limits for noise and pollution to create suitable conditions for windows to be opened and natural ventilation to be maximised.

– Some of the measures within the passive packages will impact on the visual appearance of homes. The nature of the changes and the regulations that might govern their implementation are beyond the scope of this study but are important considerations.

Building Designers

– Designers are encouraged to look to countries where warmer temperatures are commonplace and incorporate passive design solutions which are widely deployed in these areas and prove to be effective in the UK. Whilst some measures such as external shutters may change the look of the UK housing stock, design variations can be explored to fit the UK market and new trends can be established that can benefit buildings' performance.

– Project teams should be upskilled to understand which building factors affect overheating. Even when dynamic thermal modelling packages cannot be used, general concepts should be adopted such as external solar shading devices and windows with larger openable areas.

– Designers must maximise the potential for natural ventilation as this is key to reducing overheating and cooling down the building mass.

– Overheating mitigation should be included in holistic retrofit strategies that considers heating and cooling performance at once so that optimal solutions can be identified to maximise comfort and minimise energy consumption overall throughout the year.

– Designers should provide occupants with information on how to best operate buildings to maximise performance; an output of the design process should be a building operation manual which explains how building features can be used to reduce overheating on hot days.

End Users / Occupants

– Landlords and homeowners should be aware of possible interventions which they could incorporate and integrate when undertaking home improvements.

– Occupants should become aware of the ideal behaviours which help to reduce overheating, i.e., correctly controlling windows and shading, and of the benefits that these behaviours can produce in improving their indoor comfort and reducing energy bills for cooling.

Glossary

ASC	Adaptation Sub-committee
ASHP	Air Source Heat Pump
BCIS	Building Cost Information Service
BEIS	Department for Business, Energy & Industrial Strategy
BR	Building Regulations
CCC	Climate Change Committee
CIBSE	Chartered Institution of Building Services Engineers
CoP	Coefficient of Performance
DSY	Design Summer Year
EFUS	Energy Follow-up Survey
EHS	English Housing Survey
GIFA	Gross Internal Floor Area
G-value	Solar transmittance through translucent and transparent materials such as glass
GW	Global Warming
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
LETI	London Energy Transformation Initiative
OFGEM	Office of Gas and Electricity Markets
RCPs	Representative Concentration Pathways
RDSAP	Reduced data Standard Assessment Procedure
SDG	Sustainable Development Goals
SEER	Seasonal Energy Efficiency Ratio
Set point	Temperature at which a room's thermostat is set to in order achieve comfort
SRES	Special Report Emission Scenarios
TM	Technical Memorandum
TRY	Test Reference Year
U-value	Thermal transmittance of a structure
WLC	Whole Life Cycle

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Credits

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Appendices

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Appendix A: Sensitivity analyses

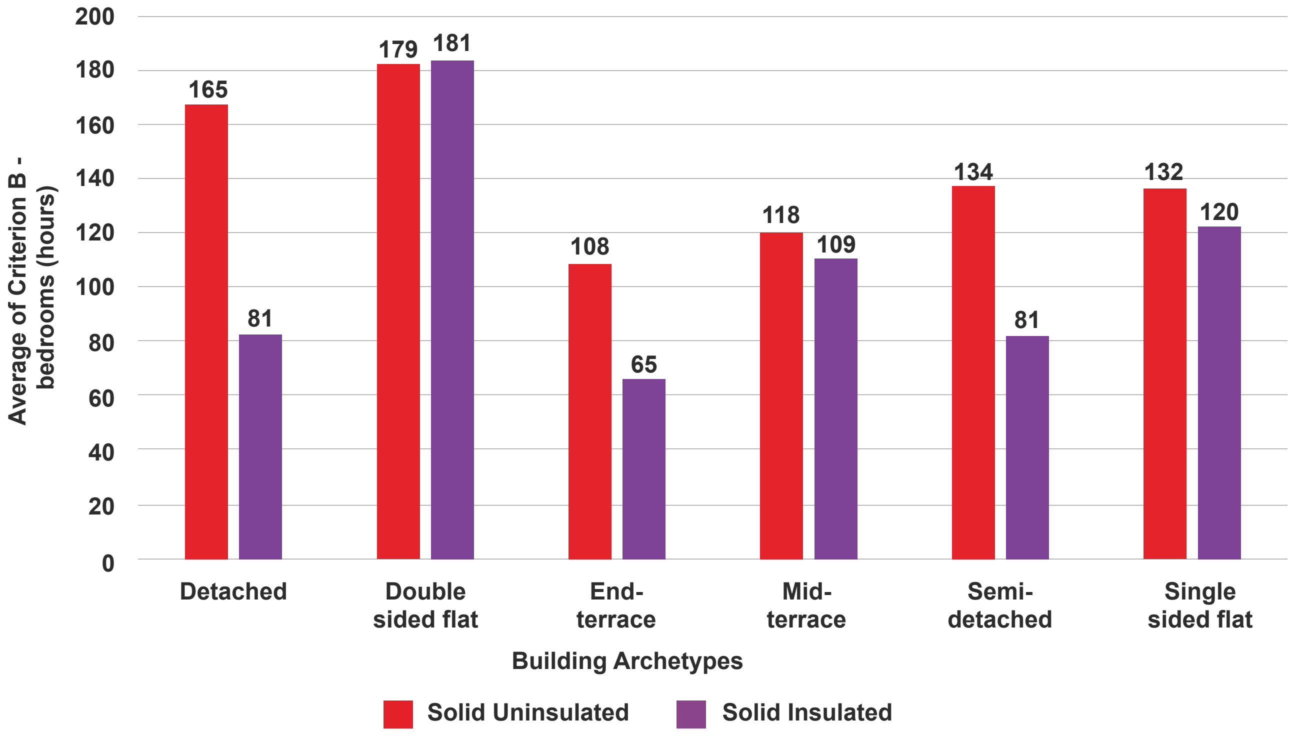
Several sensitivity analyses have been conducted to understand the impact of solid insulation wall on overheating risk in homes.

Impact of insulation in London vs Manchester

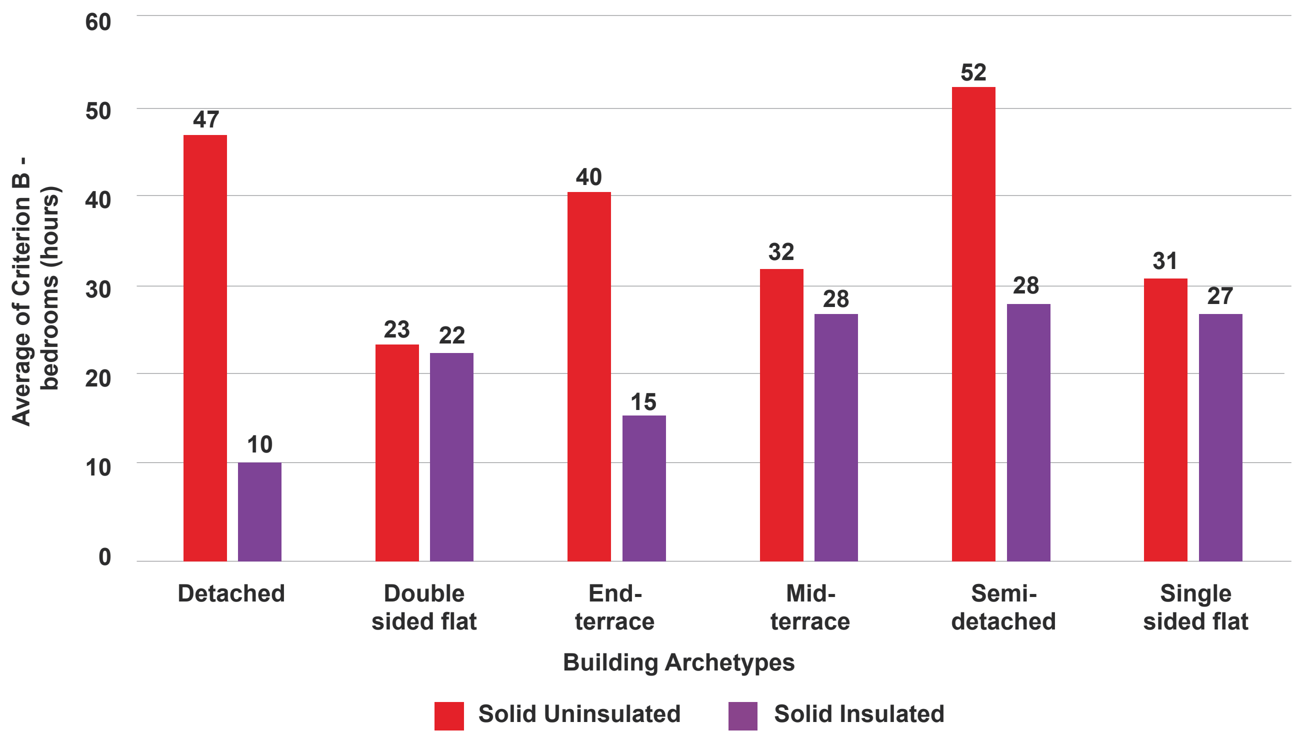
The insulation of solid wall is more effective in Manchester than in London as shown below.

This is explained by the higher solar gains in London region compared to Manchester.

Due to insulation and air tightness of the wall, once the solar radiation penetrates the buildings and without a proper ventilation, it adds up to internal gains and increases the risk of overheating.



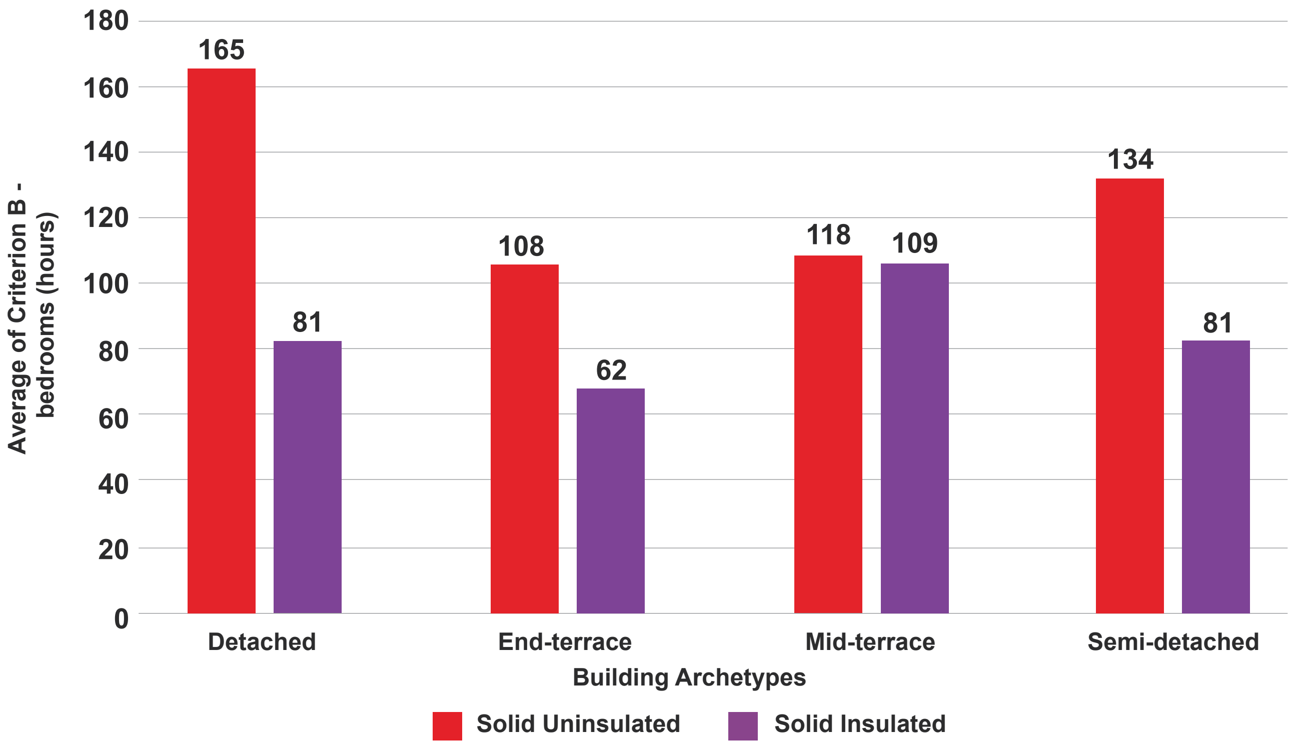
Criterion B results for insulated vs uninsulated walls - London



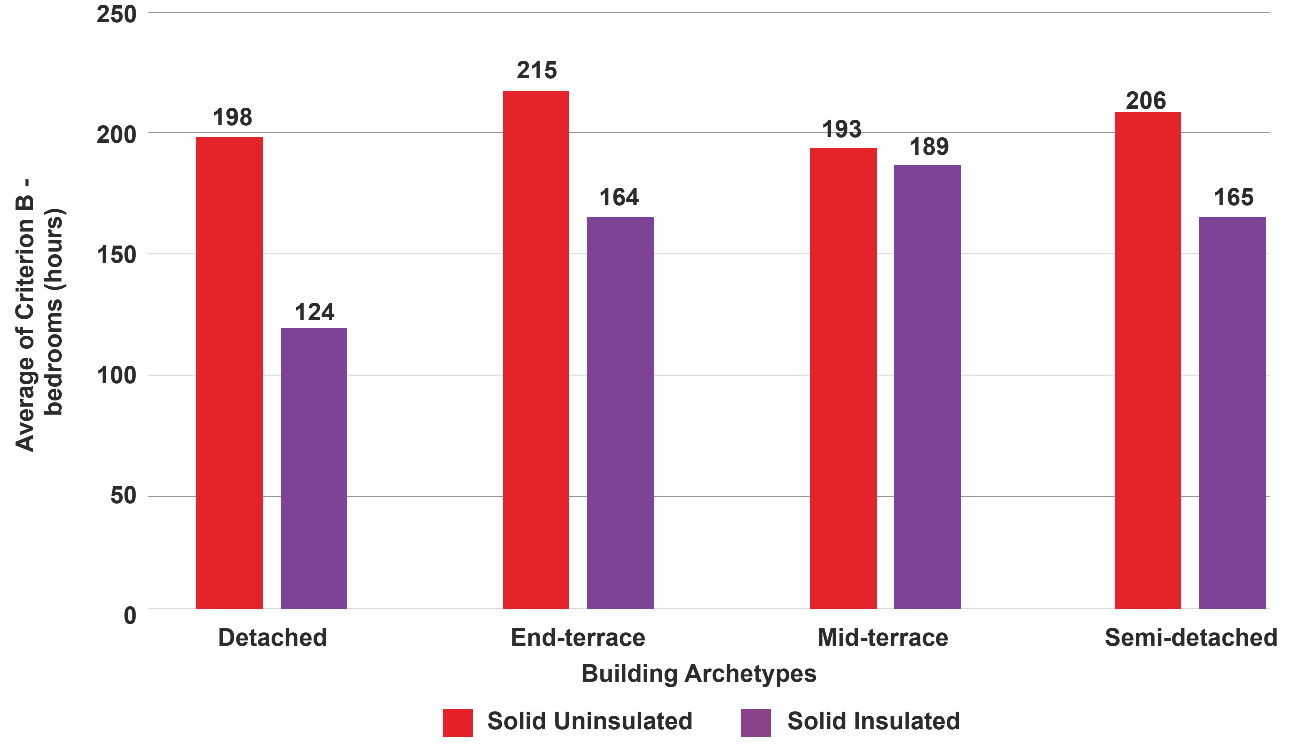
Criterion B results for insulated vs uninsulated walls - Manchester

Impact of insulation coupled to roof insulation

The solid wall insulation, when coupled with roof insulation performs better in mitigating overheating risk as shown below.



Criterion B results for insulated vs uninsulated walls – with insulated roof (London)



Criterion B results for insulated vs uninsulated walls – with uninsulated roof (London)

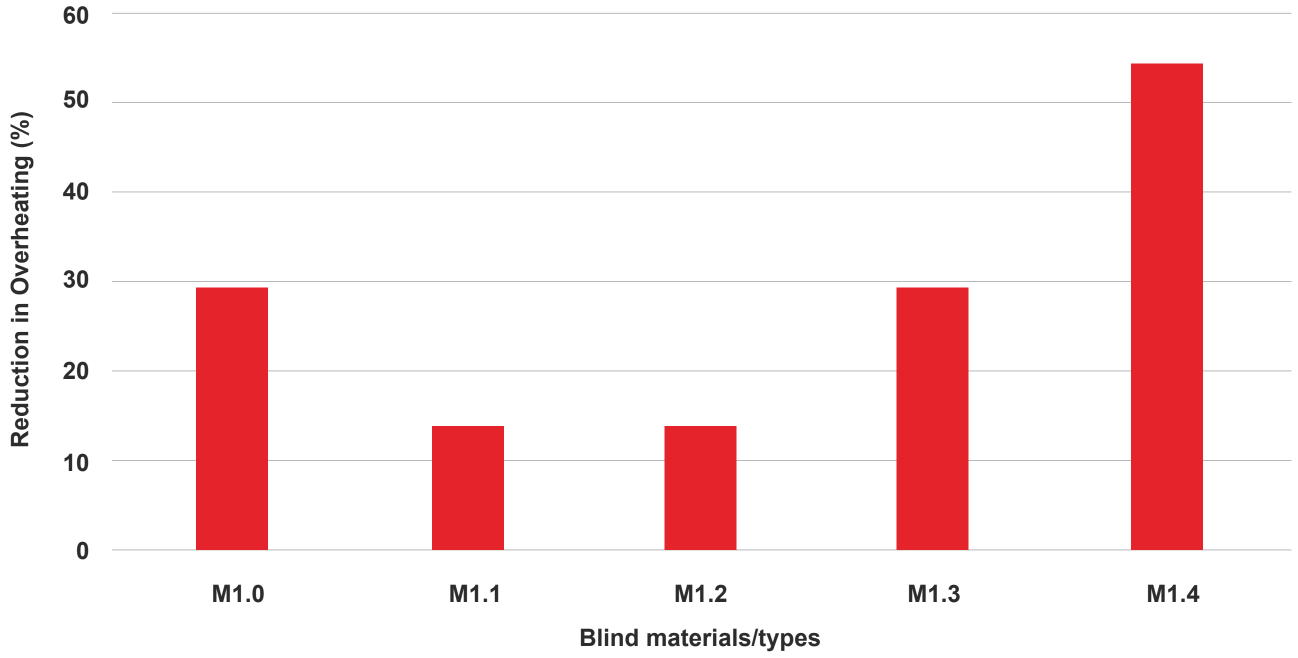
Internal blind material and operation

Blind material

A sensitivity analysis was conducted to quantify the impact of different materials and control methods of blinds in reducing overheating. The table below summarises the blind types and material properties considered in this sensitivity analysis. As shown in the graph below a roller shade blind with a high solar reflectance factor of 0.64 has the best performance in terms of reducing overheating. However, this is a very good quality roller blind that would probably not be accessible for everyone. Therefore, the shade roller – medium opaque type with a solar reflectance of 0.35 been chosen to be proposed in the mitigation packages.

After selecting the medium opaque shade roller blind, different control methods been tested such as temperature, solar, schedules etc., to study their impact on reducing overheating. The control method selected for the modelling of the mitigation packages is a solar setpoint.

Code	Type	Source	Control type	Solar reflectance
M1.0	Slatted blinds with high reflectivity slats	Designbuilder Library	Inside air T > 24	0.8
M1.1	Slatted blinds with low reflectivity slats	Designbuilder Library	Inside air T> 24	0.2
M1.2	Venetian blinds	Designbuilder Library	Inside air T>24	0.12
M1.3	Shade roller – medium opaque	Designbuilder Library	Inside air T>24	0.35
M1.4	Shade roller – LUXAFLEX	Arup – Façade team	Inside air T>24	0.64



Reduction in Criterion A overheating for different blind types

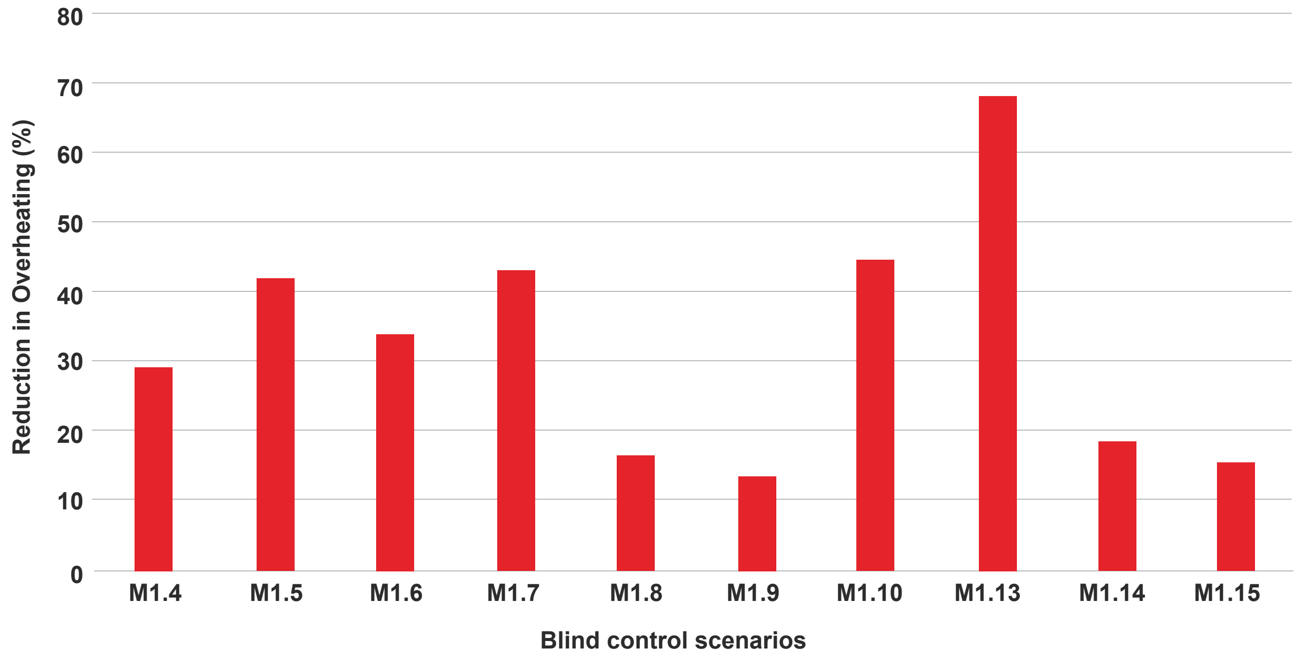
Blind controls

The following operation controls of blinds and shutters was tested in the modelling phase. This helped us to select the most suitable one for the modelling of the packages:

The most effective one seems to be the solar radiation setpoint of 100 W/m^2, however this translates into closing blinds and shutters during the whole day, which is not realistic.

After consultation with research experts in this field, a solar setpoint of 200 W/m^2 is more representative of the time when the occupant feels the need to close the blinds or shutters.

Code	Type	Source	Control type	Solar reflectance
M1.4	Shade roller – medium opaque	Arup – Façade team	Inside air T>24	0.35
M1.5	Shade roller – medium opaque	Arup – Façade team	Inside air T>22	0.35
M1.6	Shade roller – medium opaque	Arup – Façade team	Solar radiation setpoint = 120 W/m^2	0.35
M1.7	Shade roller – medium opaque	Arup – Façade team	Occupancy schedule	0.35
M1.8	Shade roller – medium opaque	Arup – Façade team	Custom schedule - shading in summer between 12 and 6PM	0.35
M1.9	Shade roller – medium opaque	Arup – Façade team	Custom schedule - shading in summer between 2 and 4 PM	0.35
M1.10	Shade roller – medium opaque	Arup – Façade team	Solar setpoint = 120 + summer	0.35
M1.13	Shade roller – medium opaque	Arup – Façade team	Solar setpoint =100 +summer schedule	0.35
M1.14	Shade roller – medium opaque	DesignBuilder Library	Solar setpoint = 150 + summer schedule	0.35
M1.15	Shade roller – medium opaque	DesignBuilder Library	Solar setpoint =200* +summer schedule	0.35



Reduction in Criterion A overheating for different control types

Appendix B: Basis of cost assessment

General assumptions

The following assumptions have been allowed for within this cost estimate:

1. All costings are for individual works (mitigations) to be set up, carried out, and completed on each Archetype without any discount for concurrent works.
2. Costs for each Archetype follow the specific requirements in the Mitigations Table provided by Arup Engineers and apply those to the Archetype dimensions specifically.
3. There is no requirement for any extraordinary site investigations.
4. The contractor's preliminaries reflect a single-phase programme for each mitigation, and unrestricted working.
5. The contractor's overheads and profit is based on the likely cost of the main contractor's head office setup, administration proportioned to each contract and reasonable profit.
6. If necessary, any relocation or decant of personnel from the surrounding work areas will be funded and facilitated separately and is not allowed for in these costs.
7. A professional fees allowance of 10% has been included to allow for design development by contractors.
8. The availability, capacity, condition and location of existing services are reasonable to facilitate the contract works to be undertaken.
9. Allowance has been made within estimates for some builder's work in connection with services, such as forming holes, pipe sleeves, fire resistant stopping and making good.
10. The estimates make no provision for structural alterations where mitigations may or may not require strength reinforcement; we have been advised to assume no structural work.
11. A small allowance has been made for delivery of items to site where this is deemed appropriate.
12. It should be noted that no contractors have been involved in the preparation of these theoretical mitigations, and benchmarks include those from social housing sources which have a potentially different procurement cost and profile, therefore assumptions and reasonable cost alterations have been made.
13. Due to the level of design information available at the time of preparing this report, these costs should be considered with a tolerance of +/- 50%.
14. All costs are in GBP (£) and the estimate base date is 2Q 2022.
15. Costs and rates have been obtained from industry price books, previous project information, historic market information and professional experience and judgement.
16. The estimates allow for testing and commissioning of mechanical and electrical services, for items such as: testing equipment and consumables, calibration, site installation tests, static and performance testing including records, commissioning including preliminary checks, and the like.
17. VAT is excluded in all mitigations currently.
18. The costs contained within this report should be considered indicative only and be used as a guide for future discussions surrounding the design development of these elements in relation to mitigating Thermal Overheating. These costs should not be used during procurement or tendering activities or to determine project or business commercial targets.
19. General exclusions
20. No allowance for tender or construction inflation.
21. Specific risk items may be associated with the design changes.
22. Utility upgrades, except for those specifically stated in the mitigation itself. All other infrastructure is assumed to support the mitigation without need for general upgrade such as spare ways on the distribution boards, sufficient power delivery to the property to power the mitigations, etc.
23. Allowances for abnormal site surveys / investigations.
24. Allowances for Other Development / Project Costs.
25. Allowances for general or special planning conditions, if required.
26. Any attempt to estimate the client's procurement and tendering methods.
27. Costs for decanting residents for any reason associated with the delivery of the project works.
28. No contamination / remediation strategy or assumptions have been made by the engineers at the time of producing this order of cost estimate, no allowance has been included for the removal and disposal of asbestos contaminated materials / substances.
29. Site specific limitations arising from listed building status, or other statutory building requirements.
30. Any archaeological investigations, wildlife mitigation measures and other extraordinary site investigation works, and the like.
31. Allowances for physical restrictions or limitations in accessing site; for example access to rear windows where no rear access etc.
32. Allowances for work outside normal working hours; premium time working/ out of hours working are assumed to not be required.

Intervention-specific assumptions

	Name	Detail/assumption
Intervention 1	Install Blinds	Cost to supply and install internal roller blinds, installed internally. Applied to all windows. Assume grey blackout blind with safety features included.
Intervention 2	Install Curtains	Cost to supply and install pair of drape curtains installed on a metal rod. Applied to all vertical bedroom and living room windows only. Standard size. Note: fewer windows achieve this intervention than with blinds as no curtain on skylights and in the non-living spaces. Also not installed in skylights.
Intervention 3	Install Fixed Shading (overhang - horizontal south, vertical east/west)	Cost to supply and install motorised awning above patio/ balcony doors. Fixed overhang above all living room and bedroom windows facing south Assume motorised awning is remote controlled and electrically powered with wind sensors. Fixed overhang assumed to be 'lead look' graphite grey, 0.595m projection, with 0.25m overhang at either end of the window. Also cost to supply and install vertically mounted sliding ladder panel (sliding behind window) for all living and bedroom windows facing east and west. Assume similar to aluminium shutter on a sliding rail.
Intervention 4	Install External natural shading - east and west orientation	Cost to supply and install (planting of) deciduous trees in front of east and west facing window (where space available) of height 2.5-3m tall Assume medium maturity tree with root ball at planting, in tree pits.
Intervention 5	Install External Shutters	Cost to supply and install aluminium shutters. Manually operated with rod crank or spring-loaded operation.
Intervention 6	Install Internal Shutters	Cost to supply and install full height internal wooden shutters. Manually operated. Assume hardwood shutters, supplied and installed.
Intervention 7	Low G window film	Cost to supply and install plastic window films that reduce the amount of solar gain. This is potentially a cheaper, less invasive mitigation that replacing all the windows with high performance glazing. 3M glazing film, or similar.
Intervention 8	Replacement of window with low g value glazing	Cost to supply and install replacement windows; uPVC frame double glazed casement windows with g value of 0.35, all glazing including all rooflights.
Intervention 9	Install openable windows	Cost to supply and install increased window openable area by replacing existing windows with less than 50% opening area, with new, openable windows. Assume replacements are the same specification as existing windows, only they are now openable. To achieve the cost metric, we used the openable window calculation and applied the replacement costs to only those window fenestrations with less than 50% opening.
Intervention 10	Install Solar Reflective Walls	Cost to supply and install solar reflective wall paint; white finish applied to walls externally.
Intervention 11	Install Solar Reflective Roof	Cost to supply and install specialist roof tile paint; paint roof with specialist solar reflective paint, using 1 coat of Climate Cooler Uni Primer and 2 coats of Climate Cooler Uni Topcoat, following jet washing preparation of the roof.

	Name	Detail/assumption
Intervention 12	Install Roof Insulation	Cost to supply and install Durarock rigid insulation boards, 140mm thick, U value 0.25, cut to size and installed between roof rafters. Assume no damp issues. New plasterboard, plaster and skim to return living spaces to existing. Conditioned room in roof so use rigid boards 140, thick U value 0.25
Intervention 13	Install Ceiling Fans	Cost to supply and install ceiling fans in every living room and bedroom. Assume no structural intervention in required. Power supply/ connection allowed for in costs, but spare ways on the distribution board are assumed.
Intervention 14	Install MVHR	Cost to supply and install MVHR system. Use of Parity model for costings; cost based on attendance fee and then priced per room, based on a social housing model for a flat. Only 5% design fees added by Arup.
Intervention 15	Install Active Cooling (Reversible heat pumps)	Cost to supply and install split units as per cooling load calculations from Jonathan Reynold's calculation; in 5 rooms; assume up to 2.5kW cooling load per room, external DX unit for 5 room therefore up to 15kW (worst case). Assume spare ways on the board and assume no structural alterations needed, only form openings, installation, materials and making good. Small BMS (control system) allowance included.

Table 28: Archetypes 1 – 4 (Houses)

Mitigation-specific assumptions

	Name	Detail/assumption
Intervention 1	Install Blinds	Cost to supply and install internal roller blinds, installed internally. Applied to all windows. Assume grey blackout blind with safety features included.
Intervention 2	Install Curtains	Cost to supply and install pair of drape curtains installed on a metal rod. Applied to all bedroom and living room windows only. Standard size.
Intervention 3	Install Fixed Shading (overhang - horizontal south, vertical east/west)	Cost to supply and install brise soleil on south facing windows, except where there is a balcony overhang. Assume 40cm spacing on aluminium brise soleil. Also supply and install on east and west facing windows, vertically mounted sliding ladder panel sliding behind window. Assume similar to aluminium shutter on a sliding rail.
Intervention 4	Install External natural shading - east and west orientation	Cost to supply and install plantation of deciduous trees in front of window (where space available) of height 2.5-3m tall Assume medium maturity with root ball at planting. NOT APPLICABLE for Archetypes 5 and 6 (the Flats)
Intervention 5	Install External Shutters	Cost to supply and install aluminium shutters. Manually operated with rod crank or spring loaded operation.
Intervention 6	Install Internal Shutters	Cost to supply and install full height internal wooden shutters. Manually operated. Assume Hardwood shutters, supplied and installed.
Intervention 7	Low G window film	Cost to supply and install plastic window films that reduce the amount of solar gain. This is potentially a cheaper, less invasive mitigation that replacing all the windows with high performance glazing. 3M glazing film, or similar.
Intervention 8	Replacement of window with low g value glazing	Cost to supply and install replace all windows with uPVC frame double glazed casement windows with g value of 0.35.
Intervention 9	Install openable windows	Cost to increase window openable area by replacing existing windows with new, openable windows. Assume same spec as existing windows, only openable. Use openable window calculation and apply the replacement to only those with less than 50% opening.
Intervention 10	Install Solar Reflective Walls	Cost to supply and paint with solar reflective white finish applied to walls externally.
Intervention 11	Install Solar Reflective Roof	Cost to supply and install solar reflective paint; applied to roof tiles, using 1 coat of ClimateCooler Uni Primer and 2 coats of ClimateCooler Uni Topcoat, following jet washing preparation of the roof. Not applicable on flats.
Intervention 12	Install Roof Insulation	Cost to supply and install Durarock rigid insulation boards, 140mm thick, U value 0.25, cut to size and installed between roof rafters. Assume no damp issues. New plasterboard, plaster and skim to return living spaces to existing. Conditioned room in roof so use rigid boards 140mm thick U value 0.25. Not applicable on flats.
Intervention 13	Install Ceiling Fans	Cost to install ceiling fans; installed in every living room and bedroom. Assume no structural intervention in required. Power supply to be allowed for, but assume spare ways on the distribution board.
Intervention 14	Install MVHR	Cos to supply and install MVHR unit, use of Parity model for costings; Cost based on attendance fee and then priced per room, based on a social housing model for a flat.
Intervention 15	Install Active Cooling (Reversible heat pumps)	Cost to supply and install split units as per cooling load calculations from Jonathan Reynold's calculation; in 5 rooms; assume up to 2.5kW cooling load per room, external DX unit for 5 room therefore up to 15kW (worst case). Assume spare ways on the board and assume no structural alterations needed, only form openings, installation, materials and making good. Small BMS (control system) allowance included.

Table 29: Archetypes 5 and 6 (Flats)

Appendix C:
Cost tables for mitigation measures

London - Location factor 1.21

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
GIFA		102m²	230m²	294m²	137m²	52m²	67m²
Intervention 1	Install Blinds	£4,356	£7,502	£7,018	£4,477	£2,541	£2,420
		£43/m²	£33/m²	£24/m²	£33/m²	£49/m²	£36/m²
Intervention 2	Install Curtains	£3,993	£8,470	£7,865	£5,687	£2,662	£2,541
		£39/m²	£37/m²	£27/m²	£41/m²	£51/m²	£38/m²
Intervention 3	Install Fixed Shading (overhang - horizontal south, vertical east/west)	£10,890	£24,200	£25,410	£16,940	£29,040	£14,520
		£106/m²	£105/m²	£86/m²	£123/m²	£560/m²	£216/m²
Intervention 4	Install External natural shading - east and west orientation	£0	£9,680	£7,260	£0	£0	£0
		£0/m²	£42/m²	£25/m²	£0/m²	£0/m²	£0/m²
Intervention 5	Install External Shutters	£20,570	£24,200	£39,930	£21,780	£19,360	£18,150
		£201/m²	£105/m²	£136/m²	£158/m²	£374/m²	£270/m²
Intervention 6	Install Internal Shutters	£13,310	£14,520	£16,940	£12,100	£9,680	£9,680
		£130/m²	£63/m²	£58/m²	£88/m²	£187/m²	£144/m²
Intervention 7	Low G window film	£3,630	£6,050	£7,260	£3,630	£2,420	£2,420
		£35/m²	£26/m²	£25/m²	£26/m²	£47/m²	£36/m²
Intervention 8	Replacement of window with low g value glazing	£30,250	£65,340	£72,600	£30,250	£24,200	£21,780
		£296/m²	£284/m²	£247/m²	£220/m²	£467/m²	£324/m²
Intervention 9	Install openable windows	£0	£25,410	£65,340	£26,620	£21,780	£18,150
		£0/m²	£110/m²	£222/m²	£194/m²	£420/m²	£270/m²
Intervention 10	Install Solar Reflective Walls	£4,840	£15,730	£22,990.00	£8,470	£8,470	£7,260
		£47/m²	£68/m²	£78/m²	£62/m²	£163/m²	£108/m²

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
Intervention 11	Install Solar Reflective Roof	£10,890	£21,780	£32,670	£19,360	£0	£0
		£106/m²	£95/m²	£111/m²	£141/m²	£0/m²	£0/m²
Intervention 12	Install Roof Insulation	£8,470	£14,520	£19,360	£14,520	£0	£0
		£83/m²	£63/m²	£66/m²	£106/m²	£0/m²	£0/m²
Intervention 13	Install Ceiling Fans	£2,420	£3,630	£3,630	£2,420	£2,420	£2,420
		£24/m²	£16/m²	£12/m²	£18/m²	£47/m²	£36/m²
Intervention 14	Install MVHR	£6,050	£7,260	£7,260	£6,050	£6,050	£6,050
		£59/m²	£32/m²	£25/m²	£44/m²	£117/m²	£90/m²
Intervention 15	Install Active Cooling (Reversible heat pumps)	£14,520	£20,570	£22,990	£13,310	£14,520	£10,890
		£142/m²	£89/m²	£78/m²	£97/m²	£280/m²	£162/m²
Total		£134,189	£268,862	£358,523	£185,614	£143,143	£116,281

Table 30: Task 2 cost table for London

Midlands and Wales - Location factor 0.98

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
GIFA		102m^2	230m^2	294m^2	137m^2	5^{2}m^2	67m^2
Intervention 1	Install Blinds	£3,519.00	£6,060.50	£5,669.50	£3,616.75	£2,052.75	£1,955.00
		£34/m^2	£26/m^2	£19/m^2	£26/m^2	£40/m^2	£29/m^2
Intervention 2	Install Curtains	£3,^{2}25.75	£6,842.50	£6,353.75	£4,594.25	£2,150.50	£2,052.75
		£32/m^2	£30/m^2	£22/m^2	£33/m^2	£41/m^2	£31/m^2
Intervention 3	Install Fixed Shading (overhang - horizontal south, vertical east/west)	£8,797.50	£19,550.00	£20,527.50	£13,685.00	£23,460.00	£11,730.00
		£86/m^2	£85/m^2	£70/m^2	£100/m^2	£453/m^2	£175/m^2
Intervention 4	Install External natural shading - east and west orientation	£0.00	£7,820.00	£5,865.00	£0.00	£0.00	£0.00
		£0/m^2	£34/m^2	£20/m^2	£0/m^2	£0/m^2	£0/m^2
Intervention 5	Install External Shutters	£16,617.50	£19,550.00	£32,257.50	£17,595.00	£15,640.00	£14,662.50
		£162/m^2	£85/m^2	£110/m^2	£128/m^2	£302/m^2	£218/m^2
Intervention 6	Install Internal Shutters	£10,752.50	£11,730.00	£13,685.00	£9,775.00	£7,820.00	£7,820.00
		£105/m^2	£51/m^2	£47/m^2	£71/m^2	£151/m^2	£116/m^2
Intervention 7	Low G window film	£2,932.50	£4,887.50	£5,865.00	£2,932.50	£1,955.00	£1,955.00
		£29/m^2	£21/m^2	£20/m^2	£21/m^2	£38/m^2	£29/m^2
Intervention 8	Replacement of window with low g value glazing	£24,437.50	£52,785.00	£58,650.00	£24,437.50	£19,550.00	£17,595.00
		£239/m^2	£229/m^2	£200/m^2	£178/m^2	£377/m^2	£262/m^2
Intervention 9	Install openable windows	£0.00	£20,527.50	£52,785.00	£21,505.00	£17,595.00	£14,662.50
		£0/m^2	£89/m^2	£180/m^2	£156/m^2	£340/m^2	£218/m^2
Intervention 10	Install Solar Reflective Walls	£3,910.00	£12,707.50	£18,572.50	£6,842.50	£6,842.50	£5,865.00
		£38/m^2	£55/m^2	£63/m^2	£50/m^2	£132/m^2	£87/m^2
Intervention 11	Install Solar Reflective Roof	£8,797.50	£17,595.00	£26,392.50	£15,640.00	£0.00	£0.00
		£86/m^2	£76/m^2	£90/m^2	£114/m^2	£0/m^2	£0/m^2
Intervention 12	Install Roof Insulation	£6,842.50	£11,730.00	£15,640.00	£11,730.00	£0.00	£0.00
		£67/m^2	£51/m^2	£53/m^2	£85/m^2	£0/m^2	£0/m^2
Intervention 13	Install Ceiling Fans	£1,955.00	£2,932.50	£2,932.50	£1,955.00	£1,955.00	£1,955.00
		£19/m^2	£13/m^2	£10/m^2	£14/m^2	£38/m^2	£29/m^2
Intervention 14	Install MVHR	£4,887.50	£5,865.00	£5,865.00	£4,887.50	£4,887.50	£4,887.50
		£48/m^2	£25/m^2	£20/m^2	£36/m^2	£94/m^2	£73/m^2
Intervention 15	Install Active Cooling (Reversible heat pumps)	£11,730.00	£16,617.50	£18,572.50	£10,752.50	£11,730.00	£8,797.50
		£115/m^2	£72/m^2	£63/m^2	£78/m^2	£226/m^2	£131/m^2
Total		£108,404.75	£217,200.50	£289,633.25	£149,948.50	£115,638.25	£93,937.75

Table 31: Task 2 cost table for Midlands and Wales

North of England and Ireland - Location factor 0.94

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
GIFA		102m^2	230m^2	294m^2	137m^2	52m^2	67m^2
Intervention 1	Install Blinds	£3,396.00	£5,848.67	£5,471.33	£3,490.33	£1,981.00	£1,886.67
		£33/m^2	£25/m^2	£19/m^2	£25/m^2	£38/m^2	£28/m^2
Intervention 2	Install Curtains	£3,113.00	£6,603.33	£6,131.67	£4,433.67	£2,075.33	£1,981.00
		£30/m^2	£29/m^2	£21/m^2	£32/m^2	£40/m^2	£30/m^2
Intervention 3	Install Fixed Shading (overhang - horizontal south, vertical east/west)	£8,490.00	£18,867.00	£19,810.00	£13,207.00	£22,640.00	£11,320.00
		£83/m^2	£82/m^2	£67/m^2	£96/m^2	£437/m^2	£169/m^2
Intervention 4	Install External natural shading - east and west orientation	£0.00	£7,546.67	£5,660.00	£0.00	£0.00	£0.00
		£0/m^2	£33/m^2	£19/m^2	£0/m^2	£0/m^2	£0/m^2
Intervention 5	Install External Shutters	£16,036.67	£18,866.67	£31,130.00	£16,980.00	£15,093.33	£14,150.00
		£157/m^2	£82/m^2	£106/m^2	£124/m^2	£291/m^2	£211/m^2
Intervention 6	Install Internal Shutters	£10,376.67	£11,320.00	£13,206.67	£9,433.33	£7,546.67	£7,546.67
		£101/m^2	£49/m^2	£45/m^2	£69/m^2	£146/m^2	£112/m^2
Intervention 7	Low G window film	£2,830.00	£4,716.67	£5,660.00	£2,830.00	£1,886.67	£1,886.67
		£28/m^2	£20/m^2	£19/m^2	£21/m^2	£36/m^2	£28/m^2
Intervention 8	Replacement of window with low g value glazing	£23,583.33	£50,940.00	£56,600.00	£23,583.33	£18,866.67	£16,980.00
		£230/m^2	£221/m^2	£193/m^2	£172/m^2	£364/m^2	£253/m^2
Intervention 9	Install openable windows	£0.00	£19,810.00	£50,940.00	£20,753.33	£16,980.00	£14,150.00
		£0/m^2	£86/m^2	£173/m^2	£151/m^2	£328/m^2	£211/m^2
Intervention 10	Install Solar Reflective Walls	£3,773.33	£12,263.33	£17,923.33	£6,603.33	£6,603.33	£5,660.00
		£37/m^2	£53/m^2	£61/m^2	£48/m^2	£127/m^2	£84/m^2
Intervention 11	Install Solar Reflective Roof	£8,490.00	£16,980.00	£25,470.00	£15,093.33	£0.00	£0.00
		£83/m^2	£74/m^2	£87/m^2	£110/m^2	£0/m^2	£0/m^2

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
Intervention 12	Install Roof Insulation	£6,603.33	£11,320.00	£15,093.33	£11,320.00	£0.00	£0.00
		£65/m^2	£49/m^2	£51/m^2	£82/m^2	£0/m^2	£0/m^2
Intervention 13	Install Ceiling Fans	£1,886.67	£2,830.00	£2,830.00	£1,886.67	£1,886.67	£1,886.67
		£18/m^2	£12/m^2	£10/m^2	£14/m^2	£36/m^2	£28/m^2
Intervention 14	Install MVHR	£4,716.67	£5,660.00	£5,660.00	£4,716.67	£4,716.67	£4,716.67
		£46/m^2	£25/m^2	£19/m^2	£34/m^2	£91/m^2	£70/m^2
Intervention 15	Install Active Cooling (Reversible heat pumps)	£11,320.00	£16,036.67	£17,923.33	£10,376.67	£11,320.00	£8,490.00
		£111/m^2	£70/m^2	£61/m^2	£75/m^2	£218/m^2	£126/m^2
Total		£104,615.67	£209,608.67	£279,509.67	£144,707.33	£111,596.33	£90,654.33

Table 32: Task 2 cost table for Northern England and Northern Ireland

South England - Location factor 1.08

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
GIFA		102m²	230m²	294m²	137m²	52m²	67m²
Intervention 1	Install Blinds	£3,870.00	£6,665.00	£6,235.00	£3,977.50	£2,257.50	£2,150.00
		£38/m²	£29/m²	£21/m²	£29/m²	£44/m²	£32/m²
Intervention 2	Install Curtains	£3,547.50	£7,525.00	£6,987.50	£5,052.50	£2,365.00	£2,257.50
		£35/m²	£33/m²	£24/m²	£37/m²	£46/m²	£34/m²
Intervention 3	Install Fixed Shading (overhang - horizontal south, vertical east/west)	£9,675.00	£21,500.00	£22,575.00	£15,050.00	£25,800.00	£12,900.00
		£95/m²	£93/m²	£77/m²	£109/m²	£498/m²	£192/m²
Intervention 4	Install External natural shading - east and west orientation	£0.00	£8,600.00	£6,450.00	£0.00	£0.00	£0.00
		£0/m²	£37/m²	£22/m²	£0/m²	£0/m²	£0/m²
Intervention 5	Install External Shutters	£18,275.00	£21,500.00	£35,475.00	£19,350.00	£17,200.00	£16,125.00
		£179/m²	£93/m²	£121/m²	£141/m²	£332/m²	£240/m²
Intervention 6	Install Internal Shutters	£11,825.00	£12,900.00	£15,050.00	£10,750.00	£8,600.00	£8,600.00
		£116/m²	£56/m²	£51/m²	£78/m²	£166/m²	£128/m²
Intervention 7	Low G window film	£3,225.00	£5,375.00	£6,450.00	£3,225.00	£2,150.00	£2,150.00
		£32/m²	£23/m²	£22/m²	£23/m²	£41/m²	£32/m²
Intervention 8	Replacement of window with low g value glazing	£26,875.00	£58,050.00	£64,500.00	£26,875.00	£21,500.00	£19,350.00
		£263/m²	£252/m²	£220/m²	£196/m²	£415/m²	£288/m²
Intervention 9	Install openable windows	£0.00	£22,575.00	£58,050.00	£23,650.00	£19,350.00	£16,125.00
		£0/m²	£98/m²	£198/m²	£172/m²	£373/m²	£240/m²
Intervention 10	Install Solar Reflective Walls	£4,300.00	£13,975.00	£20,425.00	£7,525.00	£7,525.00	£6,450.00
		£42/m²	£61/m²	£70/m²	£55/m²	£145/m²	£96/m²
Intervention 11	Install Solar Reflective Roof	£9,675.00	£19,350.00	£29,025.00	£17,200.00	£0.00	£0.00
		£95/m²	£84/m²	£99/m²	£125/m²	£0/m²	£0/m²

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
Intervention 12	Install Roof Insulation	£7,525.00	£12,900.00	£17,200.00	£12,900.00	£0.00	£0.00
		£74/m²	£56/m²	£59/m²	£94/m²	£0/m²	£0/m²
Intervention 13	Install Ceiling Fans	£2,150.00	£3,225.00	£3,225.00	£2,150.00	£2,150.00	£2,150.00
		£21/m²	£14/m²	£11/m²	£16/m²	£41/m²	£32/m²
Intervention 14	Install MVHR	£5,375.00	£6,450.00	£6,450.00	£5,375.00	£5,375.00	£5,375.00
		£53/m²	£28/m²	£22/m²	£39/m²	£104/m²	£80/m²
Intervention 15	Install Active Cooling (Reversible heat pumps)	£12,900.00	£18,275.00	£20,425.00	£11,825.00	£12,900.00	£9,675.00
		£126/m²	£79/m²	£70/m²	£86/m²	£249/m²	£144/m²
Total		£119,217.50	£238,865.00	£318,522.50	£164,905.00	£127,172.50	£103,307.50

Table 33: Task 2 cost table for Southern England

Scotland - Location factor 0.91

		Archetype 1 - Mid Terrace	Archetype 2 - Semi - Detached	Archetype 3 - Detached	Archetype 4 - End Terrace	Archetype 5 - Old Flat	Archetype 6 - Modern Flat
GIFA		102m²	230m²	294m²	137m²	52m²	67m²
Intervention 1	Install Blinds	£3,276.00	£5,642.00	£5,278.00	£3,367.00	£1,911.00	£1,820.00
		£32/m²	£25/m²	£18/m²	£24/m²	£37/m²	£27/m²
Intervention 2	Install Curtains	£3,003.00	£6,370.00	£5,915.00	£4,277.00	£2,002.00	£1,911.00
		£29/m²	£28/m²	£20/m²	£31/m²	£39/m²	£28/m²
Intervention 3	Install Fixed Shading (overhang - horizontal south, vertical east/west)	£8,190.00	£18,200.00	£19,110.00	£12,740.00	£21,840.00	£10,920.00
		£80/m²	£79/m²	£65/m²	£93/m²	£421/m²	£163/m²
Intervention 4	Install External natural shading - east and west orientation	£0.00	£7,280.00	£5,460.00	£0.00	£0.00	£0.00
		£0/m²	£32/m²	£19/m²	£0/m²	£0/m²	£0/m²
Intervention 5	Install External Shutters	£15,470.00	£18,200.00	£30,030.00	£16,380.00	£14,560.00	£13,650.00
		£151/m²	£79/m²	£102/m²	£119/m²	£281/m²	£203/m²
Intervention 6	Install Internal Shutters	£10,010.00	£10,920.00	£12,740.00	£9,100.00	£7,280.00	£7,280.00
		£98/m²	£47/m²	£43/m²	£66/m²	£140/m²	£108/m²
Intervention 7	Low G window film	£2,730.00	£4,550.00	£5,460.00	£2,730.00	£1,820.00	£1,820.00
		£27/m²	£20/m²	£19/m²	£20/m²	£35/m²	£27/m²
Intervention 8	Replacement of window with low g value glazing	£22,750.00	£49,140.00	£54,600.00	£22,750.00	£18,200.00	£16,380.00
		£222/m²	£213/m²	£186/m²	£166/m²	£351/m²	£244/m²
Intervention 9	Install openable windows	£0.00	£19,110.00	£49,140.00	£20,020.00	£16,380.00	£13,650.00
		£0/m²	£83/m²	£167/m²	£146/m²	£316/m²	£203/m²
Intervention 10	Install Solar Reflective Walls	£3,640.00	£11,830.00	£17,290.00	£6,370.00	£6,370.00	£5,460.00
		£36/m²	£51/m²	£59/m²	£46/m²	£123/m²	£81/m²
Intervention 11	Install Solar Reflective Roof	£8,190.00	£16,380.00	£24,570.00	£14,560.00	£0.00	£0.00
		£80/m²	£71/m²	£84/m²	£106/m²	£0/m²	£0/m²
Intervention 12	Install Roof Insulation	£6,370.00	£10,920.00	£14,560.00	£10,920.00	£0.00	£0.00
		£62/m²	£47/m²	£50/m²	£79/m²	£0/m²	£0/m²
Intervention 13	Install Ceiling Fans	£1,820.00	£2,730.00	£2,730.00	£1,820.00	£1,820.00	£1,820.00
		£18/m²	£12/m²	£9/m²	£13/m²	£35/m²	£27/m²
Intervention 14	Install MVHR	£4,550.00	£5,460.00	£5,460.00	£4,550.00	£4,550.00	£4,550.00
		£44/m²	£24/m²	£19/m²	£33/m²	£88/m²	£68/m²
Intervention 15	Install Active Cooling (Reversible heat pumps)	£10,920.00	£15,470.00	£17,290.00	£10,010.00	£10,920.00	£8,190.00
		£107/m²	£67/m²	£59/m²	£73/m²	£211/m²	£122/m²
Total		£100,919.00	£202,202.00	£269,633.00	£139,594.00	£107,653.00	£87,451.00

Table 34: Task 2 cost table for Scotland

Archetype	Location	Location Factor	Roof Construction	Package 1		Package 2		Package 3		Package 4		Package 5	
				Baseline	Location Cost	Baseline	Location	Baseline	Location	Baseline	Location	Baseline	Location
Mid-terrace	Birmingham	0.98	Uninsulated	£ 14,300	£ 13,980	£ 30,800	£ 30,110	£ 33,100	£ 32,360	£ 56,500	£ 55,230	£ 27,800	£ 27,180
Mid-terrace	Swindon	1.08	Uninsulated	£ 14,300	£ 15,380	£ 30,800	£ 33,110	£ 33,100	£ 35,590	£ 56,500	£ 60,740	£ 27,800	£ 29,890
Mid-terrace	London	1.21	Uninsulated	£ 14,300	£ 17,310	£ 30,800	£ 37,270	£ 33,100	£ 40,060	£ 56,500	£ 68,370	£ 27,800	£ 33,640
Mid-terrace	Birmingham	0.98	Insulated	£ 7,300	£ 7,140	£ 23,700	£ 23,170	£ 26,000	£ 25,420	£ 49,400	£ 48,290	£ 20,800	£ 20,340
Mid-terrace	Swindon	1.08	Insulated	£ 7,300	£ 7,850	£ 23,700	£ 25,480	£ 26,000	£ 27,950	£ 49,400	£ 53,110	£ 20,800	£ 22,360
Mid-terrace	London	1.21	Insulated	£ 7,300	£ 8,840	£ 23,700	£ 28,680	£ 26,000	£ 31,460	£ 49,400	£ 59,780	£ 20,800	£ 25,170
Semi-detached	Birmingham	0.98	Uninsulated	£ 25,900	£ 25,320	£ 44,100	£ 43,110	£ 53,700	£ 52,500	£ 104,100	£ 101,760	£ 45,700	£ 44,680
Semi-detached	Swindon	1.08	Uninsulated	£ 25,900	£ 27,850	£ 44,100	£ 47,410	£ 53,700	£ 57,730	£ 104,100	£ 111,910	£ 45,700	£ 49,130
Semi-detached	London	1.21	Uninsulated	£ 25,900	£ 31,340	£ 44,100	£ 53,370	£ 53,700	£ 64,980	£ 104,100	£ 125,970	£ 45,700	£ 55,300
Semi-detached	Birmingham	0.98	Insulated	£ 12,000	£ 11,730	£ 30,100	£ 29,430	£ 39,800	£ 38,910	£ 90,200	£ 88,180	£ 31,800	£ 31,090
Semi-detached	Swindon	1.08	Insulated	£ 12,000	£ 12,900	£ 30,100	£ 32,360	£ 39,800	£ 42,790	£ 90,200	£ 96,970	£ 31,800	£ 34,190
Semi-detached	London	1.21	Insulated	£ 12,000	£ 14,520	£ 30,100	£ 36,430	£ 39,800	£ 48,160	£ 90,200	£ 109,150	£ 31,800	£ 38,480
Detached	Birmingham	0.98	Uninsulated	£ 29,700	£ 29,040	£ 62,600	£ 61,200	£ 76,800	£ 75,080	£ 126,600	£ 123,760	£ 50,900	£ 49,760
Detached	Swindon	1.08	Uninsulated	£ 29,700	£ 31,930	£ 62,600	£ 67,300	£ 76,800	£ 82,560	£ 126,600	£ 136,100	£ 50,900	£ 54,720
Detached	London	1.21	Uninsulated	£ 29,700	£ 35,940	£ 62,600	£ 75,750	£ 76,800	£ 92,930	£ 126,600	£ 153,190	£ 50,900	£ 61,590
Detached	Birmingham	0.98	Insulated	£ 12,200	£ 11,930	£ 45,100	£ 44,090	£ 59,300	£ 57,970	£ 109,100	£ 106,650	£ 33,400	£ 32,650
Detached	Swindon	1.08	Insulated	£ 12,200	£ 13,120	£ 45,100	£ 48,490	£ 59,300	£ 63,750	£ 109,100	£ 117,290	£ 33,400	£ 35,910
Detached	London	1.21	Insulated	£ 12,200	£ 14,770	£ 45,100	£ 54,580	£ 59,300	£ 71,760	£ 109,100	£ 132,020	£ 33,400	£ 40,420
End-terrace	Birmingham	0.98	Uninsulated	£ 20,200	£ 19,750	£ 37,700	£ 36,860	£ 43,600	£ 42,620	£ 66,300	£ 64,810	£ 33,300	£ 32,560
End-terrace	Swindon	1.08	Uninsulated	£ 20,200	£ 21,720	£ 37,700	£ 40,530	£ 43,600	£ 46,870	£ 66,300	£ 71,280	£ 33,300	£ 35,800
End-terrace	London	1.21	Uninsulated	£ 20,200	£ 24,450	£ 37,700	£ 45,620	£ 43,600	£ 52,760	£ 66,300	£ 80,230	£ 33,300	£ 40,300
End-terrace	Birmingham	0.98	Insulated	£ 6,800	£ 6,650	£ 24,200	£ 23,660	£ 30,200	£ 29,530	£ 52,700	£ 51,520	£ 19,900	£ 19,460
End-terrace	Swindon	1.08	Insulated	£ 6,800	£ 7,310	£ 24,200	£ 26,020	£ 30,200	£ 32,470	£ 52,700	£ 56,660	£ 19,900	£ 21,400
End-terrace	London	1.21	Insulated	£ 6,800	£ 8,230	£ 24,200	£ 29,290	£ 30,200	£ 36,550	£ 52,700	£ 63,770	£ 19,900	£ 24,080
Old flat	Birmingham	0.98	NA	£ 4,800	£ 4,700	£ 7,000	£ 6,850	£ 22,200	£ 21,710	£ 36,900	£ 36,070	£ 19,500	£ 19,070
Old flat	Swindon	1.08	NA	£ 4,800	£ 5,160	£ 7,000	£ 7,530	£ 22,200	£ 23,870	£ 36,900	£ 39,670	£ 19,500	£ 20,970
Old flat	London	1.21	NA	£ 4,800	£ 5,810	£ 7,000	£ 8,470	£ 22,200	£ 26,870	£ 36,900	£ 44,650	£ 19,500	£ 23,600
Modern flat	Birmingham	0.98	NA	£ 4,600	£ 4,500	£ 6,600	£ 6,460	£ 20,900	£ 20,430	£ 34,600	£ 33,830	£ 15,000	£ 14,670
Modern flat	Swindon	1.08	NA	£ 4,600	£ 4,950	£ 6,600	£ 7,100	£ 20,900	£ 22,470	£ 34,600	£ 37,200	£ 15,000	£ 16,130
Modern flat	London	1.21	NA	£ 4,600	£ 5,570	£ 6,600	£ 7,990	£ 20,900	£ 25,290	£ 34,600	£ 41,870	£ 15,000	£ 18,150

Table 35: Cost data for modelled archetypes.

Appendix D: Full list of assumptions

Assumption	Justification / Source
The representative locations selected for the analysis are: – Swindon for South England – Birmingham for Midlands and Wales – Manchester for North of England and Ireland – Glasgow for Scotland – London	Areas of similar temperature predictions as per the CCC's 'Independent Assessment of UK Climate Risk' report.
The CIBSE weather data used to represent current, 2°C GW and 4°C GW scenarios are: – Current: 2020 High emissions 50 percentile – 2°C GW: 2080 Low emissions 50 percentile – 4°C GW: 2080 High emissions 50 percentile	Agreed with CIBSE SDG Climate Change Adaptation Working Group
Occupancy densities and profiles and internal gains are based on CIBSE TM59 templates.	CIBSE TM59
Window opening is determined based on the indoor operative temperature. The maximum openable area for each window (100% open) was calculated for each window type. During the day (7am to 11pm) windows are opened in the following increments: 22°C-23°C, windows are 25% open; 23°C-24°C, windows are 50% open; 24°C-25°C, windows are 75% open; above 25°C, 100% open. During the night, windows in unoccupied rooms are closed and windows in bedrooms are 50% open all night if the operative temperature at 11pm is 23°C or above, closed all night if below. Windows are closed once during the night if the temperature drops below 21°C and does not open it again until 7am. Internal doors are open during the day.	Starting from profiles from CIBSE TM59 and adjusted based on research from Loughborough University on typical occupants' behaviour.
Bungalow typologies are incorporated in other archetypes (detached, semi-detached and terrace house).	Bungalows represent only 9% of houses in England (based on EHS) therefore a negligible part compared to houses (70%) and flats (21%). Also the detachment aggregation in the stock model does not present bungalows as a separate type in terms of detachment, therefore the extrapolation of results to the stock model would be difficult if we were to select it as a separate archetype.
Air permeability is considered at 11.5ACH as per baseline in LETI Guidance.	Research from Loughborough University shows that air permeability has very limited impact on overheating risk for two main reasons: 1. Infiltration rates are negligible compared to window ventilation rates; 2. Infiltration gains decreases substantially during summer due lower average wind pressures and lower temperature difference between indoor and outdoor.

Assumption	Justification / Source
TRY and DSY data have been merged for each location and weather scenario to create a weather file that allows to test overheating in summer and heat demand in winter	Need to minimise simulation number for the parametric model.
The ceiling fan mitigation is modelled as reducing the perceived operative temperature by 1.2°C when operating. The ceiling fan can only operate when the zone is occupied. It tunrs on when the zone temperature exceeds 26°C and turn off when the temperature falls below 24°C. A power consumption / heat gain of 50W is applied when the fan operates.	ASHRAE, CIBSE Guide A and BSEN15251 support a reduction in operative temperature. A conservative reduction of 1.2°C was selected, which corresponds to an air velocity of 0.6 m/s.
The operation of the blinds is modelled as follows: blinds are closed when the solar radiation is > 200W/m² between the 01 May and 30 September. The blinds selected have medium performance with a reflectance of 0.35	The blinds are selected from the Library of DesignBuilder Software: Shade roll - Medium opaque. The solar radiation setpoint is chosen to be alligned with the MHCLG research study 'Research into overheating in new homes', 2019.
The operation of the exterior shutters is modelled as follows: shutters are closed when the solar radiation is > 200W/m² between the 01 May and 30 September. The shutters selected are aluminium shutters (louvre type) with the following properties: solar reflectance of 0.4 / slat angle 10 Deg, Slat Width 0.05m / Slat seperation 0.03 m.	The aluminium exterior shutters are selected from the Library of DesignBuilder Software: MicroLouvre. The solar radiation setpoint is chosen to be alligned with the MHCLG research study 'Research into overheating in new homes', 2019.
Other mitigation measures are as follows: – Low G value windows have a G value of 0.36; – Low G window film has a G value of 0.54; – Solar reflective paint has a absorptance of 0.2 and reflectivity of 0.8; – Window replacements will change any window with less than 50% openable area to 90% openable area.	– Low G window properties based on Pilkington Suncool range – Low G window film properties based on 3M Sun Control range – Solar reflective paint properties informed by Arup cool roof reserach project
For packages with active cooling, cooling has been included in each occupiable space (living rooms, kitchens and bedrooms). Cooling is available during the TM59 period (May to Sep inclusive) when the zone is occupied. Cooling set point temperature is 26°C. At 26°C the windows close. Window operation is otherwise identical to non-cooling simulations.	The cooling temperature set point of 26°C was chosen to eliminate the TM59 overheating score.

Table 36: List of assumptions.

Appendix E:
Full energy consumption results for mitigation packages applied to all representative buildings

Archetype	Location	Roof Construction	Baseline		Package 1		Package 2		Package 3		Package 4		Package 5		
			Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Cooling (kWh)
Mid-terrace	Birmingham	Uninsulated	1416	2177	1416	1636	1451	1645	1449	1671	1446	1771	1416	1636	164
Mid-terrace	Swindon	Uninsulated	1416	2016	1416	1581	1456	1592	1454	1618	1452	1719	1416	1581	218
Mid-terrace	London	Uninsulated	1416	1582	1416	1231	1512	1233	1508	1253	1502	1327	1416	1231	416
Mid-terrace	Birmingham	Insulated	1416	1582	1416	1636	1451	1645	1449	1671	1446	1771	1416	1636	164
Mid-terrace	Swindon	Insulated	1416	1538	1416	1581	1456	1592	1454	1618	1452	1719	1416	1581	218
Mid-terrace	London	Insulated	1416	1186	1416	1231	1512	1233	1508	1253	1502	1327	1416	1231	416
Semi-detached	Birmingham	Uninsulated	2361	6974	2361	5629	2411	5632	2404	5817	2401	6100	2361	5629	286
Semi-detached	Swindon	Uninsulated	2361	6256	2361	5061	2424	5062	2416	5247	2412	5544	2361	5061	388
Semi-detached	London	Uninsulated	2361	5362	2361	4299	2519	4300	2493	4465	2474	4715	2361	4299	807
Semi-detached	Birmingham	Insulated	2361	5374	2361	5629	2411	5632	2404	5817	2401	6100	2361	5629	286
Semi-detached	Swindon	Insulated	2361	4803	2361	5061	2424	5062	2416	5247	2412	5544	2361	5061	388
Semi-detached	London	Insulated	2361	4091	2361	4299	2519	4300	2493	4465	2474	4715	2361	4299	807
Detached	Birmingham	Uninsulated	2833	7295	2833	6805	2878	6819	2868	7156	2862	7453	2833	6805	238
Detached	Swindon	Uninsulated	2833	6704	2833	6294	2891	6317	2883	6683	2872	7012	2833	6294	330
Detached	London	Uninsulated	2833	5651	2833	5260	2969	5259	2941	5550	2922	5802	2833	5260	659
Detached	Birmingham	Insulated	2833	6548	2833	6805	2878	6819	2868	7156	2862	7453	2833	6805	238
Detached	Swindon	Insulated	2833	6024	2833	6294	2891	6317	2883	6683	2872	7012	2833	6294	330
Detached	London	Insulated	2833	5047	2833	5260	2969	5259	2941	5550	2922	5802	2833	5260	659
End-terrace	Birmingham	Uninsulated	1416	4363	1416	2609	1442	2624	1438	2733	1437	2901	1416	2609	139
End-terrace	Swindon	Uninsulated	1416	3937	1416	2377	1443	2392	1439	2508	1439	2672	1416	2377	190
End-terrace	London	Uninsulated	1416	3373	1416	1948	1476	1957	1470	2048	1467	2187	1416	1948	390
End-terrace	Birmingham	Insulated	1416	2482	1416	2609	1442	2624	1438	2733	1437	2901	1416	2609	139
End-terrace	Swindon	Insulated	1416	2249	1416	2377	1443	2392	1439	2508	1439	2672	1416	2377	190
End-terrace	London	Insulated	1416	1855	1416	1948	1476	1957	1470	2048	1467	2187	1416	1948	390
Old flat	Birmingham	NA	472	28	472	51	502	51	489	51	484	90	472	51	106
Old flat	Swindon	NA	472	5	472	11	528	11	508	11	489	30	472	11	186
Old flat	London	NA	472	11	472	17	596	17	544	17	512	29	472	17	397
Modern flat	Birmingham	NA	472	15	472	18	497	18	492	18	487	26	472	18	289
Modern flat	Swindon	NA	472	1	472	0	501	0	496	1	491	7	472	0	333
Modern flat	London	NA	472	4	472	4	545	4	531	4	520	9	472	4	660

Table 37: Energy consumption of each mitigation package applied to each representative building - Current weather scenario.

Archetype	Location	Roof Construction	Baseline		Package 1		Package 2		Package 3		Package 4		Package 5		
			Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Cooling (kWh)
Mid-terrace	Birmingham	Uninsulated	1416	1650	1416	1253	1481	1260	1479	1278	1473	1360	1416	1253	345
Mid-terrace	Swindon	Uninsulated	1416	1508	1416	1198	1492	1207	1490	1226	1487	1310	1416	1198	421
Mid-terrace	London	Uninsulated	1416	1131	1416	905	1592	907	1588	922	1580	987	1416	905	906
Mid-terrace	Birmingham	Insulated	1416	1209	1416	1253	1481	1260	1479	1278	1473	1360	1416	1253	345
Mid-terrace	Swindon	Insulated	1416	1160	1416	1198	1492	1207	1490	1226	1487	1310	1416	1198	421
Mid-terrace	London	Insulated	1416	869	1416	905	1592	907	1588	922	1580	987	1416	905	906
Semi-detached	Birmingham	Uninsulated	2361	5587	2361	4536	2461	4537	2450	4706	2443	4979	2361	4536	619
Semi-detached	Swindon	Uninsulated	2361	4934	2361	4046	2487	4046	2474	4207	2457	4477	2361	4046	808
Semi-detached	London	Uninsulated	2361	4106	2361	3356	2651	3356	2628	3493	2590	3708	2361	3356	1791
Semi-detached	Birmingham	Insulated	2361	4306	2361	4536	2461	4537	2450	4706	2443	4979	2361	4536	619
Semi-detached	Swindon	Insulated	2361	3823	2361	4046	2487	4046	2474	4207	2457	4477	2361	4046	808
Semi-detached	London	Insulated	2361	3179	2361	3356	2651	3356	2628	3493	2590	3708	2361	3356	1791
Detached	Birmingham	Uninsulated	2833	5802	2833	5415	2918	5420	2901	5722	2894	5999	2833	5415	529
Detached	Swindon	Uninsulated	2833	5258	2833	4950	2952	4958	2932	5271	2910	5567	2833	4950	706
Detached	London	Uninsulated	2833	4313	2833	4030	3105	4029	3063	4285	3028	4513	2833	4030	1535
Detached	Birmingham	Insulated	2833	5186	2833	5415	2918	5420	2901	5722	2894	5999	2833	5415	529
Detached	Swindon	Insulated	2833	4716	2833	4950	2952	4958	2932	5271	2910	5567	2833	4950	706
Detached	London	Insulated	2833	3846	2833	4030	3105	4029	3063	4285	3028	4513	2833	4030	1535
End-terrace	Birmingham	Uninsulated	1416	3490	1416	2059	1461	2070	1456	2166	1454	2316	1416	2059	305
End-terrace	Swindon	Uninsulated	1416	3130	1416	1845	1480	1857	1477	1961	1467	2111	1416	1845	395
End-terrace	London	Uninsulated	1416	2626	1416	1500	1558	1505	1545	1579	1529	1696	1416	1500	827
End-terrace	Birmingham	Insulated	1416	1952	1416	2059	1461	2070	1456	2166	1454	2316	1416	2059	305
End-terrace	Swindon	Insulated	1416	1736	1416	1845	1480	1857	1477	1961	1467	2111	1416	1845	395
End-terrace	London	Insulated	1416	1425	1416	1500	1558	1505	1545	1579	1529	1696	1416	1500	827
Old flat	Birmingham	NA	472	9	472	17	551	17	514	17	497	36	472	17	257
Old flat	Swindon	NA	472	4	472	3	587	3	539	3	509	9	472	3	404
Old flat	London	NA	472	5	472	5	672	5	620	5	562	10	472	5	812
Modern flat	Birmingham	NA	472	8	472	8	516	8	508	8	501	12	472	8	542
Modern flat	Swindon	NA	472	1	472	0	522	0	516	0	508	4	472	0	599
Modern flat	London	NA	472	1	472	1	591	0	575	0	556	5	472	1	1175

Table 38: Energy consumption of each mitigation package applied to each representative building – 2°C warming weather scenario.

Archetype	Location	Roof Construction	Baseline		Package 1		Package 2		Package 3		Package 4		Package 5		
			Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Equipment (kWh)	Heating (kWh)	Cooling (kWh)
Mid-terrace	Birmingham	Uninsulated	1416	1234	1416	945	1564	948	1559	963	1553	1023	1416	945	885
Mid-terrace	Swindon	Uninsulated	1416	1121	1416	900	1584	903	1579	919	1574	984	1416	900	1067
Mid-terrace	London	Uninsulated	1416	792	1416	644	1728	645	1723	657	1715	706	1416	644	1952
Mid-terrace	Birmingham	Insulated	1416	915	1416	945	1564	948	1559	963	1553	1023	1416	945	885
Mid-terrace	Swindon	Insulated	1416	868	1416	900	1584	903	1579	919	1574	984	1416	900	1067
Mid-terrace	London	Insulated	1416	621	1416	644	1728	645	1723	657	1715	706	1416	644	1952
Semi-detached	Birmingham	Uninsulated	2361	4417	2361	3602	2601	3603	2576	3744	2556	3974	2361	3602	1671
Semi-detached	Swindon	Uninsulated	2361	3885	2361	3235	2643	3235	2618	3367	2584	3595	2361	3235	2207
Semi-detached	London	Uninsulated	2361	3088	2361	2592	2857	2592	2832	2702	2788	2879	2361	2592	4129
Semi-detached	Birmingham	Insulated	2361	3415	2361	3602	2601	3603	2576	3744	2556	3974	2361	3602	1671
Semi-detached	Swindon	Insulated	2361	3052	2361	3235	2643	3235	2618	3367	2584	3595	2361	3235	2207
Semi-detached	London	Insulated	2361	2448	2361	2592	2857	2592	2832	2702	2788	2879	2361	2592	4129
Detached	Birmingham	Uninsulated	2833	4535	2833	4226	3049	4226	3014	4478	2991	4714	2833	4226	1463
Detached	Swindon	Uninsulated	2833	4100	2833	3867	3100	3868	3073	4120	3031	4366	2833	3867	1994
Detached	London	Uninsulated	2833	3218	2833	3017	3336	3016	3292	3226	3240	3418	2833	3017	3704
Detached	Birmingham	Insulated	2833	4035	2833	4226	3049	4226	3014	4478	2991	4714	2833	4226	1463
Detached	Swindon	Insulated	2833	3676	2833	3867	3100	3868	3073	4120	3031	4366	2833	3867	1994
Detached	London	Insulated	2833	2870	2833	3017	3336	3016	3292	3226	3240	3418	2833	3017	3704
End-terrace	Birmingham	Uninsulated	1416	2775	1416	1606	1541	1613	1527	1693	1515	1815	1416	1606	801
End-terrace	Swindon	Uninsulated	1416	2474	1416	1430	1557	1436	1544	1518	1535	1648	1416	1430	1019
End-terrace	London	Uninsulated	1416	2028	1416	1137	1702	1139	1686	1202	1667	1292	1416	1137	1843
End-terrace	Birmingham	Insulated	1416	1520	1416	1606	1541	1613	1527	1693	1515	1815	1416	1606	801
End-terrace	Swindon	Insulated	1416	1339	1416	1430	1557	1436	1544	1518	1535	1648	1416	1430	1019
End-terrace	London	Insulated	1416	1081	1416	1137	1702	1139	1686	1202	1667	1292	1416	1137	1843
Old flat	Birmingham	NA	472	5	472	6	650	5	601	5	549	13	472	6	797
Old flat	Swindon	NA	472	3	472	2	639	2	621	2	576	4	472	2	1066
Old flat	London	NA	472	4	472	3	761	2	719	3	659	4	472	3	1704
Modern flat	Birmingham	NA	472	3	472	4	571	4	557	3	540	7	472	4	1143
Modern flat	Swindon	NA	472	1	472	0	569	0	559	0	548	4	472	0	1217
Modern flat	London	NA	472	1	472	0	646	0	631	0	617	4	472	0	2110

Table 39: Energy consumption of each mitigation package applied to each representative building – 4°C warming weather scenario.

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