Ministry of Housing, Communities & Local Government

Research into overheating in new homes

Phase 2 report

September 2019
AECOM
Ministry of Housing, Communities and Local Government

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Introduction

In response to the recommendations in the Committee on Climate Change (CCC) Progress Report to Parliament[1] in 2015, the government has commissioned research to better understand the overheating risk in new dwellings in England and options to mitigate this risk. Phase 1 of the research was previously reported on. This report presents the results from Phase 2 which consists of a cost-benefit analysis of alternative risk mitigation strategies to reduce overheating risk to an acceptable level.

Phase 1 results

Phase 1 assessed the risk of overheating of new homes in England against the new CIBSE TM59[2] overheating criteria, defined below. Dynamic thermal simulation modelling showed that all dwelling typologies (including both houses and flats) evaluated across five geographical locations failed to comply with the criteria. The degree to which dwellings exceeded the criteria varied significantly by typology and location.

- Criterion A applies to living rooms, kitchens and bedrooms. It requires that the internal temperature does not exceed a defined comfort temperature by 1 °C or more for more than 3% of occupied hours over the summer period (1 May to 30 September).
- Criterion B applies to bedrooms only and requires that the internal temperature between 10 pm and 7 am shall not exceed 26 °C for more than 1% of annual hours.

Phase 2 methodology

A cost-benefit analysis of implementing alternative risk mitigation packages has been undertaken in line with HM Treasury Green Book and Supplementary Guidance[3]. The benefits and costs were determined at an individual dwelling level and aggregated to represent the new build stock constructed over a ten year period from 2020 to 2029. A 60 year building life was assumed.

Based on a review of the Phase 1 results, it was agreed that it was proportionate to focus this assessment on three dwelling typologies in three locations. In addition, two alternative occupancy profiles were used based on data from the English Housing Survey 2015-2016 and the UK Time Use Survey 2014-15. This gave 18 cases in total that were used to represent the English new-build housing stock.

Five alternative risk mitigation packages were assessed. These packages prioritise passive measures but also include active cooling. The impact on internal temperatures

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[1] Committee on Climate Change (2015). Reducing emissions and preparing for climate change: 2015 Progress Report to Parliament. London: Committee on climate Change.

[2] CIBSE (2017). TM59 Design methodology for the assessment of overheating risk in homes. London: The Chartered Institution of Building Services Engineers.

[3] HM Treasury (2018). The Green Book - Central Government Guidance on Appraisal and Evaluation. London: HM Treasury

was modelled using dynamic thermal simulation software to identify those packages that met the CIBSE TM59 criteria for each case. The risk mitigation package used in the cost-benefit analysis for each case was that which met the CIBSE TM59 overheating criteria at minimum capital cost, though passive strategies were always prioritised over those with active cooling.

Benefit analysis: The benefits comprised of two components:

- *Reduced mortality:* This quantified the benefit from the reduction in the number of deaths due to lower internal temperatures using well defined temperature-mortality functions i.e. relationship between risk of death and daily maximum external temperature. The analysis was only carried out for dwellings with daytime occupancy to align with peak temperature exposure.

- *Improved productivity:* This quantified the productivity benefit from less sleep disturbance at lower night time temperatures in bedrooms based on published literature.

Additional thermal modelling was undertaken to determine the benefits. In particular, to make the benefit analysis more robust, additional weather data sets (compared to the CIBSE TM59 analysis) were modelled to better represent the likely climatic conditions over the lifetime of the dwellings.

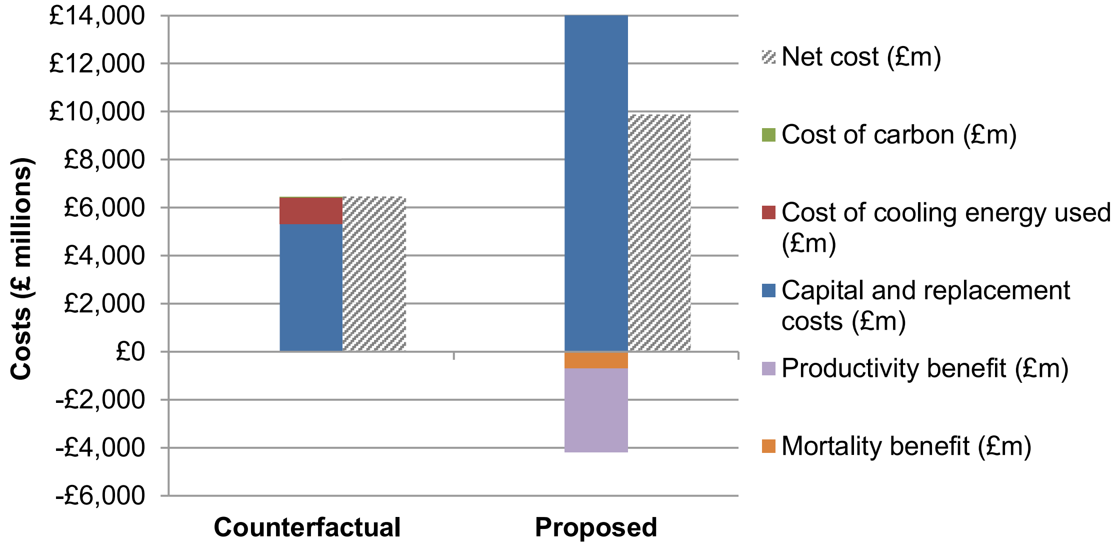
Cost analysis: This included capital cost of risk mitigation measures; replacement costs for active cooling and fabric elements (such as external shading and window replacement); fuel costs for electricity associated with running active cooling during the summer period; and social cost of carbon associated with emissions from electricity use.

Counterfactual case for the cost-benefit analysis: The costs and benefits were assessed relative to a counterfactual case where no risk mitigation measures were installed during construction (other than those to meet Part L 2013). It was assumed that a proportion of residents will choose to retrofit room air-conditioners over the building lifetime to address summer overheating.

Cost-Benefit Analysis results

A net present value (NPV) calculation was undertaken using a discount rate of 3.5% for the first thirty years reducing to 3.0% in subsequent years. Mortality related benefits have been discounted using a health discount rate of 1.5% for the first thirty years reducing to 1.29% in later years. The analysis indicates an overall net cost of £820m for installing risk mitigation measures at the time of construction relative to the counterfactual scenario (see Figure 1). This equates to a net cost of around £400 per dwelling.

Figure 1: Summary of cost-benefit analysis for new build homes in England



The results vary depending on the climate in each of the three locations assessed. The difference in results by location is also dependant on the ratio of houses to flats as the mitigation package and therefore costs vary by dwelling typology.

- London shows an average net benefit of around £2,100 per dwelling across all dwelling typologies modelled.
- Southampton (representing homes built south of London) shows an average net cost of £100 per dwelling across all typologies
- Nottingham (representing homes built north of London) shows an average net cost of around £1,300 per dwelling across all typologies.

Analysing the results further by dwelling type suggests that flats show a net benefit of around £2,700 in London and £2,900 per flat in Nottingham, and a net cost of £900 in Southampton. In contrast, houses show a net cost of £4,000 in London and £1,800 in Nottingham, and a net benefit of £200 in Southampton.

Sensitivity analysis was used to assess the impact of key variables on the results. This included variables related to the uptake of air-conditioning in the counterfactual case and the calculation of benefits. The cumulative impact of the variables tested gives a net cost of around £6,200m as a worst case scenario and a net benefit of £5,700m as a best case scenario. While this suggests a large spread in the net costs /benefits, the core analysis is based on reasonable assumptions and available evidence with potentially a low probability of the cumulative scenarios occurring. As additional data and/or research on any of these variables become available, the analysis can be refined further.

Conclusions

The analysis shows an average net benefit or a near zero cost of incorporating measures to mitigate the risk of overheating in new homes in the south of England over their life. The analysis also shows a net benefit of incorporating risk mitigation measures in flats in the north of England, but not in low-rise housing. However, the combination of mitigation measures modelled would add up to a high capital cost, which would likely result in an unacceptable reduction in housing supply. The challenge for Government is to ensure that overheating can be reduced whilst ensuring that this is done in a way that recognises the long-term challenge the UK faces to substantially increase housing supply.

Stakeholder feedback suggests that legislation offers the best route to ensure that the findings from this work inform and influence industry practice. Both the level of resources needed to demonstrate compliance as well as the required risk mitigation measures should be proportionate to the level of overheating risk which varies by dwelling typology and location. Clear and simple guidance should be produced for industry professionals to inform design choices at an early stage of the project. Additionally, guidance and or other routes to influence occupant behaviour are critical in ensuring the design features perform as intended and the positive benefits of these are maximised.

This analysis is based on the best available information today. As demonstrated by the sensitivity analysis, the outcome of the cost-benefit analysis is significantly dependant on the uncertainty of key variables. Further work could be undertaken to improve the robustness of the calculations.

1. Introduction

The Ministry of Housing, Communities and Local Government (MHCLG) commissioned AECOM and its consortium partners, London School of Hygiene and Tropical Medicine and Studio Partington, to undertake research into overheating of new homes in England. Overheating occurs when the local indoor thermal environment presents conditions in excess of those acceptable for human thermal comfort or those that may adversely affect human health. The purpose of this research is to gain a better understanding of the type of properties most at risk of overheating and undertake a cost-benefit analysis of mitigation measures to limit this risk. The research is divided into two phases – Phase 1 was previously reported on and this report presents the results from Phase 2.

As a first step, Phase 1 defined overheating for use in this project. The CIBSE TM59[4] definition of overheating was adopted as it specifically assesses the overheating risk for homes and has been developed through industry consultation. TM59 sets out two compliance criteria both of which need to be met for the dwelling to be deemed to have an acceptable risk of overheating.

Phase 1 then assessed the risk of overheating against the CIBSE TM59 criteria for eight dwelling typologies across five locations in England using dynamic thermal simulation modelling. The typologies consisted of a mix of flats and houses and take into consideration variations in building form, building size, aspect (e.g. single/ dual aspects), ventilation strategy, individual/ communal heating system and construction type. The modelling showed that all dwelling typologies evaluated across the different geographical locations failed to comply with the new CIBSE TM59 overheating criteria. The degree to which dwellings exceeded the criteria varied significantly by typology and location.

As part of Phase 2 of the project, a cost-benefit analysis (CBA) has been undertaken to assess the implications of applying alternative mitigation packages, including both passive and active cooling measures, to a range of building typologies and locations to reduce their risk to an acceptable level. The cost-benefit analysis has been undertaken in line with the Green Book and Supplementary Guidance[5].

A project Research Group consisting of representatives from academia, housebuilding industry, and industry bodies was set up at the commencement of the project to provide expert review and guidance to the project team. Meetings were held with the Research Group in Phase 1, with further meetings at the start and towards the end of Phase 2.

The report is divided into the following sections.

- Section 2 provides an overview of the cost-benefit analysis.
- Sections 3 to 7 present in more detail the methodology, inputs and assumptions of the cost-benefit analysis.

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[4] CIBSE (2017). TM59 Design methodology for the assessment of overheating risk in homes. London: The Chartered Institution of Building Services Engineers.

[5] HM Treasury (2018). The Green Book - Central Government Guidance on Appraisal and Evaluation. London: HM Treasury

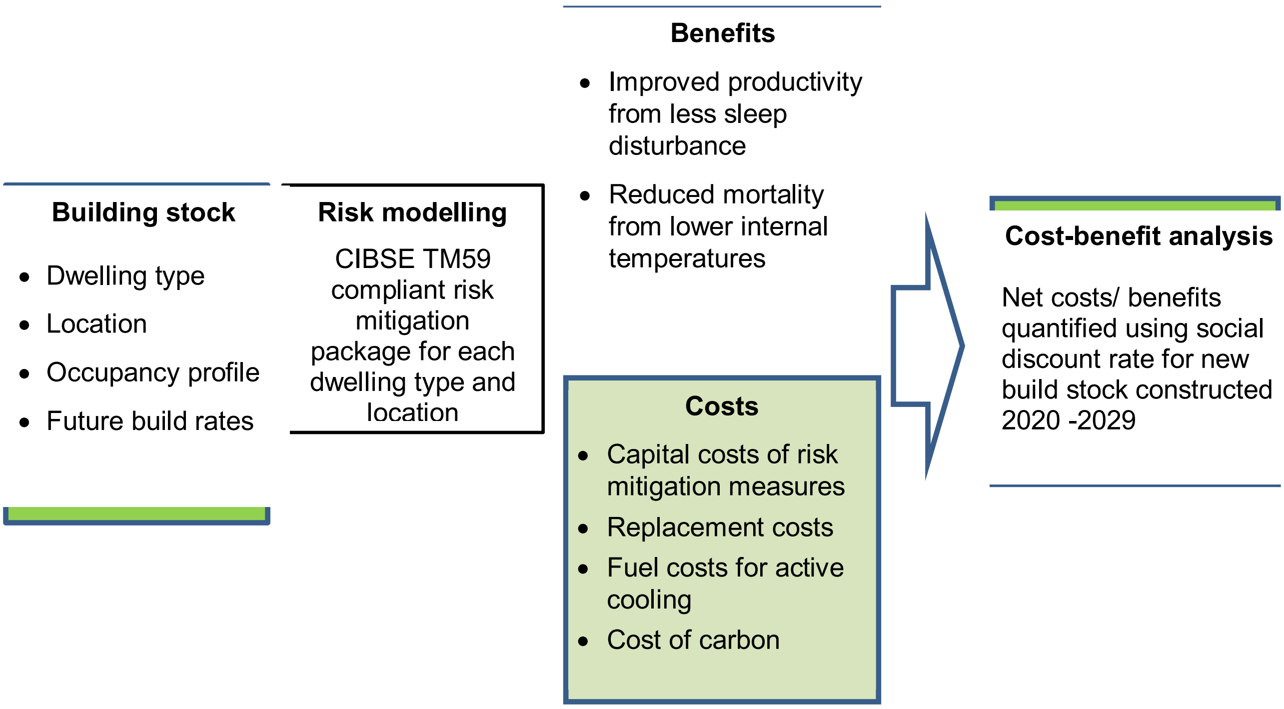
- Sections 8 and 9 present the results of the cost-benefit analysis and the findings from the sensitivity analysis.
- Section 10 sets out recommendations for refining the CBA analysis further and potential routes to bring about change in current design and construction practices to reduce overheating risk in new homes.

2. Methodology

The overarching methodology for the cost-benefit analysis is shown in Figure 1. The benefits and costs were determined at an individual dwelling level. They were then aggregated to represent the new build stock constructed over a ten year period from 2020 to 2029. Each of the components in the figure below is explained in more detail in Sections 3 to 6 of the report.

A number of simplifications have been made to the methodology. This was considered proportionate as this is a new analysis where the relative impact of each of the components and the overall outcomes were unclear. Some improvements and/or refinements to the analysis were undertaken after reviewing the initial results, focussing on those components of the analysis that impact the outcomes most significantly.

Figure 2: Overview of CBA methodology



Building stock

The following representative cases were assessed for the cost-benefit analysis.

- Three dwelling typologies: semi-detached home, single aspect apartment unit, dual aspect apartment unit
- Three locations: South of England, North of England and London region
- Two occupancy profiles: daytime occupancy, no daytime occupancy.

The dwelling types and locations were aggregated to represent the new build stock constructed in England over a ten year period from 2020 to 2029.

Risk mitigation modelling

Five overheating risk mitigation strategies were assessed for each dwelling type and location using dynamic thermal modelling. This used occupancy and other assumptions set out in the CIBSE TM59 guidance. The strategies assessed included both passive and active cooling measures. The risk mitigation strategy used in the cost-benefit analysis for each case was that which met the CIBSE TM59 overheating criteria at minimum capital cost although passive strategies were always prioritised over those with active cooling.

Benefits

The benefits were determined at an individual dwelling level. They were calculated over a 60 year period following construction.

The combination of dwelling types, locations and occupancy profiles gives a total of 18 cases. For each of these cases further dynamic thermal simulation modelling was undertaken to assess the impact of the five overheating risk mitigation strategies using average occupancy data from English Housing Survey and four different sets of weather data. For the cost-benefit analysis, the benefits were quantified based on the internal temperatures from the thermal modelling for the TM59 compliant risk mitigation package. This comprised of two components: the improved level of productivity due to less sleep disturbance and reduced mortality (additional life years) at lower internal temperatures.

The benefits were calculated relative to a counterfactual case where no risk mitigation measures were installed during construction (other than those to meet the SAP overheating test in Part L 2013) but assuming that some residents will choose to retrofit room air-conditioners over the 60 year building life.

Costs

The costs were also determined at an individual dwelling level for the TM59 compliant risk mitigation package for each dwelling type and location. The following costs were assessed.

- Capital costs: The costs of the risk mitigation measures included during construction
- Replacement costs: The costs of replacing the components for the passive or active cooling measures at the end of their life.
- Fuel costs: The costs of electricity associated with running active cooling during the summer period over the 60 year building life.
- Carbon costs: The social costs of carbon emissions

For the counterfactual case, costs associated with the retrofit of active cooling during the period following construction were included as well as associated replacement, fuel and carbon costs.

Cost-benefit analysis

To calculate the net cost and/or benefit of the risk mitigation packages, a net present value (NPV) calculation was undertaken over a 70 year period, including the 10 year construction period from 2020 to 2029 and an assumed 60 year building life.

3. Building stock

This section details the dwelling archetypes, locations and occupancy scenarios modelled. It also sets out how the individual dwelling typologies and locations are aggregated to represent new build housing stock in England as a whole.

3.1 Dwelling types and locations

Three dwelling typologies have been evaluated in Phase 2. These were selected from the 8 dwelling types modelled in Phase 1 as shown in Table 1.

Table 1: Dwelling typologies modelled in Phase 1

Type	Dwelling form	Size*	Aspects	Ventilation strategy	Heating system	Construction type	Location (Weather file)
1.	Apartment	1b2p*	Single	Nat. Vent	Individual	Mid-rise High-rise	Nottingham Leeds
1b.				MEV	Individual		LHR Southampton
1c.				MEV	Communal		LWC
2.	Apartment	2b4p	Single	Nat. Vent	Individual	Mid-rise High-rise	Nottingham Leeds
2b.				MEV	Individual		LHR Southampton
3.	Apartment	2b4p	Single	Nat. Vent	Communal	Mid-rise High-rise	Nottingham Leeds
3b.				MEV	Communal		LHR Southampton
3c.				MEV	Communal		LWC
4.	Apartment	2b4p	Dual	Nat. Vent	Individual	Mid-rise High-rise	Nottingham Leeds
4b.				MEV	Individual		LWC LHR Southampton
5.	Apartment	2b4p	Dual	Nat. Vent	Communal	Mid-rise High-rise	Nottingham Leeds
5b.				MEV	Communal		LHR Southampton
6.	Terraced house	2b4p	Dual	Nat. Vent	Individual	Masonry	All locations
7.	Semi-detached	3b5p	Triple	Nat. Vent	Individual	Masonry	All locations
8.	Detached	4b7p	Quadruple	Nat. Vent	Individual	Masonry	All locations

* b= number of bedrooms, p= number of persons

It was agreed with MHCLG and the Research Group that a reduced set of dwelling types and locations would be sufficient for Phase 2 due to similarities found across different dwelling types.

- Flat typologies were limited to one construction type (concrete frame with lightweight block infill) with a high thermal mass scenario considered within the mitigation packages. Flat typologies were modelled in Phase 1 with two construction types: high rise construction with steel frame and rainscreen claddinPre-election guidance for social media.docx

- g, and mid-rise construction with concrete frame and lightweight block infill. Phase 1 results indicated no significant difference in overheating risk between the two construction types. This was due to the thermal mass being decoupled from the internal space.

- Only individual heating systems were considered. Phase 1 showed small differences in overheating risk for individual and communal heating systems relative to other parameters. It was assumed that the communal heating was designed and installed to a good standard.

- Only 2-bed apartments (both single and dual façade) were considered, omitting the 1-bed single façade apartment. The Phase 1 analysis showed little difference in the number of hours that the CIBSE TM59 criteria were exceeded between 1-bed and 2-bed apartments.

- Only semi-detached houses were modelled. It was considered that these were sufficiently representative of terraced, semi-detached and detached homes modelled in Phase 1.

- Three of the five development locations modelled in Phase 1 were selected for Phase 2 – Nottingham, London Heathrow, and Southampton. These represented the best, worst and mid-performing locations and gave a good spread in terms of geographical locations across England.

The final set of dwellings modelled in Phase 2 is shown in Table 2. Note that MEV is used in certain locations as agreed in Phase 1 to meet Part L.

Table 2: Dwelling typologies modelled in Phase 2

Type	Dwelling form	Size	Aspects	Ventilation strategy	Heating system	Construction type	Location (Weather file)
2.	Apartment	2b4p	Single	Nat. Vent	Individual	Mid-rise	Nottingham
2b.				MEV	Individual		London Heathrow Southampton
4.	Apartment	2b4p	Dual	Nat. Vent	Individual	Mid-rise	Nottingham
4b.				MEV	Individual		London Heathrow Southampton
7.	Semi-detached	3b5p	Triple	Nat. Vent	Individual	Masonry	All 3 locations

3.2 Aggregating to new build housing stock in England

The following assumptions have been made when aggregating to the new build housing stock in England.

- The results for the 2-bed apartment apply to all new apartments and the semi-detached results to all new houses.
- The single aspect apartment results apply to 25% of new apartments and the dual aspect apartment results apply to 75% of new apartments. The project team did not find any specific data on the split of single and dual aspect flats at the regional or national level. The proposed split was agreed with the Research Group.
- In terms of geographical distribution:
    - Nottingham results apply to all homes built in the regions north of London
    - London Heathrow results apply to homes built in Greater London
    - Southampton results apply to all homes built in the regions predominantly south of London (i.e. south-east and south-west)

Additionally, the following data sources have been used to derive the new build housing stock numbers and split by region for the cost-benefit analysis.

- Current annual new build rate from data published by MHCLG (Live tables on house building: new build dwellings, Table 213: permanent dwellings started and completed, by tenure, England)[6].
- Housing split by region and dwelling type from NHBC (National House Building Council) (Housing Market Report, October 2017, Table QS4 – Percentage of homes started by region and Table QS13 – Percentage of houses by type and price at registration, by region)[7].
- Annual new build growth rate of 5% between 2020 and 2029 as a central estimate (Table 3.2, DCLG Housing Standards Review - Evidence Report, Adroit Economics, August 2014).

[6] The figure used is total completions in 2016 as figures for last quarter of 2017 were not available.

[7] Yearly data for 2016

4. Assessing overheating risk and benefits using thermal modelling

This section describes the dynamic thermal modelling undertaken to assess the risk of overheating and to quantify the benefits associated with risk mitigation packages. The internal temperatures determined from the modelling were analysed to quantify the health and productivity benefits as detailed in section 5 .

Two sets of modelling were undertaken.

- **Risk modelling:** The purpose of this modelling was to determine whether the risk mitigation strategies sufficiently controlled the risk of overheating (i.e. met the CIBSE TM59 overheating criteria). As outlined in Section 2, five overheating risk mitigation strategies were assessed for each of the three dwelling types and locations. For each of these cases, dynamic thermal modelling was undertaken to assess the risk of overheating using the CIBSE TM59 methodology and criteria. This used TM59 assumptions on dwelling occupancy and Design Summer Year 1 (DSY1) 2020s weather data as recommended by CIBSE. More detail on risk modelling is provided in Section 4.1 and the Phase 1 report.
- **Benefits modelling:** The purpose of this modelling was to help assess the benefits of applying risk mitigation strategies to new build housing. For each combination of dwelling types, locations and occupancy profiles further dynamic thermal modelling was carried out to determine the impact of five risk mitigation strategies on the internal temperatures using average occupancy data from the English Housing Survey (EHS). The modelling was carried out using four sets of weather data – DSY1 2020s, DSY1 2050s, Test Reference Year (TRY) 2020s and TRY 2050s. A further set of thermal modelling was undertaken for each case to represent a counterfactual where no risk mitigation was included as part of the building's construction. More detail on each of these aspects is provided in Section 4.2.

The risk and benefit modelling methodology differed. The risk modelling defined in CIBSE TM59 represents a relatively more demanding scenario to 'stress-test' whether the building would overheat under the moderately warm summer conditions expected over the next couple of decades and assuming maximum design occupancy (and therefore higher internal heat gains) for the dwelling. The risk modelling additionally assumed that the dwelling may be occupied by vulnerable persons in line with the overheating definition agreed with MHCLG in Phase 1. This makes the compliance criteria more stringent by reducing the upper threshold for comfort temperature by 1 °C. However, the risk modelling used 2020's DSY1 weather data in line with CIBSE TM59 guidance, so did not account for extreme weather events and a further warming of the climate in the future. The benefit modelling aimed to represent better the typical household, such that the cost-benefit analysis provided a reasonable reflection of the impact of implementing the risk mitigation strategies on the population as a whole.

The sub-sections below provide more detail on the specific assumptions and data used for the risk and benefits modelling.

4.1 Risk modelling

Each of the 9 cases representing different dwelling types and location was modelled using the CIBSE TM59 methodology to assess whether the mitigation packages set out in Section 4.1.2 below adequately addressed the risk of overheating. The mitigation strategy included in the cost-benefit analysis was that which met the TM59 criteria at lowest capital cost although passive strategies were always prioritised over those with active cooling.

The risk modelling was carried out with 2020s DSY1 weather file using standard occupancy assumptions as set out in the TM59 guidance. The TM59 guidance does not provide detailed guidance on how occupants open windows. The window opening regime used for this study is set out in Section 4.1.1 below.

The risk modelling was carried out assuming south facing living rooms. West facing living rooms were the worst performing of the different orientations modelled as part of sensitivity analysis in Phase 1. However, the south facing living rooms were modelled as these were considered broadly an average of how dwellings would perform across the different orientations.

The modelling methodology followed for the overheating risk modelling is described in more detail in the Phase 1 report. The results are summarised in Section 7.

The impact of orientation of TM59 compliance has been tested for the west orientation in case of the single aspect flat (Type 2) and house (Type 7). The results are presented in Section 7.5.

The impact of DSY1 2050s weather data on overheating risk for a single aspect flat location in Southampton has also been tested. This is because temperatures in Southampton increase by the largest amount when comparing 2020s and 2050s weather. The results are presented in Section 7.6.

4.1.1 Occupant window opening regime

The following assumptions were made in terms of how occupants would open windows during the summer months. CIBSE TM59 methodology assumes that occupants are present all day. For the risk modelling, windows, patio and balcony doors were modelled to start to open in occupied rooms during the daytime when indoor operative temperature exceeds 22°C and are fully open (to a maximum of 30°) when temperature exceeds 26°C. Similarly, window and door openings were modelled to start closing as internal temperature drops below 26°C and are fully closed when internal temperature drops below 22°C. The window opening regime is the same as used in Phase 1 for the risk modelling, with the exception of window opening being limited to 30 degrees (rather than fully open) as feedback from the Research Group suggested that this may be a more realistic reflection of occupant behaviour.

This window opening regime was applied to all risk mitigation packages with the exception of dwellings with active cooling[8], where windows are assumed to be closed when

[8] Includes dwellings with risk mitigation Package 5 and those where air-conditioning is retrofitted in the counterfactual case.

temperature exceeds 24°C. Note that where there is no daytime occupancy, the windows are assumed to be closed during the day. This applies only to the benefits modelling.

At night-time (23:00 hrs to 08:00 hrs), bedroom windows were modelled with restrictors (maximum opening angle of 10°) to reflect security concerns. The bedroom windows were modelled as being open at night only if the temperature at 23:00 hours (i.e. when the occupants are going to sleep) is greater than 23°C. Where temperature is lower than 23°C at 23:00 hours, bedroom windows were assumed to be closed throughout the night.

4.1.2 Risk mitigation packages

The five risk mitigation packages evaluated are listed below. It was assumed that air-conditioned spaces deliver the desired thermal comfort and there are no overheating related health impacts – hence no modelling was undertaken for Package 5. As mentioned in the preceding section, dwellings are assumed to be occupied during the day for the risk modelling in line with CIBSE TM59 methodology.

Table 3: Risk mitigation packages

	Passive measures	Active measures	Occupant behaviour
Package 1 (minimal or no cost to developer)	**Internal blinds** on all windows except on north façade; vertical slats on east and west facades and horizontal slats on south for effective shading. Assumed to be light coloured blinds with shading coefficient of 0.61 and short-wave radiant fraction of 0.3 (Values from IES Apache Tables for venetian blind). It is assumed that the blinds are partially open for ventilation (45° tilt) and that this does not affect air flow through the windows[9].	-	**Daytime occupancy:** Internal blinds drawn on east, west and south façades to reduce solar gains. Assumes occupant controlled blinds that were modelled using the following profile: · Incident radiation to lower blind - 200W/m² · Incident radiation to raise blind - 150 W/m² Windows closed where external temperature is 3°C higher than the internal operative temperature **No daytime occupancy (for benefits modelling only):** Internal blinds drawn during the day and windows assumed to be closed.
Package 2 **(low to medium cost to developer)** **Implications:** **Potential impact on daylight due to reduced**	**Lower g-value glazing** (0.4 reduced from 0.63) with high light transmittance (0.7). **Reduced glazing ratios in flats** to 25% of floor area, down from 28% in single aspect and 47% in dual aspect flat (without a reduction in openable glazing area). To be achieved by raising	-	**Daytime occupancy:** Windows closed where external temperature is 3°C higher than the internal operative temperature. **No daytime occupancy (for benefits modelling only):** Windows assumed to be closed.

[9] Discussions with BBSA and the Research Group did not highlight any existing studies that could provide specific data on the impact of different types of internal or external shading devices on ventilation rates.

<table>
<tr><th></th><th>Passive measures</th><th>Active measures</th><th>Occupant behaviour</th></tr>
<tr><td>glazing ratios in flats.</td><td>the sill level where possible to minimise impact on daylighting.</td><td></td><td></td></tr>
<tr><td>Package 3 (medium to high cost to developer)

Implications:
Windows need to be designed to open inwards.</td><td>Fixed external shading to allow for ventilation plus secure ventilation at night. Modelled as:
· External shutters with louvres in houses (or a design response that achieves similar transmission coefficients as shown below and does not obstruct ventilation)
Transmission factor[10] at varying sun angle – south facade
<table><tr><th>0°</th><th>15°</th><th>30°</th><th>45°</th><th>60°</th><th>75°</th><th>90°</th></tr><tr><td>1.00</td><td>0.73</td><td>0.41</td><td>0</td><td>0</td><td>0</td><td>0</td></tr></table>Transmission factor at varying sun angle – east, west and north facade
<table><tr><th>0°</th><th>15°</th><th>30°</th><th>45°</th><th>60°</th><th>75°</th><th>90°</th></tr><tr><td>0.50</td><td>0.26</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr></table>· Fixed horizontal shading with 50° altitude cut-off for south facing windows in flats. This allows for a high proportion of shading during the summer months (May to August) while allowing for solar gains in the winter months.
· Retractable louvres on east, west and north façades in flats with transmission factors as for houses above.
Reduced glazing ratios in flats to 25% of floor area, and all modelled as openable apart from the windows in the bathrooms, toilets and en-suites.
Additional openable windows on third aspect for semi-detached house to encourage cross-ventilation and bring total glazing to floor area ratio of 20%.</td><td>-</td><td>Daytime occupancy: Occupant controlled shading devices modelled using the following profile:
· Incident radiation to activate shading - 200 W/m^2
· Incident radiation to raise shading - 150 W/m^2
Windows closed external temperature is 3°C higher than the internal operative temperature.
No daytime occupancy (for benefits modelling only): External shading devices active throughout the day and windows closed.
Both occupancy scenarios: Secure ventilation at night. Bedroom windows opened to 30° between 23:00 to 8:00 hrs, if temperature at 23:00 is greater than 23°C. Where temperature is less than 23°C at 23:00 hrs, bedroom windows assumed to be closed all night.</td></tr>
</table>

[10] Fraction of light transmitted through the window taking into account shading from overhangs and/or fins. A transmission factor of 1 indicates 100% of light is transmitted.

	Passive measures	Active measures	Occupant behaviour
Package 4 (medium to high cost to developer) **Implication: Requires consideration of suitable construction systems and materials, plus adequate night-time ventilation in all rooms.** **Windows need to be designed to open inwards.**	**As for Package 3 plus high thermal mass**[11]. For semi-detached house with masonry construction, this includes: · Heavyweight blockwork and dense (wet) plaster for external walls, party walls, and internal partitions · Precast concrete planks with screed for internal ceiling/floor For the apartments with concrete frame and infill construction, this includes: · Heavyweight blockwork and dense (wet) plaster for external walls, party walls, and internal partitions · Dense plaster (ceiling), concrete slab and screed for party floors · Dense plaster (ceiling) and concrete slab for roof (warm deck)	-	As for Package 3, plus secure evening and night time ventilation irrespective of room occupancy. Living room and bedroom windows opened to 30° between 23:00 to 8:00 hrs, if temperature at 23:00 is greater than 23°C. Where temperature is less than 23°C at 23:00 hrs, windows assumed to be closed all night. Patio doors in the semi-detached house are assumed to be closed throughout the night.
Package 5 (medium to high cost to developer) **Implications: Windows need to be designed to open inwards.**	As per Package 3	Active cooling (reversible heat pumps) with a set temperature of 24°C[12]. Heat pump in cooling mode to be modelled with an Energy Efficiency Ratio (EER) of 3.2[13]	As per Package 3

The risk mitigation packages have been designed so as to prioritise passive and behaviour change measures over active measures. Hence, Package 5 includes both passive and active measures to reduce cooling energy demand. The list of packages does not include the option of active cooling only which may reduce the upfront capital cost but increase the cooling energy consumed depending on how occupants use their home. When aggregated up to the energy system level, the impact of electricity requirements to meet higher cooling

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[11] Classification as per SAP 2012 conventions (August 2017, v7.01), Appendix 5

[12] Note that in reality people may choose to set a lower temperature for cooling. The modelled set temperature assumes a conservative scenario that has relatively lower cooling energy demand while addressing the productivity and mortality related impacts of overheating.

[13] Recommended minimum requirement as per Building Services Compliance Guide for Part L 2013 for water loop heat pump

demand could be significant. Active cooling also has an impact on external temperatures, and in cities this contributes to the urban heat island effect.

The following mitigation measures/ strategies have, however, not been factored into the analysis at this time:

- Reduced internal gains from occupant activity, such as cooking or electrical equipment, as this is influenced by a complex combination of occupant behaviour and other social and cultural factors
- Ability to modify the local microclimate e.g. trees and water features (evaporative cooling) as the scope of this project is on interventions at a building level.
- Surface finishes and reflectance properties for external façade (as well as surrounding roads and pavements). Reflective finishes in dense urban environment may not always deliver the intended benefits due to scattering of reflected solar radiation.

4.2 Benefits modelling

The benefits modelling was carried out to determine the impact of five risk mitigation strategies (as described in Section 4.1.2) on the internal temperatures using four sets of weather data (see Section 4.2.1 below). The modelling was carried out for each combination of dwelling types, locations and occupancy profile using average occupancy data from EHS as set out in Section 4.2.2 and 4.2.3. A further set of thermal modelling was undertaken for each case to represent a counterfactual where no risk mitigation was included as part of the building's construction. The counterfactual case is discussed in detail in Section 4.2.4.

The window opening regime for both the risk mitigation scenarios and the counterfactual is as described in Section 4.1.1, unless modified specifically for the risk mitigation package as described in the 'occupant behaviour' column of Table 3. For the no daytime occupancy scenario, the windows are assumed to be closed during the day.

As with the risk modelling, the benefits modelling was carried out assuming south facing living rooms.

4.2.1 Climate scenarios

Design Summer Year (DSY1) and Test Reference Year (TRY) weather data were used for the benefits modelling. Both the DSY1 and TRY weather files are based on UKCP09 high carbon emissions scenario with 50% probability (DSY1/ TRY – High emissions scenario - 50th percentile).

The TRY data represents a typical year. The DSY1 data represents a moderately warm summer (i.e. warmer than a typical year). Based on current climate, it has a return period of 7 years i.e. it is expected that there is a 1-in-7 chance of temperature being equal to or hotter than DSY1 temperature data[14]. The return period for future DSY1 weather data is unknown and is the subject of further CIBSE research; however 7 years is potentially an

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[14] CIBSE Weather Files 2016 release: Technical Briefing and Testing. Available at https://www.cibse.org/getmedia/ce7a77e8-3f98-4b97-9dbc-7baf0062f6c6/WeatherData_TechnicalBriefingandTesting_Final.pdf.aspx

underestimate as the trend is for hotter than average summers to be more frequent in the future.

It was agreed that for the purpose of calculating the benefits the DSY1 weather conditions would be assumed to have a return period of 7 years. As the occurrence of DSY1 is probabilistic, each year gained one seventh of the benefit from mitigating overheating under DSY1 weather conditions and $6/7^{th}$ of the benefits from TRY weather conditions.

Both 2020s and 2050s DSY1 and TRY data were modelled and used for the benefits analysis. The 2020s weather data was applied from 2020 - 2040 and the 2050s data from 2041 - 2079[15].

Sensitivity analysis during Phase 1 showed that DSY1 2050s data increased the number of hours of overheating by a multiple of 2-5 with Nottingham weather data. However, with discount factors, benefits (and indeed costs) accrued in future years have progressively less impact on the net cost and/or benefit.

4.2.2 Number of occupants

The total number of occupants for the 2-bed flat typologies and the semi-detached house were based on the average number of occupants (i.e. the average number of adults and children) from the English Housing Survey (EHS) 2015 -2016 dataset for flats and houses respectively[16]. This means that the heat gains from occupancy assumed in the modelling broadly reflect the average across the stock. The average occupancy data from EHS is shown in the table below.

As there is limited regional variation, it was agreed to use the occupancy data for all of England across all locations. The level of occupancy in London was higher than for the other regions but it was deemed sufficient to use the national data for the benefit calculations.

Table 4: Average occupancy data from EHS (Source: MHCLG)

Average number of occupants	North England	London	South England	All of England
Houses				
Adults	1.99	2.32	2.04	2.03
Children under 16	0.50	0.55	0.50	0.50
Total	2.48	2.87	2.54	2.54
Flats				
Adults	1.41	1.71	1.50	1.53
Children under 16	0.15	0.43	0.29	0.28
Total	1.55	2.14	1.79	1.81
All dwelling types				
Adults	1.91	2.03	1.94	1.93
Children under 16	0.45	0.49	0.47	0.46
Total	2.36	2.52	2.41	2.39

[15] 2020s weather data is representative of the time period 2011-2040. The 2050s weather data is representative of the time period 2041-2070. For the current analysis, the 2050s DSY and TRY data was applied from 2070 onwards until 2079.

[16] Data provided by MHCLG after analysing EHS data

4.2.3 Occupancy scenarios

Two occupancy scenarios have been modelled for the benefit analysis. Each of the three dwelling types has been modelled both with and without day time occupancy. This captures, for instance, the exposure to elevated internal temperatures during the day which in turn impacts on benefits accrued (this is discussed further in Section 5).

For the two scenarios, occupancy profiles were developed for the flat and house typologies as shown in Table 5 to Table 8. These were developed based on discussions with University College London (UCL) and a broad steer from TM59 occupancy profiles. The shaded figures show the proportion of maximum occupant gains that will be assumed at a given hour taking into account the number of occupants assumed in that room and whether the occupants are awake or asleep. The second column on the left shows the maximum occupancy in that room. The values are non-integers to reflect the average number of occupants per dwelling identified in Section 4.2.2. So, in any given hour the internal occupancy gains in a room were calculated based on the heat gain per person (from CIBSE TM59) multiplied by the maximum occupancy in that room (second column in the tables below) and the proportion of occupant gains assumed in that hour (shaded cells in the tables below).

Table 5: 'Daytime occupancy' scenario for 2-bed flats

	No. of occupants	Proportion of maximum occupancy gains in each hourly period*																							
		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15 -16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Living/ kitchen	1.05	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Double Bed 1	1.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.7
Single Bed 2	0.3	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.7
Max. occupancy in dwg**	1.8																								

* 1=100% of gains from occupants, 0=0%, 0.5 = half the occupancy compared to full bedroom occupancy and so 50% gains, 0.7 reflects a lower metabolic rate at night in line with TM59. Occupancy gains assumed to be 75 W/person sensible and 55 W/person latent. During sleeping hours these gains are reduced by 30%.
**At any given hour

Table 6: 'No daytime occupancy' scenario for 2-bed flats

	No. of occupants	Proportion of maximum occupancy gains in each hourly period*																							
		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15 -16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Living/ kitchen	1.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0
Bed 1	1.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.7
Bed 2	0.3	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.7
Max. occupancy in dwg**	1.8																								

Table 7: 'Daytime occupancy' scenario for 3-bed semi-detached house

	No. of occupants	Proportion of maximum occupancy gains in each hourly period *																							
		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15 -16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Living	1.5	0	0	0	0	0	0	0	0	0	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0	0
Kitchen/ Dining	1.5	0	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0
Bed 1	2	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.7
Bed 2	0.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.7
Bed 3																									
Max. occup. in dwg**	2.5																								

Table 8: 'No daytime occupancy' scenario for 3-bed semi-detached house

	No. of occupants	Proportion of maximum occupancy gains in each hourly period *																							
		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15 -16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Living	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75	0.75	0.75	0.75	0.75	0	0
Kitchen/ Dining	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25	0	0
Bed 1	2	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.7
Bed 2	0.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.7
Bed 3																									
Max. occup. in dwg**	2.5																								

To scale up the benefits to the new build housing stock in England, the modelling results for the two occupancy scenarios described above have been weighted based on the data analysed from the UK Time Use Survey 2014-15.

The UK Time Use Survey (TUS) sample comprises 4,741 households (9388 people) in England, Scotland, Wales and Northern Ireland, and is considered representative of the population. People in selected households completed a time diary exercise in which respondents were asked to record their daily activities. For the purpose of this research, the data required from the TUS was whether people were at home during the hottest hours of the day. This was defined as 3 or more hours at home between the hours of 11am-5pm. Weekend and weekday data was merged together using a weighting of 5/7 and 2/7 respectively.

The data was analysed by MCHLG and is summarised in the table below. Because of the small difference in results between houses and flats, the proportional split of daytime and non-daytime occupancy for all dwellings was used for the benefit analysis.

Table 9: Split of daytime and non-daytime occupancy for new build stock

	Houses	Flats	All dwellings
Daytime occupancy	32.90%	31.83%	32.75%
No daytime occupancy	67.10%	68.17%	67.25%

4.2.4 Counterfactual case

The counterfactual case models the predicted approach taken if there is no policy intervention and no risk mitigation strategies are included during construction other than those considered in Phase 1 to meet Part L 2013.

Over the building life, the counterfactual case assumes some residents will choose to retrofit measures to address summer overheating. It is assumed those residents will install active cooling which will adequately address the risk of overheating. No change in occupant behaviour is assumed.

In practice, it is expected that the counterfactual will be more complex than this. However, it is difficult to predict the future and a relatively simple approach has been modelled for this analysis.

Note that there will be some constrained sites with minimal scope for natural ventilation. For dwellings located on such sites, developers may choose to install active cooling. It is assumed that the risk of overheating would be adequately controlled for these dwellings and there would not be any health impact associated with overheating (and in turn no benefits associated with the mitigation packages). Hence, this scenario has been excluded from the cost-benefit analysis. However, it would be beneficial to specifically address the design approaches developers can take to mitigate the cooling energy demand for dwellings in such locations in any guidance produced for developers.

4.2.4.1 Retrofitting mitigation measures

It is assumed that room air-conditioners will be retrofitted in the living room and bedrooms, instead of a central system. This is because of the challenges and complexities of retrofitting central systems in existing dwellings (e.g. floor to ceiling heights, routing ductwork, etc.).

The Phase 1 report identified limited information on retrofit rates for air conditioning based on external weather. As agreed with the Research Group, the uptake rate for air-conditioning was calculated based on a formula derived from US data.[17]

The US study provides an algorithm that estimates the potential increase in market saturation as a function of long term increases in cooling degree days (CDD).

S_0 (market saturation) = 0.944 – 1.17 exp(-0.00298*CDD)

Uptake rates were determined separately for each of the three locations (Nottingham, London Heathrow and Southampton) and applied to all the housing stock representative of that location as outlined in Section 3.

Three weather files were used – 2020s DSY1, 2050s DSY1 and 2080s DSY1. DSY1 weather data was used (instead of TRYs or a combination of the two) because there is anecdotal evidence to suggest that extreme weather events often act as a trigger for action (e.g. the extreme summer in London in 2003). This gave three snapshots in time for uptake of air-conditioning – 2020, 2050 and 2080 which, along with current penetration

[17] Sailor D J, Pavlova A A (2003). Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. *Energy* 28 (9): 941-951

rate for air-conditioning (estimated at 2%; refer Section 4.2.4.2[18]), were used to derive annual values between 2020 and 2089. These annual values were then used to calculate the proportion of the housing stock retrofitted with air-conditioning under the counterfactual scenario.

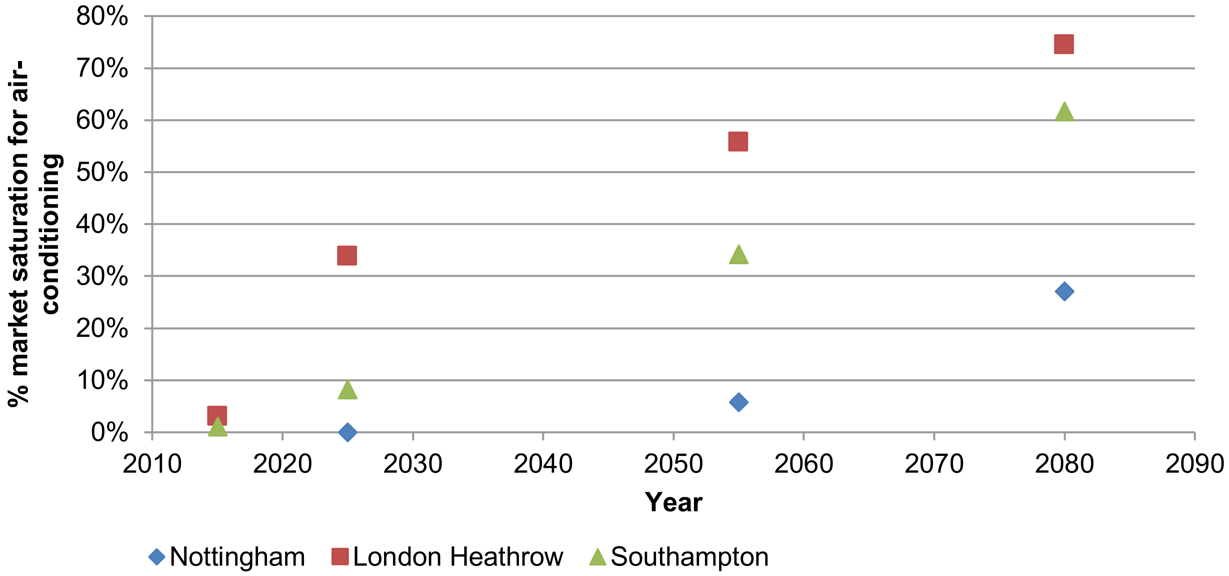
Cooling degree days were calculated from the base temperature of 18.3°C used in the US study.

The results from the analysis are presented in the Table 10. Figure 3 shows the market saturation rates used for the cost-benefit analysis. Linear interpolation has been used to derive the uptake rates for intermediate years.

Table 10: Counterfactual scenario - Cooling Degree Days and predicted market saturation for air-conditioning by location

Location	DSY1 Weather Data	Cooling Degree Days (CDD)	S_0 (%)
Nottingham	2020	46	-7.6%
	2050	93	5.8%
	2080	185	27.0%
London Heathrow	2020	221	33.8%
	2050	371	55.7%
	2080	593	74.4%
Southampton	2020	103	8.2%
	2050	223	34.2%
	2080	427	61.6%

Figure 3: Counterfactual scenario – Predicted market saturation for air-conditioning by location



[18] Note that this figure is an indicative average for the national stock. Current uptake rate of 1% is assumed for Southampton and 3% for London, which reflect the range of figures quoted in other studies.

Sensitivity analysis has been undertaken to make an allowance for potential cultural and behavioural differences for residential air conditioning between the US and England, using a ± 25% variation on the central estimate. This is presented in Section 9.

Cooling energy demand and fuel consumption was then modelled for the different dwellings typologies and locations using IES software, assuming an energy efficiency ratio (EER) of 2.6 (minimum requirement as per Building Services Compliance Guide for Part L 2013) and assuming the dwellings are cooled to 24°C. The modelled fuel costs for different locations, dwelling types and weather files are presented in Section 6.

4.2.4.2 Occupant behaviour

The Energy Technology Institute (ETI) funded Consumer Response and Behaviour project (CRaB) provides some insights into what occupants currently do to keep cool in summer based on a quantitative social survey of 2,313 households. The survey results indicated that only about 2% of households have mechanical cooling. About 84% of the households opened windows and/or doors, either as a standalone measure or in conjunction with other mitigation measures. Potentially more households keep cool by opening windows but have not reported this because they may have windows open for other reasons[19]. About 26% used shading to keep cool, with only 4% of the sample having some form of external shading. No specific information is available on the threshold temperature at which occupants tend to open windows.

Drawing on these insights, the following counterfactual case was modelled:

- Assume windows are open when the relevant room is occupied (excluding wet rooms).
- Gradual opening profile to simulate on average what may be happening across the stock.

Refer Section 4.1.1 for detailed assumptions on window opening profiles.

[19] Gary R (2018). What do households do to keep cool? 10th Windsor Conference: Rethinking comfort. Windsor, UK

5. Quantifying economic value of mortality and productivity benefits

Overheating can have direct effects on health, comfort and productivity (during exposure and for a period afterwards). It can also disrupt sleep (itself an adverse effect) with consequential effects on health, safety and productivity. There is a significant challenge in assigning an economic cost to overheating (or an economic benefit from avoiding overheating).

It was agreed by MHCLG and the Research Group that the economic benefit of mitigating overheating should be determined based on a combination of:

- The direct impact of overheating on health mortality[20]
- The indirect impact of overheating on productivity due to sleep disruption.

5.1 Mortality related benefits

This analysis looks to quantify the benefit from the reduction in the number of deaths associated with summer overheating in new homes in England through the installation of risk mitigation measures.

Higher temperatures are linked to an increase in mortality rates, and this response is not just seen at extreme temperatures. There are well-defined temperature-mortality functions i.e. relationships between risk of death and daily maximum external temperature.[21] Separate functions have been derived for different regions/ locations of England and Wales. As an example, the temperature-mortality relationship for London is shown in Figure 4. The y-axis indicates the relative risk for mortality as a function of external temperature.

Mortality rates increase significantly above a ‘threshold temperature’, as is indicated by the shape of the curve in Figure 4. This heat threshold temperature also varies by location; as an example it is 24.8°C for London. As an approximation, the temperature-mortality relationship above the ‘threshold temperature’ can be assumed to be log-linear, so that

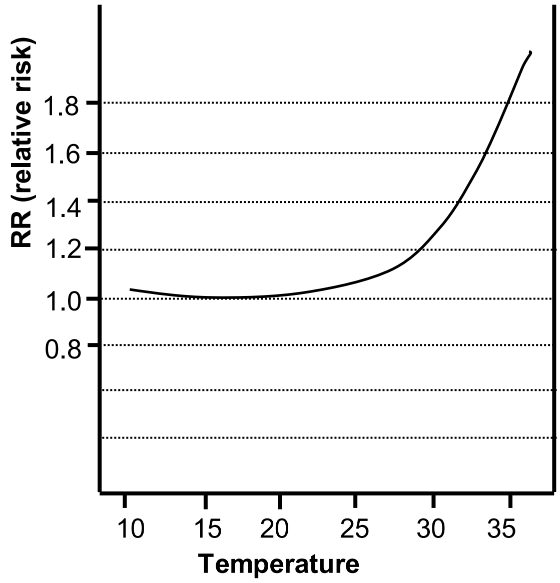
[20] There is less clear evidence for computing the direct adverse effect of heat on morbidity. Poor correlation has been observed between heatwaves and hospital admissions*. Also, mortality impacts are likely to dominate the overall economic benefit. Therefore it was agreed with MHCLG to confine the analysis to mortality related impacts.

*Kovats RS, Hajat S, Wilkinson P. Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. *Occupational and Environmental Medicine* 2004;61:893-898.

[21] Armstrong BG, Chalabi Z, Fenn B, Hajat S, Kovats S, Milojevic A, Wilkinson P (2011). The association of mortality with high temperatures in a temperate climate: England and Wales. *Journal of Epidemiology and Community Health*, Apr 65(4):340-5.

each degree Celsius increase in temperature above the threshold results in the same proportional increase in mortality[22].

Figure 4: Temperature-mortality association for London



Source: Armstrong et al., Association of mortality with high temperatures in a temperate climate: England and Wales, 2011

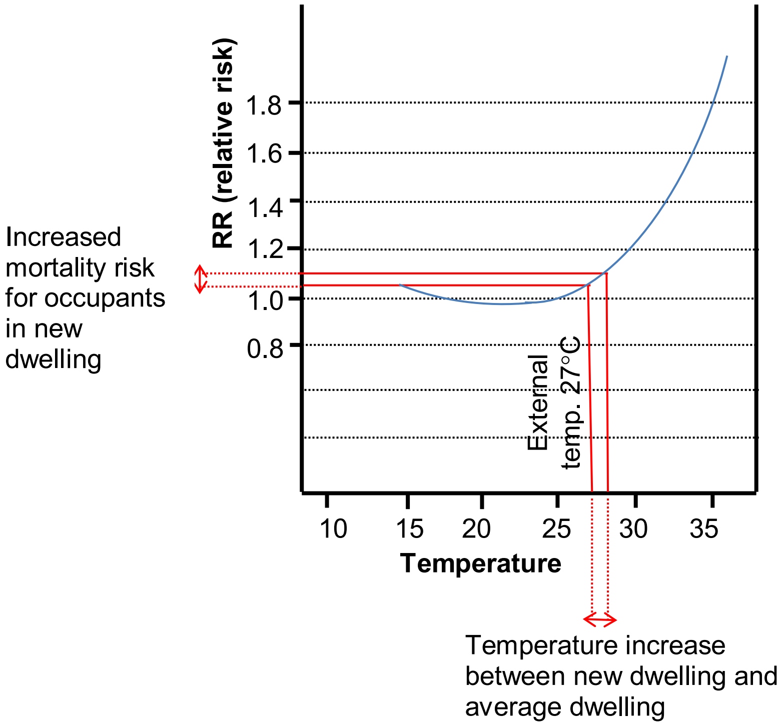
5.1.1 Link to internal temperatures

There is currently no established relationship between the internal temperature in a dwelling and mortality. The approach adopted in this project is summarised below. It is based on the expert input from the London School of Hygiene and Tropical Medicine and University College London.

The relationship between an increased risk of mortality and the indoor operative temperature has been determined by comparing the temperature of an individual dwelling to the average of all other dwellings in the region at the same outdoor temperature. This is referred to as the dwelling-specific 'temperature anomaly'. If newer homes have a higher internal temperature than the average of all other dwellings in the region, then their occupants' relative mortality risk would be higher. Thus, if a new built dwelling located in London has an indoor temperature 1°C warmer than the average dwelling in London when the daily maximum (outdoor) temperature is, for example, 27°C we assume this is the same as the occupants in the dwelling of the average temperature, experiencing the same 1°C rise in the external temperature. Therefore the risk to the individuals occupying that dwelling would be determined by moving up the (external) temperature-mortality curve by 1°C to 28°C. This is illustrated in the figure below.

[22] Note that the curve is in fact closer to a quadratic function for London, but is reasonably (and more simply) approximated by the log-linear assumption.

Figure 5: Example of increased mortality risk relative to an average dwelling in London



Using the approach outlined above, it is thus necessary to estimate the 'temperature anomaly' – the difference between the indoor temperature of the dwelling of interest and the average indoor temperature for all other dwellings in the region. The average indoor temperature for all dwellings in a region is unknown; therefore it must be modelled using building simulation software. To run detailed models on all dwellings in the region however requires significant amount of data and resources. Based on discussions with Phil Symonds and Anna Mavrogianni from UCL it was determined that simulation work by UCL and the London School of Hygiene and Tropical Medicine (LSHTM) using the English Housing Survey (EHS) dataset provides a reasonable estimate of the average indoor temperature for the existing dwelling stock relative to external temperature[23]. The UCL team kindly agreed to provide the relevant data for the purpose of this research.

Based on this data the following formula was derived for the existing dwelling stock[24].

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[23] This work and related research has been published in the following papers

Taylor J, Wilkinson P, Picetti R, Symonds P, Heaviside C, Macintyre H L, Davies M, Mavrogianni A, Hutchinson, E (2018). Comparison of built environment adaptations to heat exposure and mortality during hot weather, West Midlands region, UK. *Environment International*. doi:10.1016/j.envint.2017.11.005

Taylor, J G, Symonds P, Wilkinson P, Heaviside C, Macintyre H, Davies, M, Mavrogianni A, Hutchinson, E (2018). Estimating the Influence of Housing Energy Efficiency and Overheating Adaptations on Heat-Related Mortality in the West Midlands, UK. *Atmosphere*. doi:10.3390/atmos9050190

[24] To derive the relationship between external and internal temperatures for the existing dwelling stock, UCL provided a scatter plot of the mean daytime (8am to 10pm) indoor maximum temperature in the living room as a function of external 2 day mean maximum temperature (over the summer months July-September). The two-day rolling mean was used as this is what was used to derive the external temperature-mortality relationship. A linear trend line for the scatter plot (R-squared 0.89) gave the relationship shown in the main text.

Indoor temperature = 0.7802x + 8.048
where, x is the external 2 day mean maximum temperature

There are inherent differences between the AECOM and UCL simulations. Different simulation software and weather data was used and there were differences in modelling assumptions[25]. However, this was considered acceptable for the analysis. The purpose of this analysis is to determine the difference in mortality risk for new dwellings before and after mitigation measures. Hence the data has been used to evaluate the difference in their temperature anomalies (i.e. how the internal temperature for each alternative differs from the average for the stock in that region). This limits the impact of the differences in approach between the UCL and AECOM models.

5.1.2 Calculation of mortality related benefits

The mortality benefit calculations were carried out for the different dwelling type and locations and the 5 risk mitigation packages. The calculations were also done for the 'no mitigation' case to allow the relative benefits to be assessed for use within the counterfactual scenario. Calculations were done using four sets of weather data: DSY1 and TRY data for 2020s and 2050s. Note that the mortality benefit was only assessed for dwellings with daytime occupancy.

Data from the UK Time Use Survey was used to understand the type of occupants living in those property types, broken down by age and sex, and in turn to compute the mortality benefits. The UK Time Use Survey data was analysed by MHCLG to give a percentage breakdown of occupancy by gender and 5-year age bands for the houses and flats as shown in Table 11.

Table 11: Daytime occupancy scenario - Breakdown of occupancy by dwelling type, age and gender

	Houses		Flats	
5 year age bands	Male	Female	Male	Female
08-10	1.23%	0.89%	0.97%	1.23%
11-15	2.02%	2.07%	0.31%	0.54%
16-20	3.07%	3.97%	3.21%	1.14%
21-25	2.71%	2.01%	3.50%	3.23%
26-30	1.81%	3.31%	3.92%	6.07%
31-35	2.02%	3.81%	5.81%	5.38%
36-40	2.57%	3.08%	1.89%	3.47%
41-45	2.80%	4.20%	3.57%	3.60%

[25] In Phase 1 of this project, the project ream reviewed work by CIBSE (unpublished report dated 10/08/2016) that compared the overheating risk in a sample of apartments using three different dynamic simulation software. This indicated that while the percentage overheating hours for each software follow a logical trend there were significant differences (as much as three times in instances based on the sample and variables tested) across the three software types. The differences in results are largely attributable to fundamental differences in the software, which (apart from one of the software) are not open source and therefore not open to scrutiny and/or detailed comparison.

	Houses		Flats	
5 year age bands	Male	Female	Male	Female
46-50	3.05%	3.81%	3.26%	2.29%
51-55	3.30%	3.41%	3.70%	2.24%
56-60	2.94%	3.51%	2.65%	1.60%
61-65	3.33%	3.48%	5.20%	2.92%
66-70	3.97%	4.93%	4.27%	1.37%
71-75	3.45%	3.94%	2.07%	1.95%
76-80	3.11%	4.45%	1.43%	4.46%
81-85	1.94%	2.32%	3.96%	4.94%
86-90	1.03%	1.55%	0.98%	1.63%
91-95	0.23%	0.55%	0.35%	0.63%
95+	0.02%	0.13%	0.24%	0.00%

The risk of dying on a given day (i) is:

$RR_{(Ti+\delta Ti)}$ x (daily mortality rate)$_k$

where,

- $RR_{(Ti+\delta Ti)}$ is the relative risk for mortality at a given external temperature T_i and difference in temperature anomaly δT_i before and after mitigation measures where there is daytime occupancy, and
- the daily mortality rate for age-sex group k is determined from published tables for England[26], adjusted for seasonality[27]

The risk of death was converted to number of life years saved using life expectancy data for each age-sex group.[28] This gave the number of life years saved for each dwelling type, location and risk mitigation strategy relative to the 'no mitigation' scenario.

The analysis assumes the occupants of these dwellings are representative of the general population. In addition, it assumes that the population today remains static and will be representative of the population over the next 70 years (of a 10 year build cycle and a 60 year life of buildings). In practice, the general population is expected to age over the coming years as people live longer. In addition immigration may also affect demographics. The elderly have a greater mortality risk from overheating and assuming a static population is likely to underestimate the benefits of applying mitigation measures. In contrast, the analysis assumes constant population numbers and does not remove those that die from overheating, which is likely to overestimate the risk and therefore the benefits of mitigation measures. It is unclear how these uncertainties balance out overall.

[26] Office for National Statistics (2017).Dataset: Mortality rates (qx), principal projection, England and Wales.

[27] The annual mortality rate was used for the calculations, adjusted for the summer months, and averaged by 5 year age bands to align with the dwelling occupancy data from Time Use Survey (see Section 4.2.3).

[28] Office for National Statistics (2017).Dataset: Life tables, principal projection, England and Wales.

5.1.3 Monetary value of mortality benefits

The number of life years saved for all the occupants living in the property under a certain risk mitigation scenario were converted into a monetary value based on the value of Quality Adjusted Life Year (QALY) of £60,000 as a central estimate[29]. An annual uplift was applied to this value to compute the monetary value in future years based on the predicted annual growth in average GDP per person. The percentage annual growth figures are taken from guidance published by the Department of Transport[30].

5.2 Productivity related benefits

As highlighted in the Phase 1 report, sleep disruption is a critical factor in assessing the adverse impact of overheating. This section summarises the impact of overheating on sleep disruption and the consequent impacts of sleep disruption and sets out the approach taken for evaluating the economic cost of the associated impacts.

5.2.1 The impact of overheating on sleep

Whilst it is well established that overheating can disrupt sleep, evidence on critical temperatures and magnitude of effect due to overheating is less clear. The challenge for the current analysis was therefore to determine the magnitude of disruption caused by any given temperature or deviation from the usual temperature range.

Phase 1 included a review of published research and concluded the following[31]:

- Overheating could reasonably be estimated to reduce good sleep by one or two hours (or cause an equivalent reduction in sleep quality). This can be expected to vary considerably across the population but provides an approximate quantification.
- There is little research that identifies the threshold temperature that is considered so warm as to cause sleep disruption and almost none in the UK.

Based on this evidence, and the threshold figure of 26°C adopted in this study to assess the overheating risk for bedrooms (CIBSE TM59 Criterion B), the following is assumed for the purpose of this analysis:

- Where the bedroom temperature exceeds 26°C for 2 hours or more it reduces sleep by one hour per night, increasing to two hours when exceeded for 4 hours or more.
- Additionally, one hour of sleep is assumed to be lost where the bedroom temperature exceeds 29°C for one hour or more, increasing to two hours of sleep lost where it exceeds 29°C for two hours or more. This allows for greater impact at warmer temperatures.

Sensitivity analysis has been carried out on these figures and the results are presented in Section 9.

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[29] HM Treasury (2018). The Green Book - Central Government Guidance on Appraisal and Evaluation. London: HM Treasury

[30] Department of Transport (May 2018). WebTAG Databook. London: Department of Transport. Available at https://www.gov.uk/government/publications/webtag-tag-data-book-may-2018

[31] Refer to Section 5.1.2 of the Phase 1 report for detailed references.

5.2.2 The impact of sleep disruption

The Phase 1 report reviewed the impact of sleep disruption[32]. In summary, sleep disruption has multiple and interrelated effects on physiological function, health, performance, safety and quality of life. It can also have other negative impacts e.g. on domestic and other relationships, assaults and poor purchase/investment decisions.

5.2.3 Valuing impacts

5.2.3.1 Selection of sources

The objective was to devise a method based on existing sources of evidence to put an economic value to sleep-related benefits of reducing the risk of domestic overheating. This is equivalent to measuring the economic harms that arise when a home becomes overheated.

A full evaluation would need to take into account the effects of sleep disruption on risk of injury at home and elsewhere, illness and death, quality of life, and productivity at home and in the workplace. These effects will all vary between population groups and depend on the duration of periods of overheating – within and between sleep periods. This would require a massive literature review and econometric exercise, and would still lack good evidence in many areas. To undertake such an exercise was beyond the capacity of this project.

Fortunately, other studies have sought to estimate the overall impact of sleep disruption and these analyses are useful in simplifying the current exercise. We have therefore reviewed the available work to identify which sources would be most relevant. In doing this, we have considered the following criteria.

1. Sleep disruption due to persistent sleep disorders does not necessarily have the same effect as sleep disruption due to a period of overheating. Persistent conditions may be assumed to result in greater demand on health services and to have a greater likelihood of having comorbidities such as obesity and diabetes. Thus, the impact of diagnosed disorders is likely to be greater that the effect of overheating, even allowing for the different number of nights affected.
2. More generally, any analysis that directly addresses sleep disruption due to overheating would be most useful or, failing this, another cause that is in some way comparable.
3. Evidence is most relevant if it is from England or other locations with comparable climate, economy or culture.
4. Recent evidence is likely to be more relevant and easily applicable.
5. Reviews and meta-analysis are less prone to error than single studies, especially single studies that are smaller or unrepresentative.
6. Evaluation of impacts via sleep disruption should avoid double-counting mortality impacts.

[32] Refer to Section 5.1.2 of the Phase 1 report for detailed references.

7. The analysis should not be subject to any obvious commercial interests that might be a source of bias.

Based on these criteria, two studies were identified that were most relevant for our project: Hafner et al. (2016) and Defra (2014). The former has been used as the principal study with the latter providing an upper end estimate and sense check.

5.2.3.2 Hafner et al. (2016)[33]

This analysis is an independent research by RAND Europe. The report outlines a useful and relevant approach to measure the economic impact of sleep loss, using a large, recent, detailed UK data set on reported sleep quality and personal health and productivity. It assesses the impact of sleep disruption rather than clinically defined sleep disorders and it separately evaluates health and productivity effects. It is very focused on social causes of sleep loss, particularly workplace issues; it does not refer to overheating or other indoor environmental causes of sleep disruption. However, by addressing non-clinical factors that are not necessarily persistent, it has some comparability with the context of overheating.

The relevant part of this analysis is the estimate of effects of short sleep duration on productivity. Relative to sleeping 7-9 hours, “productivity loss” was estimated to be 1.47% higher if sleeping 6-7 hours and 2.36% higher if sleeping <6 hours. The authors convert this to, respectively, 3.7 and 6.0 working days lost per year.

A necessary assumption has been that impact is proportional to the number of days when sleep is disrupted. Implicitly this assumes that a short period of sleep disruption has a rapid effect, rather than the effect needing to accumulate over weeks. This is consistent with the evidence cited above and with most people’s experience. There could even be an argument that the impact will be greater for people who are not accustomed to experiencing reduced sleep.

Hafner et al. count mortality as having an impact on productivity, which is technically double-counting; however this is a small part of the whole impact on productivity. Also, this is probably balanced by the authors not taking account of quality of sleep, “peer effects” (whereby co-workers become more efficient), or occasional incidents that incur a cost beyond routine lost productivity.

5.2.3.3 Defra (2014)[34]

This is a recent report focused on noise related impacts in England. The analysis is specific to environmental noise although it establishes some key principles for monetising outcomes of sleep disruption (such as annoyance, amenity and productivity) using DALYs (disability-adjusted life years) or QALYs (quality-adjusted life years).

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[33] Marco Hafner, Martin Stepanek, Jirka Taylor, Wendy M Troxel, Christian van Stolk (2016). Why sleep matters- the economic costs of insufficient sleep: A cross-country comparative analysis. RAND Europe.

[34] Department of Environment Food and Rural Affairs (2014). Environmental Noise: Valuing impacts on sleep disturbance, annoyance, hypertension, productivity and quiet. Department of Environment Food and Rural Affairs.

A key difference between noise and overheating is that there is a vast literature on the relationship between noise and sleep disturbance but very little quantifying the impact of high temperatures on sleep. Also, households exposed to environmental noise are exposed routinely rather than on some days in summer. On the other hand, heatwaves are likely to affect a larger proportion of the population than noise. The pattern of sleep disruption would be quite different, so assumptions would need to be made. The report, as a minimum, offers a reality check in relation to the (large) economic impact that an environmental stressor can have. Also, the use of marginal estimates of the cost of a 1 dB increase in noise is analogous to estimating the effect of a 1°C increase in temperature.

The analysis for the purpose of this study was based on Defra's Chapter 5 (impact on productivity) because this part is most directly comparable with the Hafner *et al.* evaluation. Because this was a reality check, not the main analysis, the focus has been on estimating a value in the upper region of the possible range.

Unlike Hafner *et al.*, the Defra approach does not discriminate on the basis of number of hours of sleep lost. Hence there is one threshold for temperature disrupting sleep. For consistency with the Hafner *et al.* approach, the same temperatures and periods were adopted that are assumed to result in either one or two hours of sleep lost (i.e. temperature exceeds 29°C for one hour or more or exceeds 26°C for 2 hours or more).

5.2.4 Monetary value of productivity benefits

Based on the evidence relating to the impact of overheating on sleep in section 5.2.1, the night-time bedroom temperatures were translated to an outcome of sleep being reduced by either 1 or 2 hours. The analysis was done for each dwelling type, location and weather data for the counterfactual case and the 5 risk mitigation packages. The calculations on numbers of hours of sleep lost were done at the individual bedroom level in the dwelling.

Hafner et al. proposes multipliers to convert loss of sleep to annual productivity impact (i.e. days lost). The multipliers were used to work out the days lost per year for all occupants in the dwelling. This used the occupancy data in the dwellings and the bedrooms as described in Sections 4.2.2 and 4.2.3.

The working days lost per year were converted into an economic value using a GDP/head parameter. The GDP per head figure was derived from a published figure of £29,674 (2015 prices) from the Office for National Statistics (ONS) (GDP per head: Table P, January 2018) and converted into 2018 prices by applying the annual rate inflation in recent years (ONS, Consumer price inflation, UK, Jan 2018). An annual uplift was applied to this figure to compute the monetary value in future years based on the percentage annual growth in average GDP per person taken from guidance published by the Department of Transport[35]. This percentage annual growth ranges between 0.71% and 2.01% over the analysis period, i.e 2020 to 2089.

The Defra study places the potential productivity cost of the prevailing levels of environmental noise at £3-6bn per annum assuming one person employed per dwelling. To estimate an upper threshold value for productivity related benefits using the Defra study, the economic impact is estimated as the upper threshold of that range (i.e. £6bn;

[35] Department of Transport (May 2018). WebTAG Databook. London: Department of Transport. Available at https://www.gov.uk/government/publications/webtag-tag-data-book-may-2018

adjusted to 2018 prices) multiplied by the proportion of new build homes where sleep is affected by overheating (relative to those affected by noise) and the mean productivity impact in those homes (representing the proportion of a year during which sleep is disturbed).

6. Cost of risk mitigation packages and counterfactual retrofit package

This section sets out the capital costs, replacement costs, fuel costs associated with active cooling systems, and the cost of carbon used for the cost-benefit analysis[36].

6.1 Capital costs

The capital costs of the risk mitigation measures set out in Section 4.1.2 were estimated based on Spon's Architects' and Builders' Price Book 2018 and internal AECOM residential cost data. Costs are based on Q1 2018 outer London prices and include 12% uplift for preliminaries and 10% for overheads and profit. This reflects typical practice in the industry. Costs exclude VAT (Value Added Tax) and inflation. A breakdown of the costs is presented in Appendix A.

The capital costs below reflect the cost of specific technologies or building elements (such as shading devices) plus any costs and/or savings related to increase or decrease in window areas or switching from fixed windows to openable windows. In the case of the dual aspect flat, for instance, the relatively lower capital costs for Packages 2-5 compared to Package 1 is attributable to the significant cost savings from reduced window areas (the capital cost of opaque wall elements being less than for glazing).

The costs for the counterfactual scenario (Package 0 below) are based on room air-conditioners being retrofitted in the living room and bedrooms. These costs only apply to the air-conditioned stock in line with the estimated uptake rate of air-conditioning (refer Section 4.2.4.1).

Table 12: Capital costs for counterfactual and risk mitigation packages (£/dwelling)

	0 *	1	2	3	4	5
Semi-detached house	£8,400	£660	£1,615	£4,080	£17,480	£15,850
Dual aspect flat	£6,975	£2,550	£40	£3,170	£9,480	£9,200
Single aspect flat	£6,500	£1,400	£1,375	£4,500	£10,325	£10,530

*when air-conditioning is installed, costs only apply to the proportion of housing stock that is assumed to be air-conditioned under the counterfactual scenario

Some of the risk mitigation packages may also incur additional capital costs for compliance with current Part L, where for instance the mitigation measures impact on winter solar gains or where active cooling systems are included (e.g. in case of Package

[36] Note that the capital costs of the risk mitigation measures would typically be the cost to the developer of compliance with any relevant future policy, and some of all of these costs might be passed onto the home buyer depending on the market conditions. The cost of retrofitting air-conditioning under the counterfactual scenario and any replacement costs (both in case of the risk mitigation packages and the counterfactual; see Section 6.2) would be incurred by the home owner or the landlord/ social housing provider. The fuel costs outlined in Section 6.3 are projected costs to the occupants (either tenants or owner-occupiers) of operating the active cooling systems.

5). The increase or decrease in window areas also affects heating demand in winters. Part L calculations carried out for the three dwelling types and the five risk mitigation strategies indicate that Package 2 has the most impact on winter heating demand followed by Package 5. In both instances, however, the capital cost impact is estimated to be marginal (assuming costs of photovoltaic panels as a proxy to make up the shortfall). These costs have therefore not been included in Table 12 above.

6.2 Replacement costs

The replacement costs and/ or savings for fabric elements and active cooling are accounted for in the cost-benefit analysis. Replacement costs for fabric elements include the additional cost of low g-value glazing in case of Package 2 and cost of external shading for Packages 3, 4 and 5. Cost savings from reduced window areas (resulting in avoided cost of replacement) are also accounted for in the analysis.

The replacement period is modelled as 15 years for active cooling and 30 years for windows, external shutters and louvres[37]. Fixed horizontal shading on south façades in flats is assumed to have a replacement period of 60 years and therefore replacement costs for this element are not included in the model. It is assumed that the replacement costs are the same as the original capital costs.

Table 13: Replacement costs for fabric elements (£/dwelling)

	0*	1	2	3	4	5
Semi-Detached			£1,615	£5,510	£5,510	£5,510
Dual Aspect			-£3,180	-£2,765	-£2,765	-£2,765
Single Aspect			£1,075	-£60	-£60	-£60

Table 14: Replacement costs for active cooling (£/dwelling)

	0*	1	2	3	4	5
Semi-Detached	£8,400					£11,770
Dual Aspect	£6,975					£6,030
Single Aspect	£6,500					£6,030

*when air-conditioned

6.3 Fuel costs for air-conditioning

Table 15 sets out the energy consumption for cooling calculated using dynamic thermal simulation modelling for the different dwelling types, locations and weather data. The energy needed for cooling is higher for Package 0 than for Package 5; the latter has passive cooling measures which result in lower solar gains and therefore lower internal temperatures. As would be expected, more cooling energy is needed in a DSY1 year than a TRY year. Also the flat typologies show a higher cooling demand relative to the houses under the ‘no mitigation’ scenario due to the higher heat gains per unit floor area (e.g. due

[37] CIBSE (2014).Guide M: Maintenance Engineering & Management. London: The Chartered Institution of Building Services Engineers.

to larger glazing areas and higher occupant density compared to houses) and therefore higher internal temperatures.

For the cost-benefit analysis, the consumption figures were converted to annual fuel costs using future projections of domestic retail prices for electricity in line with Table 4 of the Green Book supplementary guidance on valuation of energy use and greenhouse gas emissions.[38]

Table 15: Fuel consumption for cooling for counterfactual case and Package 5 (kWh/ year per dwelling)

		DSY1 2020s		DSY1 2050s		TRY 2020s		TRY 2050s	
London		Pk. 0*	Pk. 5	Pk. 0*	Pk. 5	Pk. 0*	Pk. 5	Pk. 0*	Pk. 5
Daytime	Semi-Detached	738	297	1033	466	342	83	758	281
	Dual Aspect	1621	196	2044	334	906	50	1591	189
	Single Aspect	886	223	1155	357	417	63	830	223
Non-Daytime	Semi-Detached	960	286	1205	437	625	114	956	301
	Dual Aspect	2220	193	2573	313	1702	64	2210	214
	Single Aspect	1051	388	1522	522	914	237	1193	408
Nottingham		Pk. 0*	Pk. 5	Pk. 0*	Pk. 5	Pk. 0*	Pk. 5	Pk. 0*	Pk. 5
Daytime	Semi-Detached	217	78	386	135	158	52	269	106
	Dual Aspect	698	50	1001	90	640	30	940	59
	Single Aspect	327	57	497	110	310	36	479	73
Non-Daytime	Semi-Detached	437	77	621	145	383	54	568	100
	Dual Aspect	1661	53	1933	112	1594	37	1857	78
	Single Aspect	949	259	1125	348	924	195	1101	284
Southampton		Pk. 0*	Pk. 5	Pk. 0*	Pk. 5	Pk. 0*	Pk. 5	Pk. 0*	Pk. 5
Daytime	Semi-Detached	505	167	754	326	167	39	451	129
	Dual Aspect	1362	120	1741	240	833	25	1274	90
	Single Aspect	654	148	891	260	366	37	628	114
Non-Daytime	Semi-Detached	718	169	941	295	515	50	747	156
	Dual Aspect	2094	120	2404	216	1829	31	2147	112
	Single Aspect	1051	279	1262	392	914	197	1131	310

*when air-conditioned

[38] Department for Business Energy and Industrial Strategy (Dec 2017). Valuation of energy use and greenhouse gas – Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government, London: Department for Business Energy and Industrial Strategy. Data tables 1 to 19: supporting the toolkit and the guidance.

6.4 Cost of carbon associated with cooling energy

The societal cost of carbon emissions associated with electricity for cooling has been accounted for in the cost-benefit analysis. The annual carbon emissions associated with energy consumption for cooling were calculated using projected emissions factors as set out in Table 1 of the Green Book supplementary guidance on valuation of energy use and greenhouse gas emissions.[39] The grid-average emissions factors for the domestic sector were used for the analysis.

The carbon emissions were converted to costs using projected annual carbon prices (2017 £/tCO_2e) in Table 3 of the Green Book supplementary guidance referred to above. The analysis uses the central estimate for the traded sector.

[39] Department for Business Energy and Industrial Strategy (Dec 2017). Valuation of energy use and greenhouse gas – Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government, London: Department for Business Energy and Industrial Strategy. Data tables 1 to 19: supporting the toolkit and the guidance.

7. Selection of packages for CBA

This section sets out the results of the overheating risk modelling carried out in line with CIBSE TM59 methodology for the three locations using 2020s DSY1 weather data. These results along with the capital cost data presented in the preceding section have been used as the basis to select risk mitigation packages for the cost-benefit analysis. The risk mitigation strategy used in the cost-benefit analysis for each case is that which meets the CIBSE TM59 overheating criteria at minimum capital cost, though passive strategies are always prioritised over those with active cooling.

The impact of orientation and using 2050s weather data for the selection of overheating risk mitigation packages has been tested. The results are presented in Section 7.5 and Section 7.6.

7.1 Nottingham weather data

Both flat typologies exceed CIBSE TM59 criterion A for the ‘no mitigation’ scenario, with the number of overheating hours progressively reducing from Package 1 to 5. Both of these typologies also show a low risk of overheating under criterion B. Package 3 is the least capital cost compliant package for the single aspect flat in this location. In case of the dual aspect flat, Package 2 is the least cost compliant package.

For the semi-detached house, risk modelling with Nottingham weather data indicates that the dwelling complies with criterion A under all mitigation scenarios with only a marginal exceedance in the living room for the base-case dwelling (‘no mitigation’ scenario, Package 0). In contrast, the dwelling fails criterion B for the ‘no mitigation’ scenario and Packages 1 and 2. Package 3 is therefore the least capital cost compliant package for the semi-detached dwelling in this location.

Note that in all cases, Package 5 results in no overheating hours as active cooling is assumed to adequately control the internal environment.

Figure 6: Percentage overheating hours – Nottingham DSY1 2020s – Criterion A

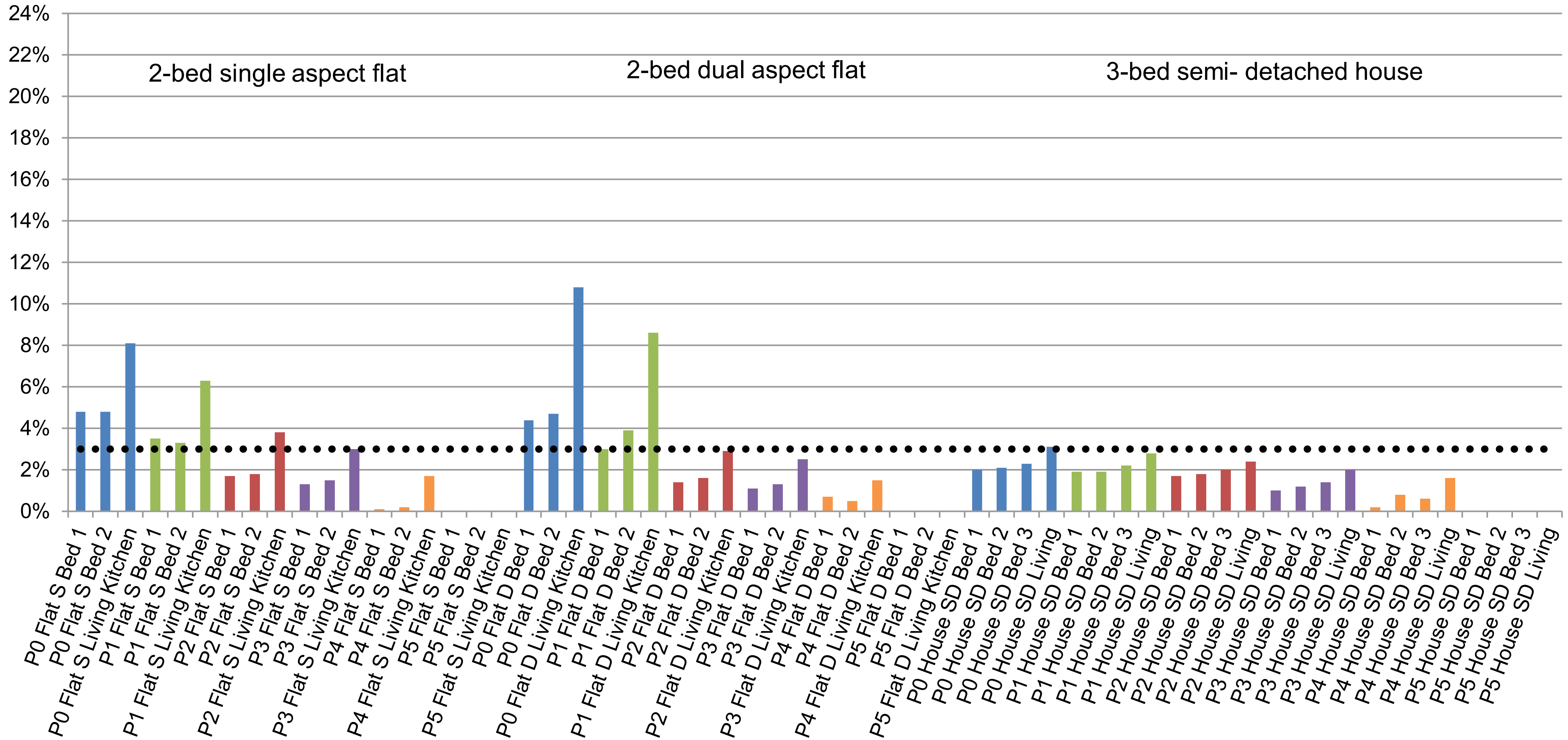
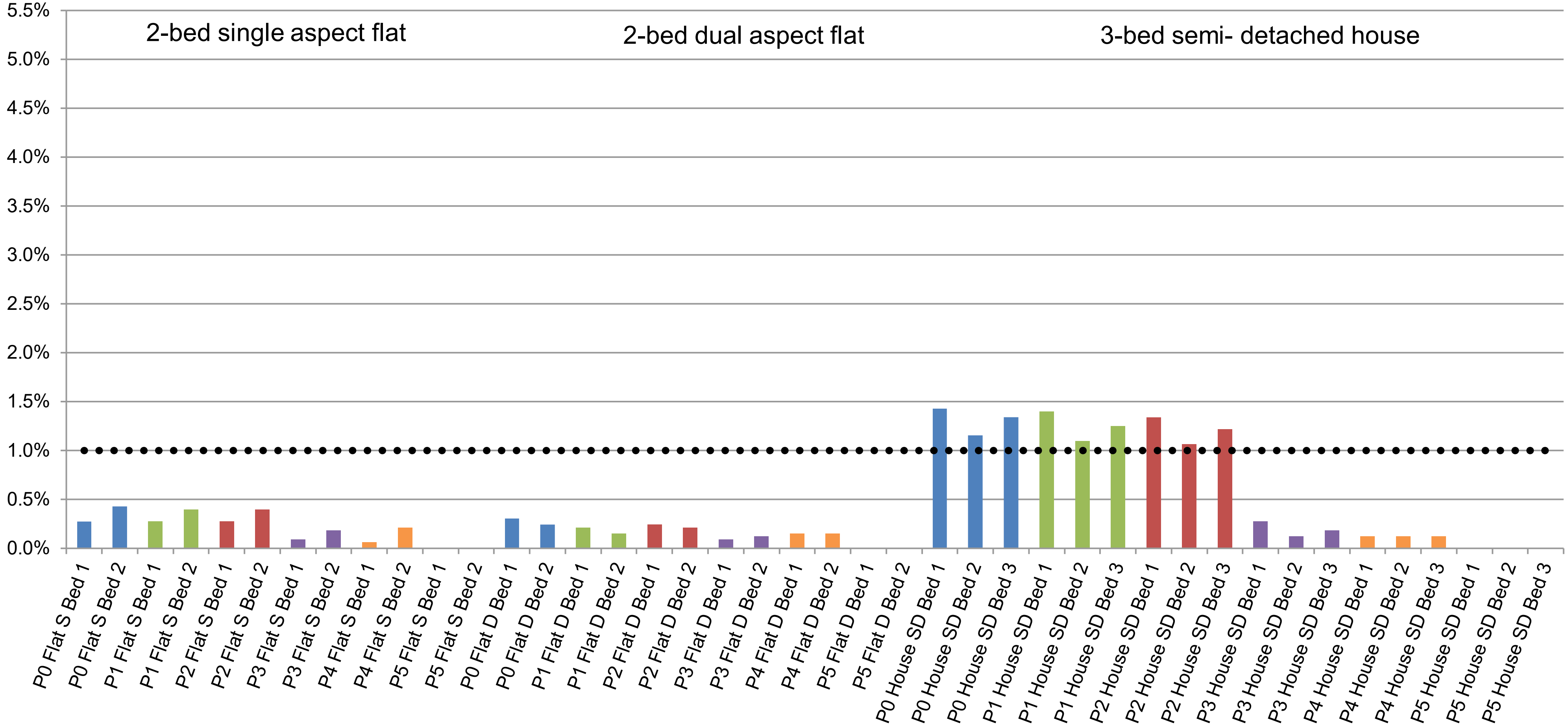


Figure 7: Percentage overheating hours – Nottingham DSY1 2020s – Criterion B



7.2 London weather data

London shows the highest overheating risk of the three locations modelled.

The single and dual façade flat typologies both exceed criterion A for the 'no mitigation' scenario and for Packages 1-4 and 1-3 respectively. They exceed criterion B for the base case and Packages 1 and 2. The single aspect flat also exceeds the compliance threshold for criterion B in case of Package 4 due to the fabric retaining heat during the day and releasing it overnight. This phenomenon also occurs, to a smaller extent, in the dual aspect flat but does not cause non-compliance. For the single aspect, Package 5 with active cooling is the only compliant package. For the dual aspect flat, Package 4 is the least capital cost compliant package.

The semi-detached dwelling exceeds the 3% compliance threshold for criterion A for the base case and Packages 1- 3. It fails criterion B for the base case and Packages 1 and 2. Package 4 is therefore the only compliant package with passive measures in the case of the semi-detached dwelling.

Figure 8: Percentage overheating hours – London Heathrow DSY1 2020s – Criterion A

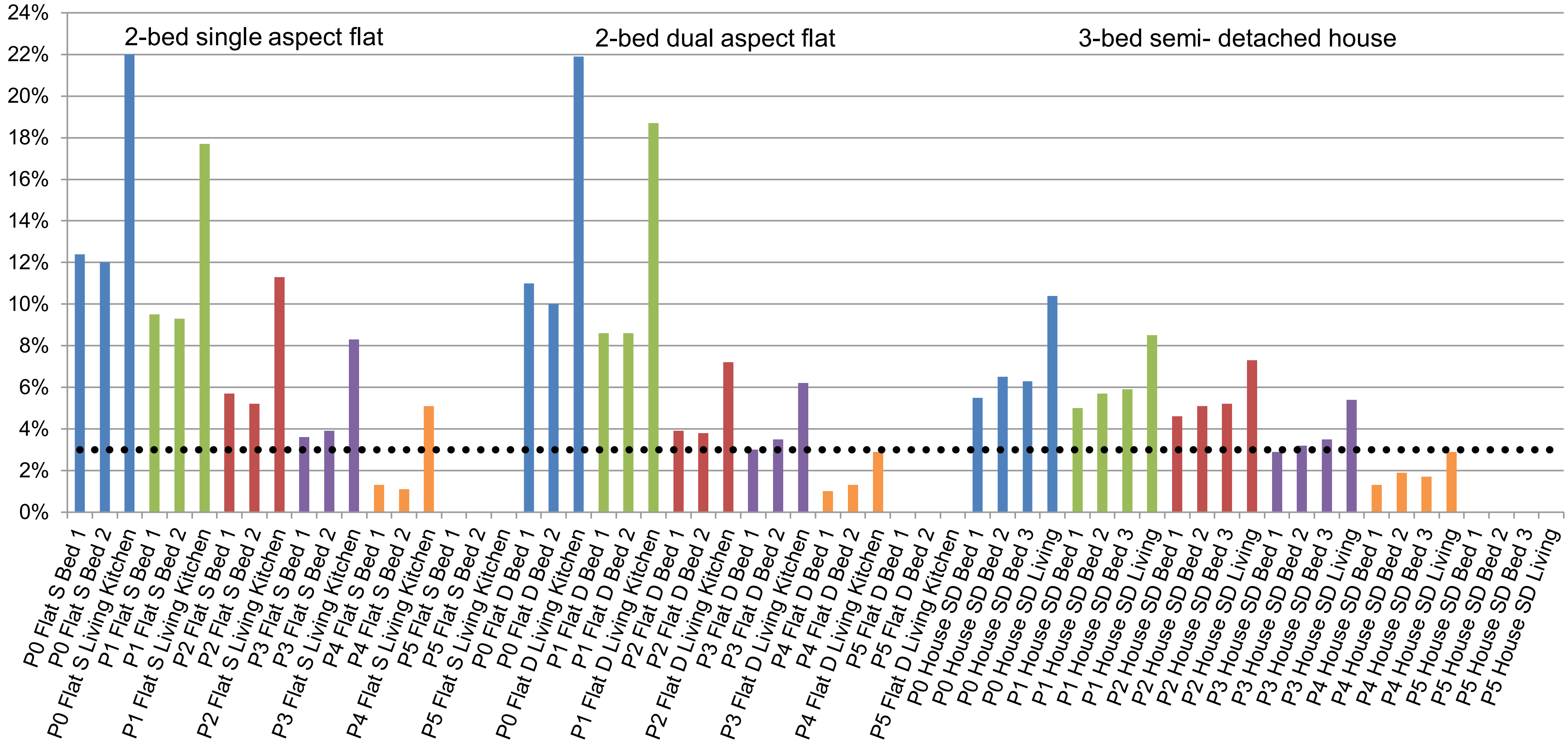
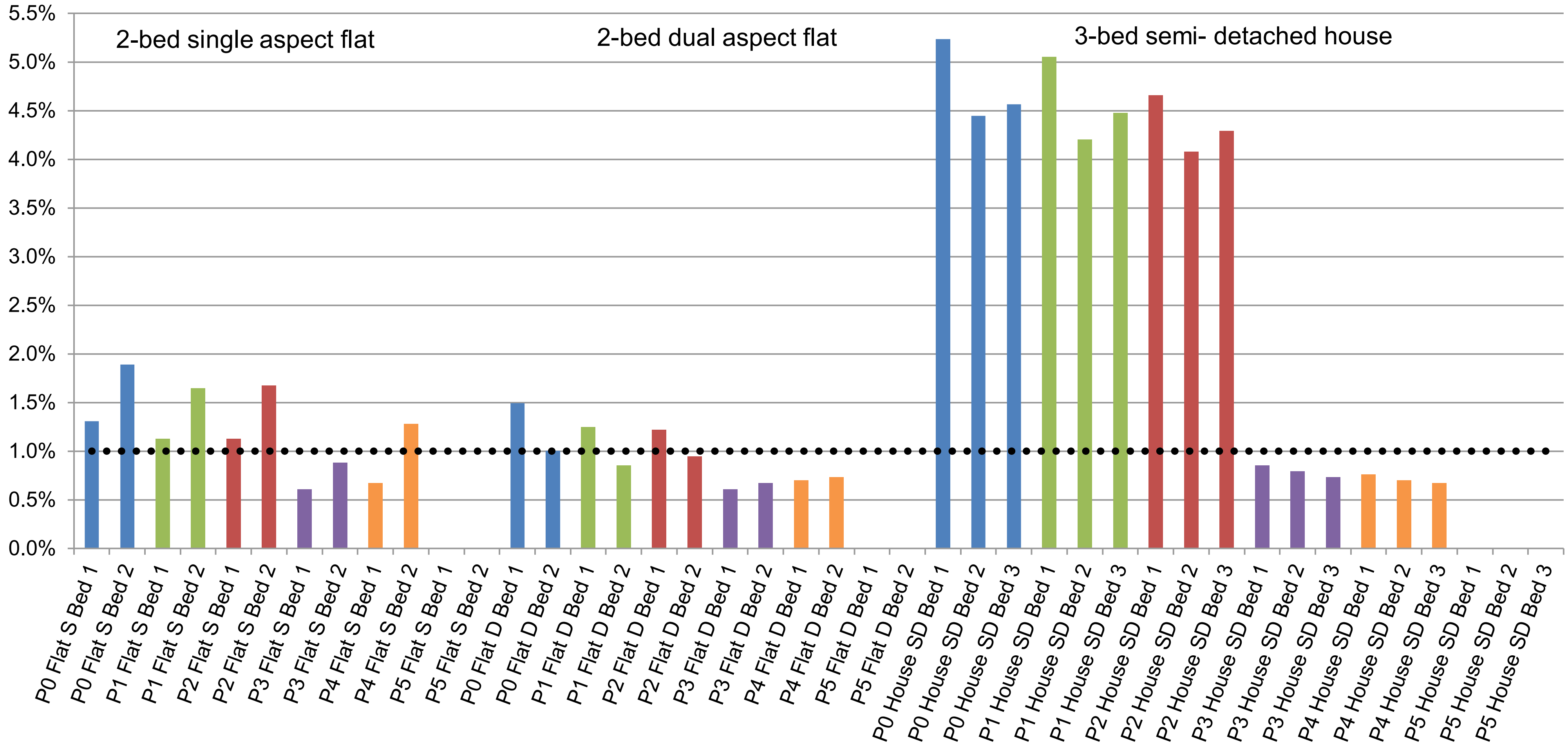


Figure 9: Percentage overheating hours – London Heathrow DSY1 2020s – Criterion B



7.3 Southampton weather data

The dwelling typologies show a similar trend for criteria A and B as with the Nottingham weather data, though the percentage exceedance is far higher for Southampton.

Both flat typologies fail to comply with criterion A for the ‘no mitigation’ scenario and Packages 1 to 3. They all meet criterion B. Package 4 is the least-cost compliant package for the single aspect and dual aspect flats.

The semi-detached dwelling fails to comply with criterion A for the ‘no mitigation’ scenario and for Package 1. It fails criterion B for the ‘no mitigation’ scenario and Packages 1 and 2. Package 3 is therefore the least capital cost compliant package for the semi-detached dwelling in this location as is the case for Nottingham.

Figure 10: Percentage overheating hours – Southampton DSY1 2020s – Criterion A

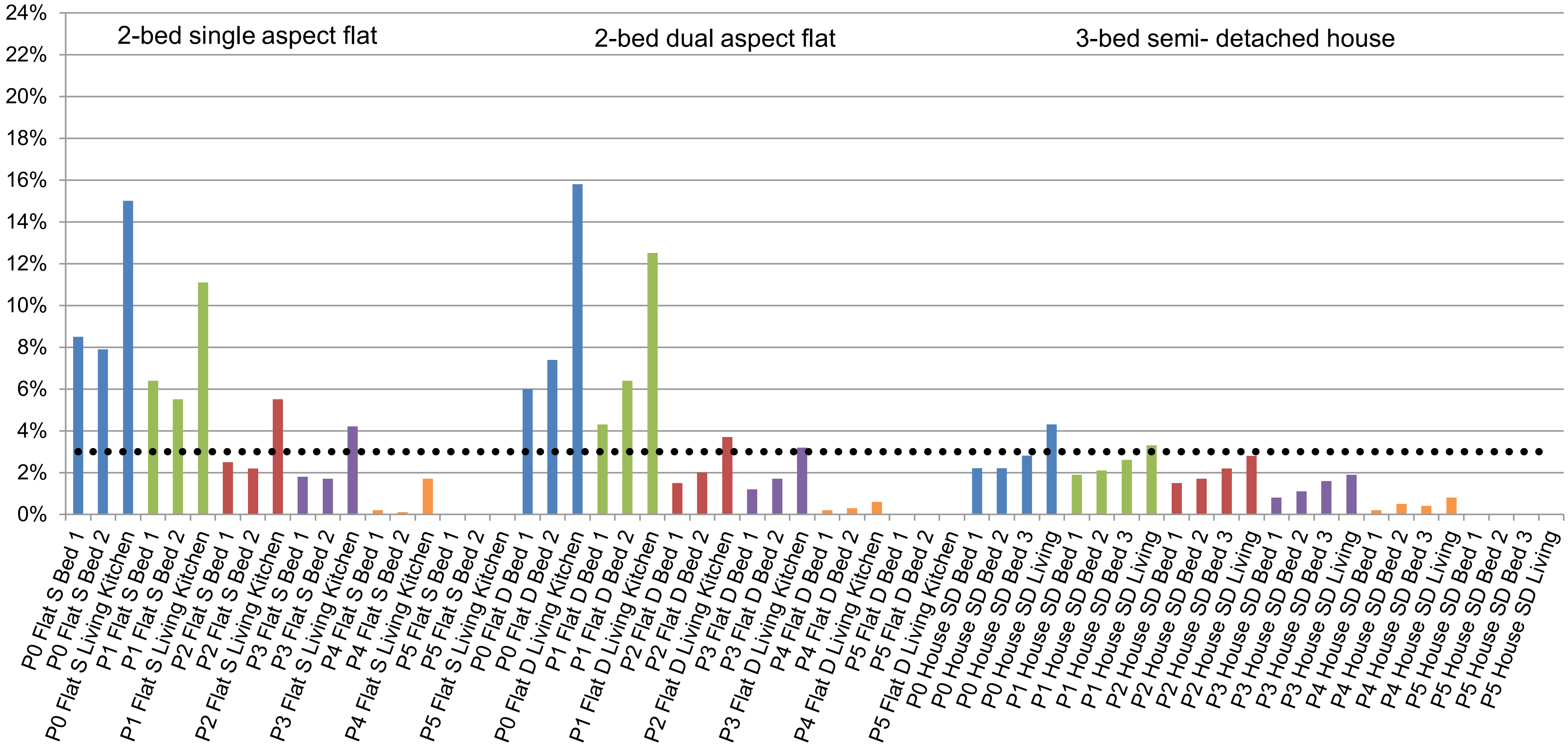
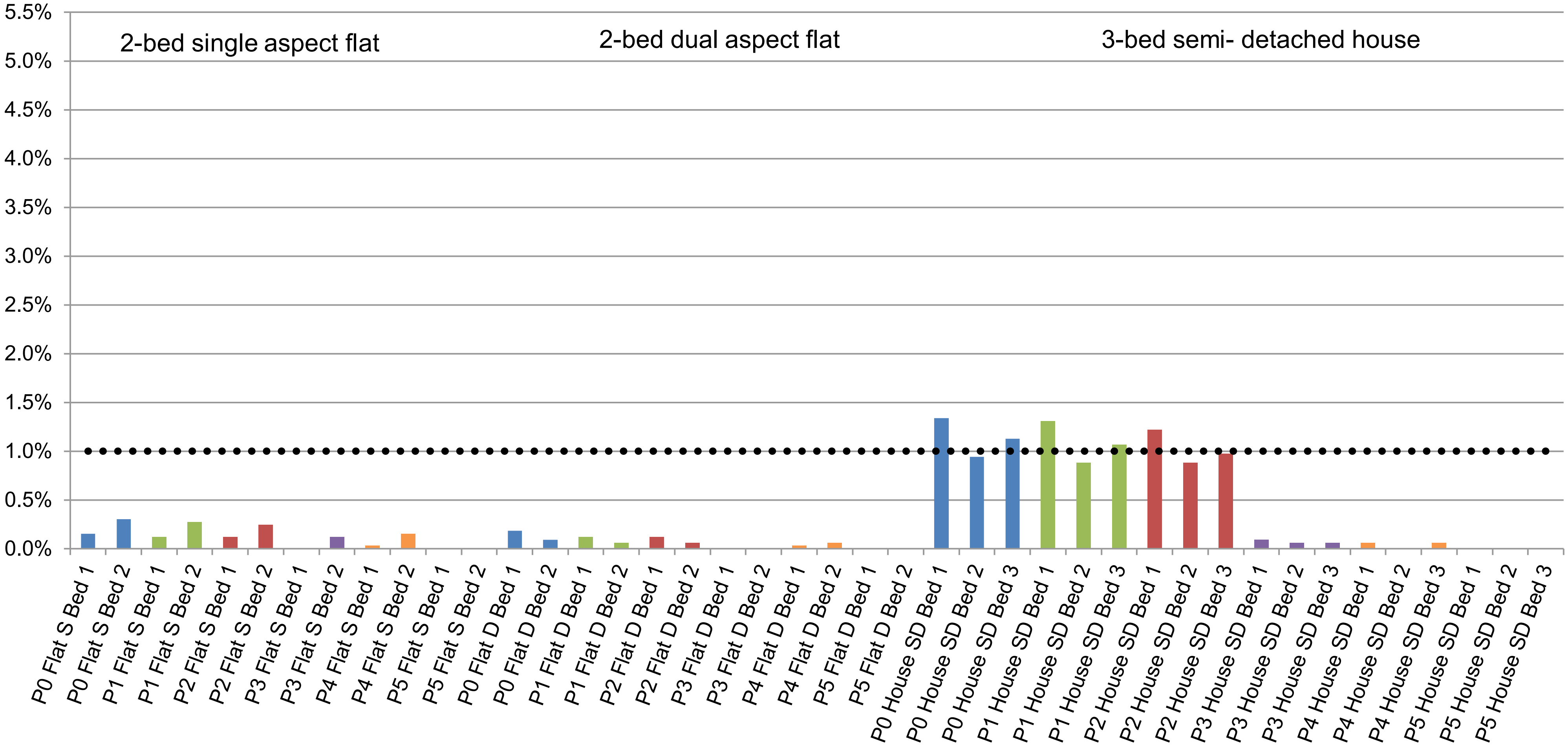


Figure 11: Percentage overheating hours – Southampton DSY1 2020s – Criterion B



7.4 Summary results

The table below summarise the compliant packages used for the CBA analysis for all locations and dwelling typologies.

Table 16: Risk mitigation package by location and dwelling type

Location	Dwelling type	Package
Nottingham	Semi-detached	3
	Flat – single aspect	3
	Flat – dual aspect	2
London	Semi-detached	4
	Flat – single aspect	5
	Flat – dual aspect	4
Southampton	Semi-detached	3
	Flat – single aspect	4
	Flat – dual aspect	4*

* The dual-aspect flat in Southampton only marginally fails Package 3, with 3.2% overheating hours in the living room under Criterion A.

Note that the packages listed above are the least cost compliant options out of Packages 1-4. Package 5 is chosen only where none of the packages with passive measures comply. More advanced packages than those listed are also compliant, and may well be cost effective and/or technically suitable depending on the site context.

7.5 Impact of orientation on package selection

The impact of orientation on package selection was tested for the 'worst-case' west orientation for both the single aspect flat and semi-detached house. As expected, these indicate that both dwelling types in all three locations have a higher risk of overheating compared to those orientated south. This is reflected in the number of overheating hours assessed using both Criterion A and B.

The table below presents the least cost, compliant packages for the west facing living rooms. The rows in bold highlight deviations from south facing living rooms. The analysis indicates that dwelling orientation affects package selection for the single aspect flat but not for the semi-detached house. As would be expected, orientation has a greater impact on overheating risk (and therefore package selection) in single aspect flats compared to properties with two or more aspects.

Table 17: Risk mitigation package by location and dwelling type - Livings rooms oriented west

Location	Dwelling type	Package
Nottingham	Semi-detached	3
	Flat – single aspect	**4**
London	Semi-detached	4
	Flat – single aspect	5
Southampton	Semi-detached	3
	Flat – single aspect	**5**

7.6 Impact of 2050s weather data on package selection

The impact of 2050s weather data on package selection was tested for the single aspect flat using the DSY1 2050s weather data for Southampton. The results of the overheating risk modelling are presented Figure 12 and Figure 13 below. As expected, the percentage overheating hours increase substantially, for instance, increasing from 15% to 23% in the living room for the 'no mitigation' scenario. The 'no mitigation' scenario now also exceeds the compliance threshold for criterion B.

Figure 12: Percentage overheating hours – Southampton DSY1 2050s – Single aspect flat - Criterion A

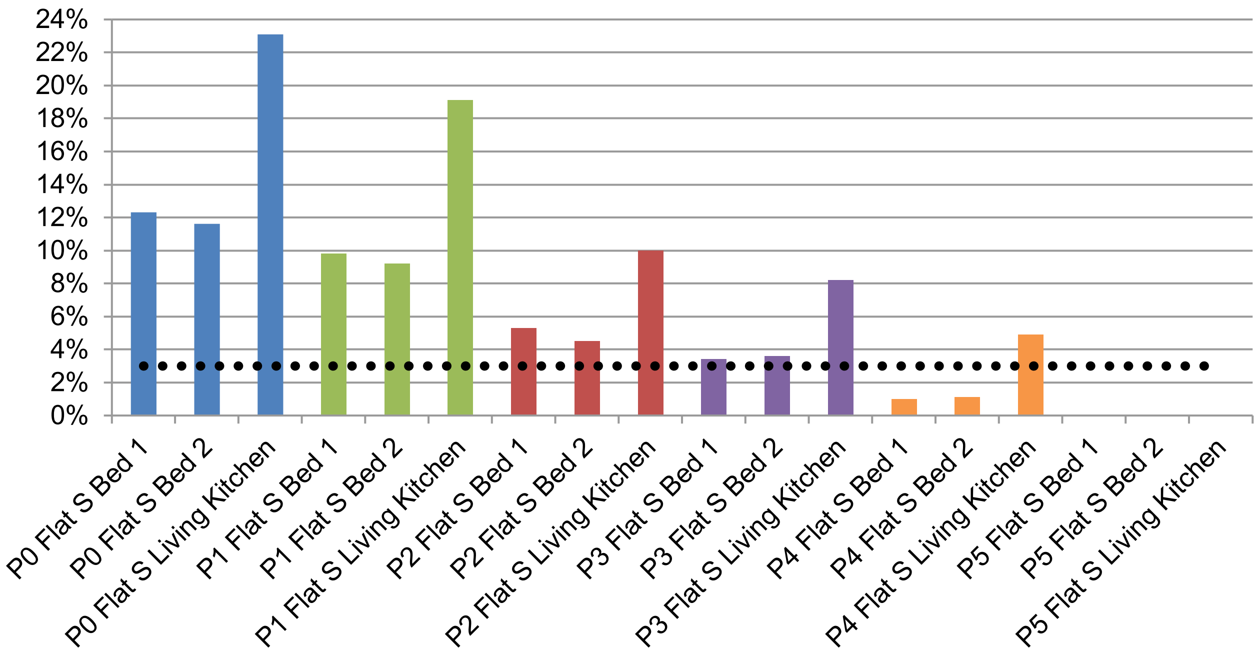
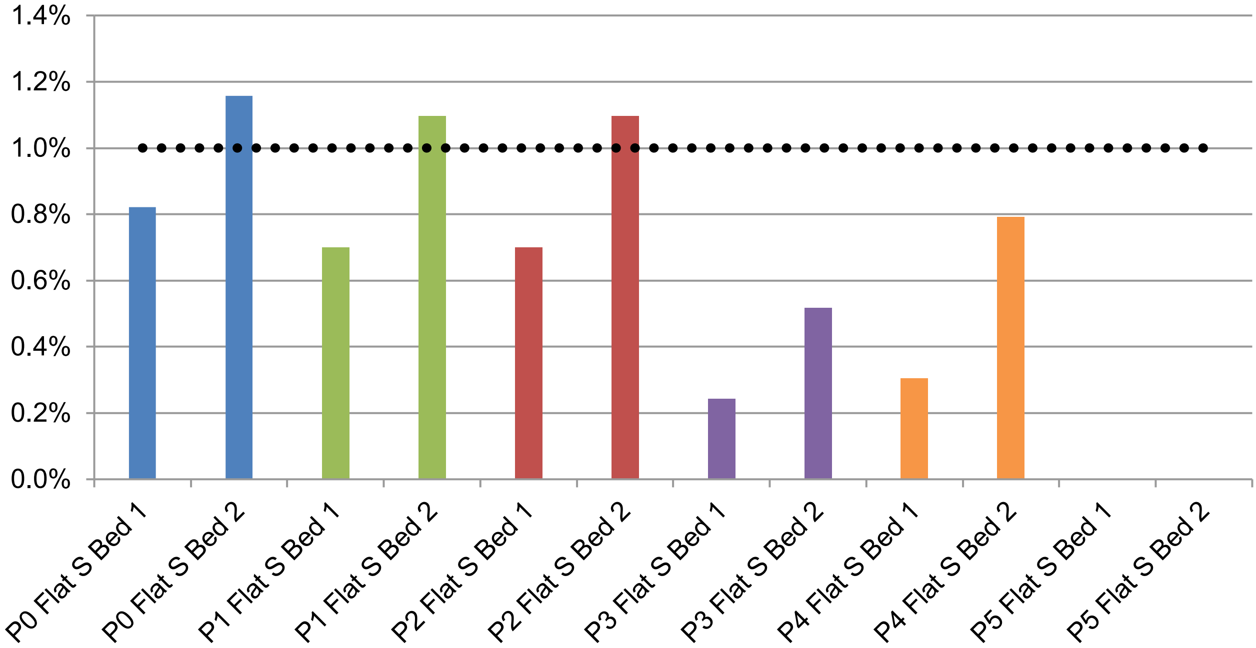


Figure 13: Percentage overheating hours – Southampton DSY1 2050s – Single aspect flat - Criterion B



Package 4, which was the least cost compliant package when modelled with the 2020s weather data, no longer meets the CIBSE TM59 compliance thresholds for criterion A; Package 5 with active cooling is the only compliant package based on 2050s weather data.

This indicates that while there may be some case for building additional resilience in building design and services to cope with higher overheating risk in future years, this would need to be weighed against the additional benefits that such an approach could deliver. It is worth noting that the CIBSE TM59 methodology recommends using the 2020s weather data.

8. Cost-benefit analysis

8.1 Results from the mortality analysis

The tables below set out the results of the mortality analysis based on the methodology described in Section 5.1. The results are aggregated for all occupants in the dwelling.

The ‘number of life years saved per dwelling’ was calculated based on the average life expectancy of the general population and the split of occupancy profile by age bands for the specific dwelling type derived from a combination of UK 2014-15 Time Use Survey and the EHS dataset. The numbers of life years were converted into an economic impact based on the value of Quality Adjusted Life Year (QALY) of £60,000 as a central estimate in line with the Green Book guidance.

This indicates that the economic benefit of applying risk mitigation measures ranges from £7- £391 per year per dwelling depending on location, dwelling type, risk mitigation package and weather data. The economic impact is proportional to internal temperatures and therefore highest for London location, higher with DSY1 weather data (representing a moderately warm summer) than TRY data (representing a typical year), and higher in the 2050s relative to the 2020s. Additional tables showing the number of life years saved per dwelling relative to Package 0 are included in Appendix B.

Table 18: Economic value of life years saved in a DSY1 year per dwelling relative to P0 (£ per annum, undiscounted)

		DSY1 2020s					DSY1 2050s				
London		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£20	£28	£41	£77	£124	£27	£39	£61	£126	£251
	Dual Aspect	£42	£167	£176	£207	£241	£56	£228	£244	£303	£391
	Single Aspect	£34	£74	£84	£112	£156	£49	£109	£126	£172	£281
Nottingham		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£7	£9	£14	£30	£63	£13	£18	£27	£57	£112
	Dual Aspect	£20	£84	£90	£104	£125	£31	£130	£140	£170	£205
	Single Aspect	£14	£34	£39	£52	£77	£22	£52	£60	£84	£132
Southampton		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£11	£19	£26	£47	£74	£23	£37	£56	£105	£179
	Dual Aspect	£36	£139	£144	£166	£186	£50	£211	£222	£266	£325
	Single Aspect	£29	£71	£74	£93	£121	£44	£111	£123	£162	£239

Table 19: Economic value of life years saved in TRY year per dwelling relative to P0 (£ per annum, undiscounted)

London		TRY 2020s					TRY 2050s				
		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£4	£6	£7	£15	£22	£8	£11	£16	£38	£77
	Dual Aspect	£12	£46	£48	£55	£60	£35	£132	£139	£159	£186
	Single Aspect	£6	£14	£15	£22	£29	£23	£48	£50	£68	£101
Nottingham		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£5	£7	£10	£18	£38	£9	£13	£19	£38	£78
	Dual Aspect	£15	£60	£63	£71	£85	£21	£87	£94	£110	£138
	Single Aspect	£10	£21	£23	£31	£48	£16	£37	£43	£57	£91
Southampton		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£3	£4	£5	£9	£15	£8	£12	£16	£29	£44
	Dual Aspect	£14	£44	£45	£49	£53	£27	£99	£103	£113	£124
	Single Aspect	£7	£14	£14	£18	£23	£22	£47	£51	£62	£77

8.2 Results from sleep disruption analysis

Table 20 and Table 21 present the results for the economic impact of sleep disruption on productivity based on the methodology described in Section 5.2. As with the mortality analysis, the results are aggregated for all occupants in the dwelling.

Additional tables showing the productivity impact expressed as % impact on GDP are included in Appendix B. The productivity impact is converted into an economic value based on a GDP per head figure of £31,208 (2018 prices). The results indicate that the economic benefit ranges from £0 - £429 per year per dwelling depending on location, dwelling type, package and weather data. As with the mortality analysis, the economic benefit is proportional to internal temperature and therefore highest for London location, and higher in the 2050s relative to the 2020s.

Table 20: Annual productivity benefit per dwelling in DSY1 year relative to P0 (£ per annum, undiscounted)

		DSY1 2020s					DSY1 2050s				
		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£10	£20	£97	£99	£129	£14	£20	£170	£181	£244
	Dual Aspect	£7	£7	£21	£19	£36	£14	£13	£52	£46	£90
	Single Aspect	£2	£1	£19	£18	£33	£7	£4	£52	£41	£86
Non-Daytime	Semi-Detached	£43	£80	£224	£236	£249	£46	£93	£371	£387	£429
	Dual Aspect	£52	£110	£135	£140	£146	£78	£171	£238	£257	£274
	Single Aspect	£42	£62	£85	£87	£97	£64	£101	£178	£173	£213

		DSY1 2020s					DSY1 2050s				
		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£7	£9	£28	£28	£36	£5	£8	£39	£46	£60
	Dual Aspect	£0	£0	£5	£2	£6	£4	£2	£11	£7	£17
	Single Aspect	£0	£0	£6	£7	£7	£1	£1	£10	£10	£15
Non-Daytime	Semi-Detached	£11	£20	£49	£52	£52	£10	£24	£85	£96	£99
	Dual Aspect	£14	£23	£29	£29	£29	£27	£51	£61	£65	£65
	Single Aspect	£9	£15	£21	£22	£22	£10	£23	£32	£33	£38

		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£0	£3	£23	£25	£25	£2	£7	£89	£89	£102
	Dual Aspect	£2	£2	£2	£2	£2	£6	£6	£14	£11	£20
	Single Aspect	£0	£0	£0	£0	£0	£6	£6	£11	£8	£18
Non-Daytime	Semi-Detached	£18	£30	£64	£64	£64	£28	£60	£185	£190	£193
	Dual Aspect	£15	£32	£34	£34	£34	£46	£88	£104	£106	£106
	Single Aspect	£2	£9	£11	£11	£11	£13	£32	£47	£48	£52

Table 21: Annual productivity benefit per dwelling in TRY year relative to P0 (£ per annum, undiscounted)

		TRY 2020s					TRY 2050s				
		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£1	£1	£16	£16	£16	£5	£10	£72	£69	£83
	Dual Aspect	£0	£0	£0	£0	£0	£4	£5	£17	£18	£23
	Single Aspect	£0	£0	£0	£0	£0	£2	£2	£14	£12	£19
Non-Daytime	Semi-Detached	£8	£20	£47	£47	£47	£34	£71	£188	£195	£198
	Dual Aspect	£11	£19	£19	£19	£19	£50	£87	£105	£111	£111
	Single Aspect	£5	£7	£7	£7	£7	£21	£37	£53	£55	£60

		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£1	£4	£17	£17	£17	£0	£0	£38	£41	£41
	Dual Aspect	£0	£0	£0	£0	£0	£2	£2	£6	£6	£6
	Single Aspect	£0	£0	£0	£0	£0	£4	£5	£7	£7	£7
Non-Daytime	Semi-Detached	£6	£9	£30	£30	£30	£10	£21	£70	£70	£70
	Dual Aspect	£13	£19	£19	£19	£19	£23	£47	£51	£51	£51
	Single Aspect	£5	£7	£7	£7	£7	£15	£25	£30	£30	£30

		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	£3	£3	£5	£5	£5	£0	£0	£14	£16	£19
	Dual Aspect	£0	£0	£0	£0	£0	£0	£0	£4	£4	£4
	Single Aspect	£0	£0	£0	£0	£0	£0	£0	£5	£4	£5
Non-Daytime	Semi-Detached	£1	£5	£7	£7	£7	£5	£13	£30	£33	£33
	Dual Aspect	£2	£4	£4	£4	£4	£12	£17	£21	£21	£21
	Single Aspect	£2	£2	£2	£2	£2	£3	£3	£9	£9	£9

Additional analysis was undertaken to compare the economic impact of sleep disruption on productivity determined using the Hafner study and the Defra study. As proposed in Section 5.2.3, the former has been used as the principal approach for this study and the latter used here only to provide an upper end estimate and sense check. The comparison was based on the productivity impact due to overheating aggregated for all new homes built in a given year for the 'no mitigation' scenario (i.e. Package 0).

- Hafner study: The total economic impact in a DSY1 year for all new build homes built in that year is £8.4m (2018 prices) based on the regional distribution and split of housing typologies set out in Section 3.
- Defra study: This study gives the upper threshold of the potential productivity cost of environmental noise as £6billion per annum. This figure was adjusted by the proportion of new build homes where sleep is affected by overheating and the proportion of the year during which sleep is affected compared to the number of homes and the proportion of the year during which sleep is affected by environmental noise. This results in an economic impact of ~£73m per annum (2018 prices).

The Defra estimate was intended to provide an estimate of the upper threshold value for productivity related benefits. The comparison suggests that the core estimates on the productivity related benefits due to overheating using the Hafner approach are well below the upper threshold suggested by the Defra study.

8.3 Comparison of proposed and counterfactual scenario

Table 22 summarises the results of the cost-benefit analysis for new homes projected to be built in England from 2020 to 2029. This is presented graphically in Figure 14. A net present value (NPV) calculation was undertaken using a social discount rate of 3.5% for the first thirty years and reducing to 3.0% in subsequent years in line with the Green Book. Mortality related benefits have been discounted using a health discount rate of 1.5% for the first thirty years reducing to 1.29% in later years. This is again in line with Green Book guidance.The positive values represent costs and the negative values represent benefits over the life of the building. The productivity and mortality benefits are presented relative to the counterfactual – hence a value of zero in the counterfactual column.

The analysis indicates an overall net cost of £820m for the proposed (risk mitigation) scenario relative to the counterfactual scenario. This equates to a net cost of around £400 per dwelling.

Note that capital costs of the risk mitigation measures under the proposed scenario are borne by the developer (with some or all these passed on to the home buyer depending on the market conditions), while under the counterfactual scenario these would be borne by the landlord or the owner-occupier. So the capital expenditure is borne by different stakeholder groups in the proposed and counterfactual scenario. The results discussed above are the net cost to society, and exclude VAT from the calculations. Allowing for the relevant rate of VAT on capital, replacement and fuel costs[40] gives a net benefit of £140m, which equates to around £60 per dwelling.

[40] This includes 0% VAT on proposed risk mitigation packages implemented in new homes, 20% VAT on measures retrofitted under the counterfactual scenario, 20% VAT on replacement costs for both proposed and counterfactual; and 5% VAT on fuel costs.

Table 22: Summary of cost-benefit analysis for new build homes in England

	Counterfactual	Proposed	Net cost
Capital and replacement costs (£m)	£4,798	£11,624	£6,826
Cost of cooling energy used (£m)	£1,835	£93	-£1,742
Carbon emissions - traded (£m)	£46	£4	-£42
Carbon emissions - non traded (£m)	£0	£0	£0
Mortality impact relative to counterfactual (£m)	£0	-£1,293	-£1,293
Productivity impact relative to counterfactual (£m)	£0	-£2,933	-£2,933
Net cost (£m)	£6,678	£7,494	£816
Net cost (£ per dwelling)			£379

Figure 14: Summary of cost-benefit analysis for new build homes in England

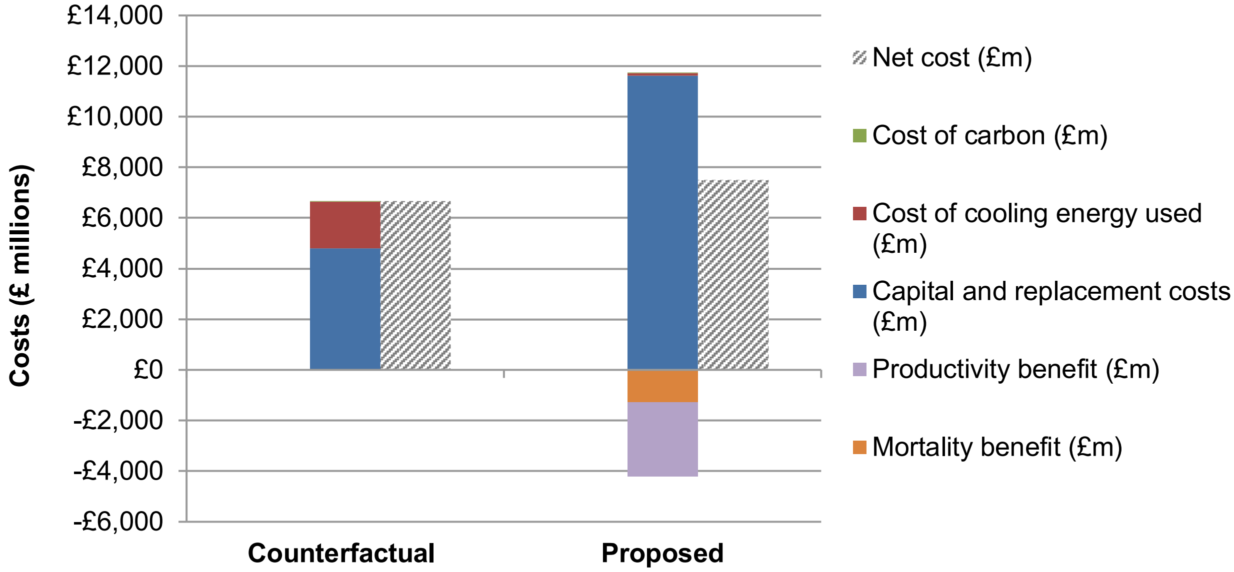


Table 23 and Figure 15 provide a breakdown of the costs and benefits by region.

- London shows a net benefit of around £2,100 per dwelling.
- Southampton (representing locations south of London) shows a net cost of around £100 per dwelling.
- Nottingham (representing locations north of London) shows a relatively higher net cost of £1,300 per dwelling.

As is evident from the risk modelling results discussed in Section 7, London has higher internal temperatures (and therefore higher mortality and productivity related benefits from implementing risk mitigation packages) compared to the other locations as well as higher projected uptake rate for air-conditioning that increases the costs for the counterfactual case. Also, London has a high proportion of new build flats that have lower capital and replacement costs for the advanced risk mitigation packages (i.e. Package 4 and 5) compared to the houses. These factors mean that on average the dwellings in London show a significant net benefit. In contrast, there is a higher proportion of new build houses than flats built in locations outside of London.

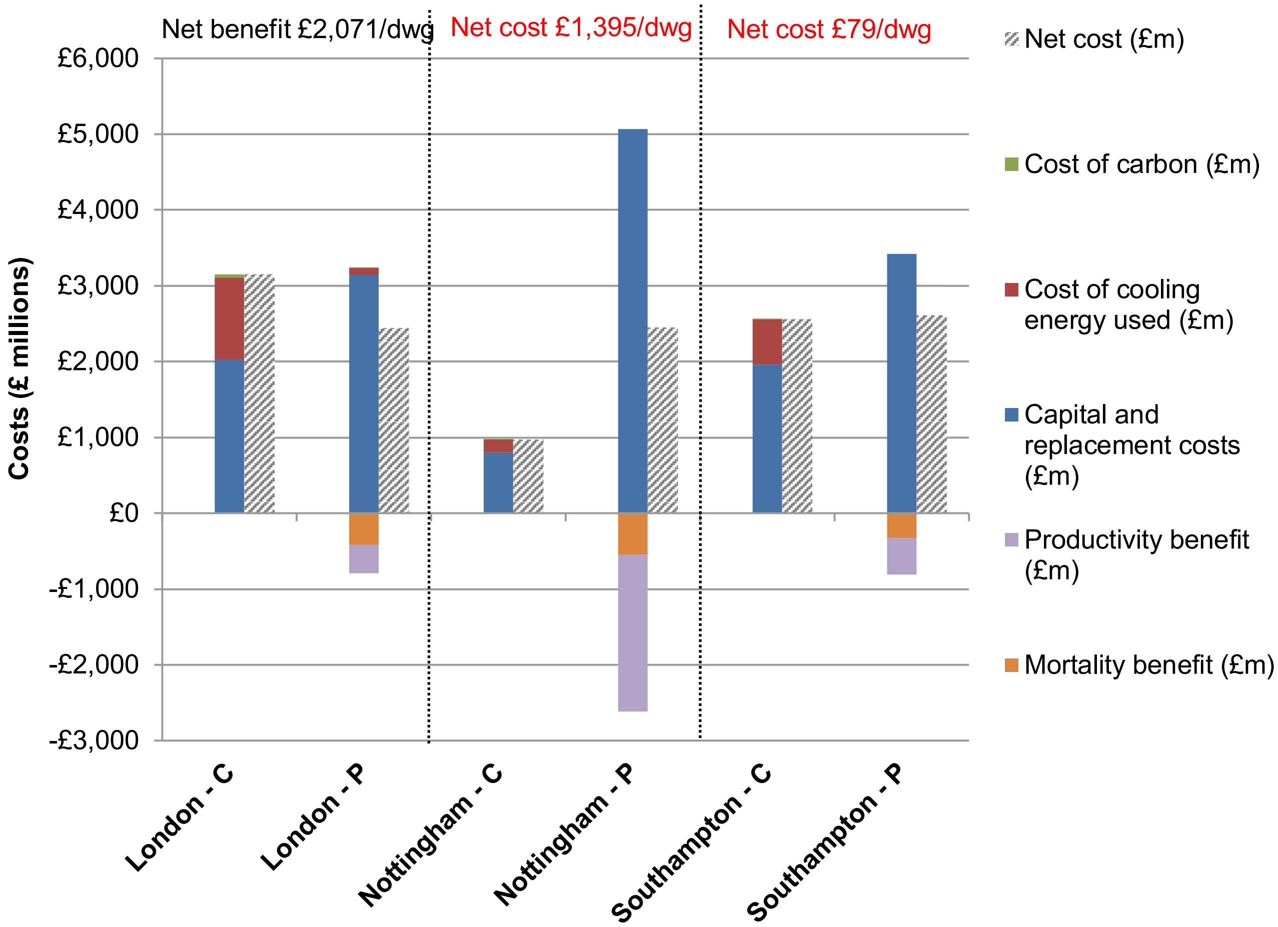
Breaking down the results further by dwelling type suggests that flats show a net benefit of around £2,700 in London and £2,900 per flat in Nottingham, and a net cost of £900 in Southampton. This different trend is because the dual aspect flat in Southampton marginally fails Package 3 (with only the living room exceeding the 3% compliance threshold for Criterion A by 0.2%) and the additional benefits accrued from implementing Package 4 do not offset the significant additional capital costs. In contrast, houses show a net cost of £4,000 in London and £1,800 in Nottingham, and a net benefit of £200 in Southampton. The mitigation measures chosen comply with the TM59 criteria as described in Section 7.

The CBA models takes into account the benefits accrued in a DSY1 year based on a 1 in 7 chance of each year being a DSY1 year. Note that this is potentially a conservative scenario given that the trend is for hotter than average summers to be more frequent in the future. The DSY1 year represents a moderately warm summer, and the analysis does not currently account for the benefits that could potentially accrue from more extreme weather conditions (e.g. DSY 2 and DSY 3 weather data). Also, the analysis does not account for some of the potential health impacts (e.g. morbidity) although the principal ones have been accounted for. The benefits presented in this study are therefore potentially an underestimation but are counteracted by limited data/ uncertainties around some of the other streams of analysis such as the productivity related benefits and the uptake rate for air-conditioning.

Table 23: Summary of cost-benefit analysis by region

	London			North of London (Nottingham)			South of London (Southampton)		
	Counterfactual	Proposed	Net cost	Counterfactual	Proposed	Net cost	Counterfactual	Proposed	Net cost
Capital & replacement costs (£m)	£2,032	£3,139	£1,108	£805	£5,065	£4,260	£1,962	£3,420	£1,458
Cost of cooling energy used (£m)	£1,073	£93	-£980	£167	£0	-£167	£594	£0	-£594
Carbon emissions - traded (£m)	£45	£4	-£41	£0	£0	£0	£0	£0	£0
Mortality impact relative to counterfactual (£m)	£0	-£412	-£412	£0	-£552	-£552	£0	-£329	-£329
Productivity impact relative to counterfactual (£m)	£0	-£383	-£383	£0	-£2,066	-£2,066	£0	-£485	-£485
Net cost (£m)	£3,149	£2440	-£709	£972	£2,447	£1,475	£2,556	£2,607	£50
Net cost (£ per dwelling)			-£2,071			£1,257			£79

Figure 15: Summary of cost-benefit analysis by region



Net benefit £2,071/dwg
Net cost £1,395/dwg
Net cost £79/dwg
Costs (£ millions)
£6,000
£5,000
£4,000
£3,000
£2,000
£1,000
£0
-£1,000
-£2,000
-£3,000
London - C
London - P
Nottingham - C
Nottingham - P
Southampton - C
Southampton - P
Net cost (£m)
Cost of carbon (£m)
Cost of cooling energy used (£m)
Capital and replacement costs (£m)
Productivity benefit (£m)
Mortality benefit (£m)

9. Sensitivity analysis

The sensitivity analysis assesses the impact of key variables on the CBA results. These include

- **Uptake rate for air-conditioning:** There are a number of social, economic and environmental factors that would affect the uptake of air-conditioning in the future. In terms of the cost-benefit analysis, a change in the uptake rate has two, partly counter-balancing, outcomes. For instance, if the uptake for air-conditioning is increased it results in: (i) greater capital and replacement costs in the counterfactual which makes the risk mitigation packages relatively more attractive, and (ii) reduced productivity and mortality benefits of implementing the risk mitigation measures. A ±25% variation on the cooling degree days (which in turn affects the market saturation) has been modelled.
- **Impact of overheating on sleep (and in turn productivity related benefits):** A review of published literature indicated that while it is well established that overheating can disrupt sleep, the evidence on critical temperatures and magnitude of effect due to overheating is less clear. Section 5.2.1 sets out the assumptions around threshold temperatures and number of hours the threshold temperature is exceeded to result in 1 or 2 hours of sleep lost. The sensitivity analysis looks to quantify the impact of a ±1°C variation in the threshold temperatures and a ±50% variation in the number of hours the threshold temperatures are exceeded on the CBA results. These variables have been tested in combination to give an upper and lower end of the range of productivity related benefits, i.e. -1°C and 50% lower hours providing an upper end of productivity related benefits and +1°C and 50% higher hours providing the lower end of that range.
- **Life expectancy of occupants and impact on mortality related benefits:** The mortality related benefits in the core analysis have been quantified using average life expectancy data for the general population. However, it is likely that vulnerable individuals and those with underlying medical conditions are affected most, rather than an average healthy individual. Research by London School of Hygiene and Tropical Medicine suggests that the majority of deaths due to heat are among individuals who would have had a remaining life expectancy of at least 6 months[41]. This gives the lower end of the range for mortality related benefits.

The impact of each of the three categories of variables on the CBA results has been modelled independently and cumulatively as summarised in the table below. The results are presented in Figure 16 and Figure 17 respectively.

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[41] Rehill N, Armstrong B, Wilkinson W(2015). Clarifying life lost due to cold and heat: a new approach using annual time series. BMJ Open

Table 24: Sensitivity analysis scenarios

Low	High	Low –Cumulative	High –Cumulative
Lower uptake rate for air-conditioning	Higher uptake rate for air-conditioning	Lower uptake rate for air-conditioning	Higher uptake rate for air-conditioning
Lower productivity benefits (increase in threshold temperature and hours exceeded that result in 1 or 2 hours of sleep lost)	Higher productivity benefits (decrease in threshold temperature and hours exceeded that result in 1 or 2 hours of sleep lost)	Lower uptake rate for air-conditioning + Lower productivity benefits	Higher uptake rate for air-conditioning + Higher productivity benefits
Lower mortality benefits (remaining life expectancy of at least 6 months for individuals affected by heat)	-	Lower uptake rate for air-conditioning + Lower productivity benefits + Lower mortality benefits	-

The results indicate that lowering the uptake rate for air-conditioning results in a net cost for the whole of England of £2,540m, while increasing the uptake rate for air-conditioning gives a net benefit of £690m, compared to a net cost of £820m in the core scenario.

Reducing the life expectancy for calculating the mortality related benefits gives a net cost of £2,040m for the proposed scenario relative to the counterfactual.

The productivity related sensitivity analysis has the largest impact on the net cost/ benefit. A 1°C increase in threshold temperature along with 50% lower hours of exceedance above that threshold result in a net cost of around £2,820m compared to a net benefit of £4,930m for the "-1°C and 50% lower hours" scenario.

The cumulative impact of all three categories of variables gives a net cost of £6,200m as a worst case scenario and a net benefit of £5,700m as a best case scenario, compared to a net cost of £820m in the core scenario.

While this suggests a huge spread in the net costs relative to the counterfactual, the core analysis is based on available data and evidence. There is also a low probability of the underpinning variables that make up the cumulative scenarios occurring concurrently. As additional data and/or research on any of these variables become available, these can be used to refine the analysis further.

Figure 16: Sensitivity analysis showing net cost for proposed scenario relative to counterfactual

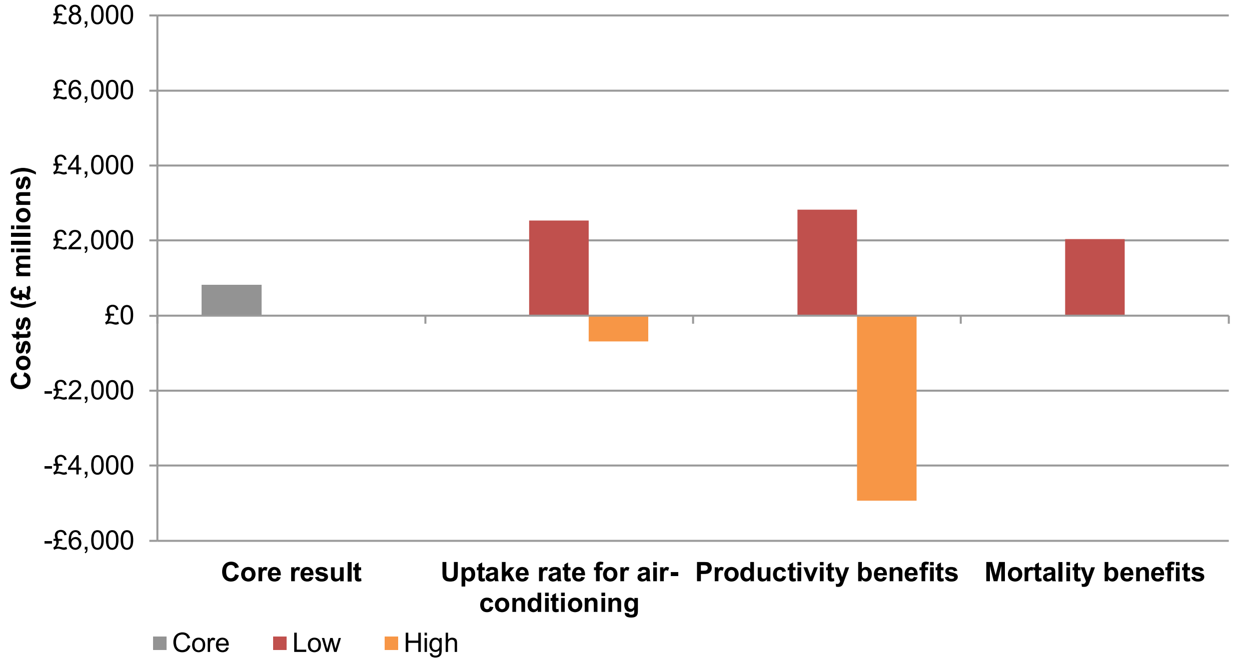
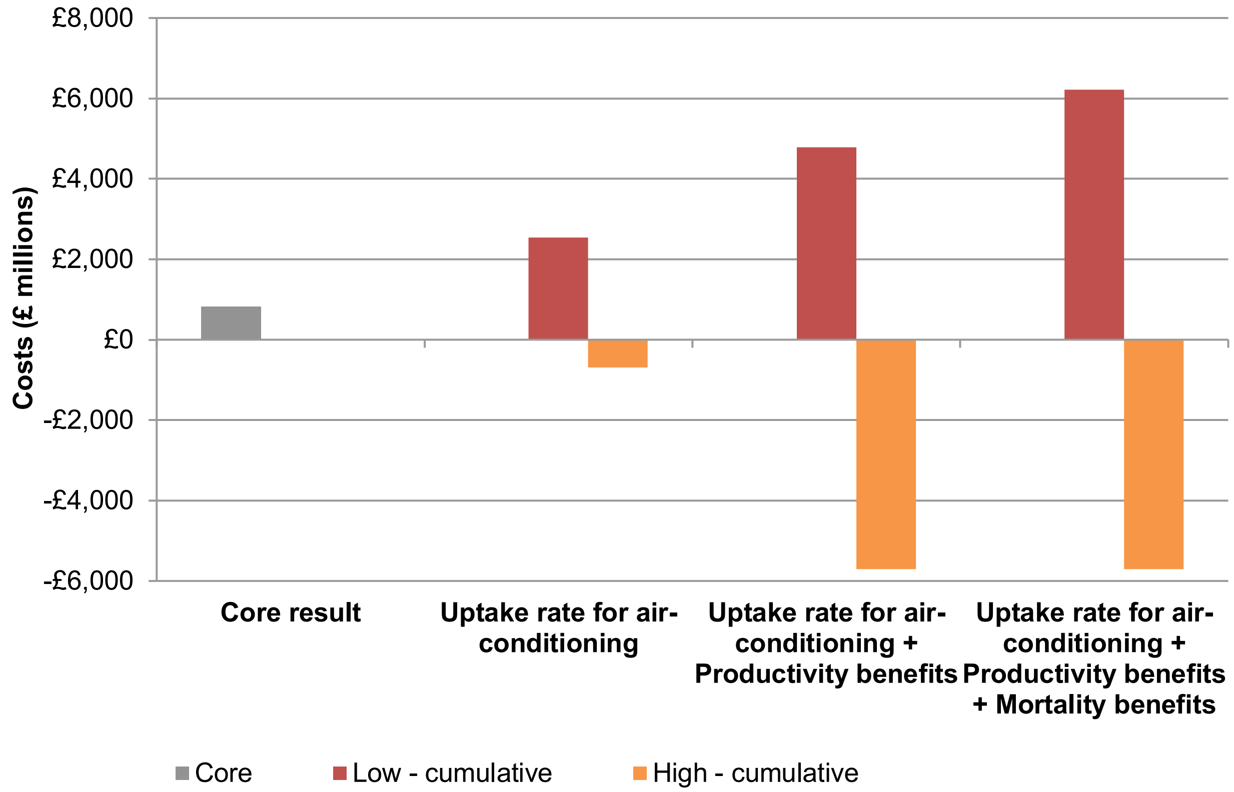


Figure 17: Sensitivity analysis showing net cost for proposed scenario relative to counterfactual – Cumulative



10. Conclusions and next steps

10.1 Potential routes to influence industry practice

The analysis shows an average net benefit or a near zero cost of incorporating measures to mitigate the risk of overheating in new homes in the south of England over their life. The analysis also shows a net benefit of incorporating risk mitigation measures in flats in the north of England. Allowing for VAT in the analysis gives a near zero cost on average for all new build homes in England.

Potential routes to bring about change in current design and construction practices to reduce overheating risk in new build homes include legislation, guidance for developers and other stakeholders, or guidance targeted at occupants.

Any legislation would need to consider the impact of dwelling type and location on overheating risk and the scale/ type of mitigation measures required. It would also need to consider the tools needed to assess overheating risk, both in terms of their rigour and complexity. The current overheating assessment methodology in SAP lacks the rigour to both comprehensively assess the risk of overheating as well as model the impact of mitigation strategies on winter heating demand. Dynamic thermal simulation tools on the other hand can be relatively complex and time-consuming. Tools and/or assessment methodology could potentially be varied depending on dwelling type and/or location, with more complex dynamic modelling tools targeted at high risk dwellings, such as flats with high glazing ratios.

Critically the legislation would need to consider the year round energy and carbon performance of dwellings in an integrated way so that trades offs between winter energy performance and overheating in summer can be adequately assessed.

Any legislation would need to be accompanied by appropriate guidance for developers and design teams, including the various professionals involved in decision-making and delivery. The guidance should be designed to be clear and simple, preferably setting out the options as a decision-tree depending on the dwelling type and site context. Guidance should help design teams to make informed decisions at design development stage / pre-planning thereby allowing for greater flexibility in design choices at an early stage of the project.

10.2 Recommendations for refining cost-benefit modelling

Feedback from the Research Group as well as review of available evidence on key aspects of the CBA carried out as part of this research has highlighted the following areas for further research.

- **Validation of the overheating criteria for new residential buildings.** Criterion A is derived from work on non-domestic buildings. Criterion B is derived from a 1975 study of only 21 volunteers in South-East England, which offers limited evidence because of the small sample size and potential behavioural changes across the population since the study was conducted.
- **Validation of some of the modelling inputs and assumptions**. As an example, occupant behaviour (such as opening of windows) during warmer weather is a critical

assumption. The assessment of the risk of overheating in Phase 1 is based on what was considered reasonable behaviour, but the evidence is limited. Reasonable assumptions have been made on how occupants would employ mitigation measures in Phase 2, and this impacts on the calculated benefits, though again the data is limited.

- **Validation of modelling outputs.** The dynamic simulation models provide predictions of internal conditions by applying different algorithms and, to some degree, produce different results. It was proposed that the outputs should be validated against measurements on real homes.

- **Validation of health impacts.** The health benefits of applying risk mitigation measures were quantified based on current published literature. However, none of the literature directly addresses the research questions posed in this project. Reasonable assumptions have been made in quantifying the health impacts based on the evidence available. The sensitivity analysis demonstrates the significance of the choice of these assumptions on calculating the benefits of alternative risk mitigation approaches.

- **Expansion of research to other housing types and locations.** The analysis considered a number of common dwelling types and configurations/ layouts. This could be expanded to include a greater range of typologies.

Appendix A Breakdown of capital cost data for risk mitigation and counterfactual retrofit packages

	Single aspect flat ($61m^2$)	**Dual aspect flat ($72m^2$)**	**Semi-detached house ($114\ m^2$)**
Package 0*			
Split DX a/c systems comprising external wall mounted condenser, internal wall mounted fan coil unit and interconnecting refrigerant pipework (including commissioning)	£4,325	£4,800	£5,500
Condensate disposal, room controller and power supply	£975	£975	£1,300
Builder's work in connection	£1,200	£1,200	£1,600
Total	**£6,500**	**£6,975**	**£8,400**
Package 1			
Internal blinds; manually operated	**£1,400**	**£2,550**	**£660**
Package 2			
Low g-value glazing plus reduced glazing ratio of 25% in flats	£6,575	£7,955	£6,995
Omit standard double glazing	*-£5,500*	*-£11,135*	*-£5,380*
Exposed wall (in lieu of reduced glazing area)	£300	£3,220	£0
Total	**£1,375**	**£40**	**£1,615**
Package 3			
External shading	£4,260	£4,850	£2,660
Openable glazing plus reduced glazing ratio of 25% in flats and increased glazing ratio of 20% in house	£2,282	*-£995*	£4,480
Omit fixed glazing	*-£2,343*	*-£3,905*	*-£1,635*
Exposed wall (in lieu of reduced/ increased glazing area)	£300	£3,220	*-£1,425*
Total	**£4,500**	**£3,170**	**£4,080**
Package 4			
Package 3 costs plus			
Heavyweight blockwork and dense plaster in	£6,170	£9,010	£13,740

	Single aspect flat (61m²)	Dual aspect flat (72m²)	Semi-detached house (114 m²)
external and party walls			
Omit lightweight blockwork and plasterboard finish in external and party walls	*-4,605*	*-£6,708*	*-£10,016*
Heavyweight blockwork and dense plaster in internal partitions	£6,698	£6,034	£10,202
Omit metal stud and plasterboard internal partitions	*-£3,107*	*-2,800*	*-4,733*
Dense plaster for ceiling (50% area)	£896	£1,055	-
Omit plasterboard finish for ceiling (50% area)	*-£860*	*-£1,013*	-
Precast concrete planks and screed for intermediate floor	-	-	£9,732
Omit timber intermediate floor	-	-	*-£6,636*
Allowance for surface mounted services	£633	£732	£1,106
Total**	**£10,325**	**£9,480**	**£17,480**
Package 5			
Package 3 costs plus			
Extra-over for reverse cycle heat pump (including commissioning)	£1400	£1400	£2,530
Fan coil units to living room and bedrooms	£2,400	£2,400	£4,800
Pipework / valves for chilled water to fan coil units; Ductwork / attenuators / grilles to living room and bedrooms	£1,480	£1,480	£2,960
Condensate disposal, room controller and power supply	£750	£750	£1,480
Total	**£10,530**	**£9,200**	**£15,850**

*when air-conditioning is installed; costs only apply to the proportion of housing stock that is assumed to be air-conditioned under the counterfactual scenario

**Note that Package 4 may impact on building structure and/or foundations. These have not been accounted in the cost estimates.

Appendix B Mortality and productivity impact tables

B.1 Supplementary tables for Section 8.1 Results from the mortality analysis

Table 25: Number of life years saved in DSY1 year per dwelling relative to P0

		DSY1 2020s					DSY1 2050s				
London		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	0.0003	0.0005	0.0007	0.0013	0.0021	0.0005	0.0006	0.0010	0.0021	0.0042
	Dual Aspect	0.0007	0.0028	0.0029	0.0034	0.0040	0.0009	0.0038	0.0041	0.0051	0.0065
	Single Aspect	0.0006	0.0012	0.0014	0.0019	0.0026	0.0008	0.0018	0.0021	0.0029	0.0047
Nottingham		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	0.0001	0.0002	0.0002	0.0005	0.0010	0.0002	0.0003	0.0005	0.0010	0.0019
	Dual Aspect	0.0003	0.0014	0.0015	0.0017	0.0021	0.0005	0.0022	0.0023	0.0028	0.0034
	Single Aspect	0.0002	0.0006	0.0007	0.0009	0.0013	0.0004	0.0009	0.0010	0.0014	0.0022
Southampton		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	0.0002	0.0003	0.0004	0.0008	0.0012	0.0004	0.0006	0.0009	0.0018	0.0030
	Dual Aspect	0.0006	0.0023	0.0024	0.0028	0.0031	0.0008	0.0035	0.0037	0.0044	0.0054
	Single Aspect	0.0005	0.0012	0.0012	0.0015	0.0020	0.0007	0.0018	0.0020	0.0027	0.0040

Table 26: Number of life years saved in TRY year per dwelling relative to P0

		TRY 2020s					TRY2050s				
London		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	0.0001	0.0001	0.0001	0.0002	0.0004	0.0001	0.0002	0.0003	0.0006	0.0013
	Dual Aspect	0.0002	0.0008	0.0008	0.0009	0.0010	0.0006	0.0022	0.0023	0.0026	0.0031
	Single Aspect	0.0001	0.0002	0.0002	0.0004	0.0005	0.0004	0.0008	0.0008	0.0011	0.0017
Nottingham		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	0.0001	0.0001	0.0002	0.0003	0.0006	0.0002	0.0002	0.0003	0.0006	0.0013
	Dual Aspect	0.0003	0.0010	0.0011	0.0012	0.0014	0.0004	0.0015	0.0016	0.0018	0.0023
	Single Aspect	0.0002	0.0004	0.0004	0.0005	0.0008	0.0003	0.0006	0.0007	0.0009	0.0015
Southampton		1	2	3	4	5	1	2	3	4	5
Daytime	Semi-Detached	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0002	0.0003	0.0005	0.0007
	Dual Aspect	0.0002	0.0007	0.0007	0.0008	0.0009	0.0005	0.0017	0.0017	0.0019	0.0021
	Single Aspect	0.0001	0.0002	0.0002	0.0003	0.0004	0.0004	0.0008	0.0008	0.0010	0.0013

B.2 Supplementary tables for Section 8.2 Results from sleep disruption analysis

Table 27: Productivity impact per dwelling in DSY1 year (% GDP)

		DSY1 2020s						DSY1 2050s					
London		0	1	2	3	4	5	0	1	2	3	4	5
Daytime	Semi-Detached	0.41%	0.38%	0.35%	0.10%	0.10%	0.00%	0.78%	0.74%	0.72%	0.24%	0.20%	0.00%
	Dual Aspect	0.11%	0.09%	0.09%	0.05%	0.05%	0.00%	0.29%	0.24%	0.25%	0.12%	0.14%	0.00%
	Single Aspect	0.11%	0.10%	0.10%	0.05%	0.05%	0.00%	0.28%	0.25%	0.26%	0.11%	0.15%	0.00%
Non-Daytime	Semi-Detached	0.80%	0.66%	0.54%	0.08%	0.04%	0.00%	1.37%	1.23%	1.08%	0.19%	0.13%	0.00%
	Dual Aspect	0.47%	0.30%	0.12%	0.04%	0.02%	0.00%	0.88%	0.63%	0.33%	0.11%	0.05%	0.00%
	Single Aspect	0.31%	0.18%	0.11%	0.04%	0.03%	0.00%	0.68%	0.48%	0.36%	0.11%	0.13%	0.00%

Nottingham		0	1	2	3	4	5	0	1	2	3	4	5
Daytime	Semi-Detached	0.12%	0.09%	0.09%	0.02%	0.03%	0.00%	0.19%	0.17%	0.17%	0.07%	0.04%	0.00%
	Dual Aspect	0.02%	0.02%	0.02%	0.01%	0.01%	0.00%	0.05%	0.04%	0.05%	0.02%	0.03%	0.00%
	Single Aspect	0.02%	0.02%	0.02%	0.00%	0.00%	0.00%	0.05%	0.05%	0.05%	0.02%	0.02%	0.00%
Non-Daytime	Semi-Detached	0.17%	0.13%	0.10%	0.01%	0.00%	0.00%	0.32%	0.29%	0.24%	0.05%	0.01%	0.00%
	Dual Aspect	0.09%	0.05%	0.02%	0.00%	0.00%	0.00%	0.21%	0.12%	0.05%	0.01%	0.00%	0.00%
	Single Aspect	0.07%	0.04%	0.02%	0.00%	0.00%	0.00%	0.12%	0.09%	0.05%	0.02%	0.02%	0.00%

Southampton		0	1	2	3	4	5	0	1	2	3	4	5
Daytime	Semi-Detached	0.08%	0.08%	0.07%	0.01%	0.00%	0.00%	0.33%	0.32%	0.30%	0.04%	0.04%	0.00%
	Dual Aspect	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.06%	0.05%	0.05%	0.02%	0.03%	0.00%
	Single Aspect	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.06%	0.04%	0.04%	0.02%	0.03%	0.00%
Non-Daytime	Semi-Detached	0.20%	0.15%	0.11%	0.00%	0.00%	0.00%	0.62%	0.53%	0.42%	0.02%	0.01%	0.00%
	Dual Aspect	0.11%	0.06%	0.01%	0.00%	0.00%	0.00%	0.34%	0.19%	0.06%	0.01%	0.00%	0.00%
	Single Aspect	0.04%	0.03%	0.01%	0.00%	0.00%	0.00%	0.17%	0.12%	0.07%	0.02%	0.01%	0.00%

Table 28: Productivity impact per dwelling in TRY year (% GDP)

		TRY 2020s						TRY 2050s					
London		0	1	2	3	4	5	0	1	2	3	4	5
Daytime	Semi-Detached	0.05%	0.05%	0.05%	0.00%	0.00%	0.00%	0.27%	0.25%	0.24%	0.04%	0.05%	0.00%
	Dual Aspect	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.07%	0.06%	0.06%	0.02%	0.02%	0.00%
	Single Aspect	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.06%	0.05%	0.05%	0.02%	0.02%	0.00%
Non-Daytime	Semi-Detached	0.15%	0.13%	0.09%	0.00%	0.00%	0.00%	0.63%	0.52%	0.41%	0.03%	0.01%	0.00%
	Dual Aspect	0.06%	0.03%	0.00%	0.00%	0.00%	0.00%	0.36%	0.20%	0.08%	0.02%	0.00%	0.00%
	Single Aspect	0.02%	0.01%	0.00%	0.00%	0.00%	0.00%	0.19%	0.13%	0.07%	0.02%	0.02%	0.00%

Nottingham		TRY 2020s						TRY 2050s					
		0	1	2	3	4	5	0	1	2	3	4	5
Daytime	Semi-Detached	0.05%	0.05%	0.04%	0.00%	0.00%	0.00%	0.13%	0.13%	0.13%	0.01%	0.00%	0.00%
	Dual Aspect	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.01%	0.01%	0.00%	0.00%	0.00%
	Single Aspect	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.01%	0.01%	0.00%	0.00%	0.00%
Non-Daytime	Semi-Detached	0.10%	0.08%	0.07%	0.00%	0.00%	0.00%	0.22%	0.19%	0.16%	0.00%	0.00%	0.00%
	Dual Aspect	0.06%	0.02%	0.00%	0.00%	0.00%	0.00%	0.16%	0.09%	0.01%	0.00%	0.00%	0.00%
	Single Aspect	0.02%	0.01%	0.00%	0.00%	0.00%	0.00%	0.10%	0.05%	0.02%	0.00%	0.00%	0.00%

Southampton		0	1	2	3	4	5	0	1	2	3	4	5
Daytime	Semi-Detached	0.02%	0.01%	0.01%	0.00%	0.00%	0.00%	0.06%	0.06%	0.06%	0.02%	0.01%	0.00%
	Dual Aspect	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
	Single Aspect	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
Non-Daytime	Semi-Detached	0.02%	0.02%	0.01%	0.00%	0.00%	0.00%	0.11%	0.09%	0.06%	0.01%	0.00%	0.00%
	Dual Aspect	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.07%	0.03%	0.01%	0.00%	0.00%	0.00%
	Single Aspect	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	0.02%	0.02%	0.00%	0.00%	0.00%