Indoor overheating and mitigation of converted lofts in London, UK.

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Abstract

In the UK, there has been an increase in the number of loft conversions in properties, driven by demands for increased floor areas of dwellings to accommodate more individuals or increase property values. While rooms directly underneath roofs are known to have increased overheating risks, there is little research available that quantifies this risk, and how to mitigate it cost-effectively. This paper seeks to evaluate overheating risks in loft conversions, using Integrated Environmental Solutions Virtual Environment to dynamically simulate indoor temperatures in a semi-detached dwelling in London, UK, under current and future (2050s and 2080s medium and high emissions) climate scenarios. Adaptive overheating risk and energy consumption is calculated with and without passive overheating adaptations that reduce solar gains, increase ventilation, or add thermal insulation. Marginal Abatement Cost Curves (MACC) are then used to select the most cost-effective adaptations based on installation and ongoing energy consumption costs. Results estimate 11,340 – 12,210 more summertime Category I overheating degree hours for the loft than conventional bedrooms in the dwelling under the current climate; total Category I loft overheating degree hours may increase to 20,319 by 2080. While external shutters and night purge ventilation were the most effective at reducing overheating degree hours (96% and 89%, respectively), the most cost-effective solutions considering capital and ongoing costs are ventilation strategies, including nighttime purge ventilation, advance ventilation, and cross ventilation. Passive adaptations are not capable of

eliminating overheating entirely, and by the 2080s active cooling is likely to be required to maintain comfortable indoor conditions in lofts.

Practical applications

Converted lofts - present in 5.8% of English and 10.8% of London dwellings - are at significantly elevated risk of high indoor temperatures relative to conventional rooms. Passive adaptations such as ventilation and shading can effectively mitigate loft overheating until around 2080, after which active measures become necessary. When capital and ongoing costs are considered, the most cost-effective heat mitigating adaptations are night and advance ventilation and internal curtains/blinds. Heat mitigating adaptations for converted lofts should become mandatory, and such spaces should not be occupied by the vulnerable or elderly during hot weather.

Keywords

Overheating; Loft conversions; MACC Curve; Building Simulation

1. Introduction

In many parts of the UK, the high cost of housing per square metre and the demand for extra living space means that loft conversions are increasingly seen to be a good investment, with estimates suggesting that they can add up to 20% to property values (1) . However, evidence suggests that top floor flats are at risk of elevated indoor temperatures (2), and converted lofts – typically with low thermal mass – may be particularly vulnerable to high indoor temperatures; indeed occupants of lofts - or rooms directly under roofs - have been shown to have an increased risk of heat-related mortality during heatwaves (3). Climate change is projected to increase average temperatures, as well as the frequency and duration of heatwave events in the UK (4), and summers such as 2003 where 2000 heat-related deaths occurred in England and Wales (5) are expected to become the norm by mid-century. Therefore, loft conversions may be particularly vulnerable to overheating in future climates. The risk of loft overheating may be further exasperated by the fact that the majority of conversions are likely to occur in urban areas, where housing is in greatest demand, but where night-time temperatures may be elevated due to Urban Heat Island (UHI) effects. In addition, it is thought that the majority of loft conversions are extra bedrooms: occupants typically have stricter thermal comfort requirement during sleep (6), while high night-time temperatures are an important contributor to heat-related mortality (7,8).

There is little evidence to indicate the degree to which loft overheating may be an issue in the UK, including a lack of published data on the prevalence of loft conversions. Empirical indoor temperature data from lofts is currently limited to monitoring data from a single dwelling that indicates a high risk of night time overheating (9). Due to their relative infrequency, converted lofts are often excluded from large-scale monitoring or stock modelling studies into heat risk, and previous research on indoor temperatures in the UK has generally focused on monitoring (10–12) or modelling (2,13–16) indoor temperatures in living rooms and primary bedrooms. Results from such studies support the conclusion that top-floor flats – or dwellings below a roof - have an elevated overheating risk relative to dwellings on the ground or middle floors. Outside of the UK, Skarning, Hviid and Svendsen modelled loft overheating and energy consumption for a zero energy loft in Copenhagen and Rome (17), however the building characteristics modelled in this study differ significantly from the typical converted loft in the UK. There have also been numerous studies that seek to examine how energy efficient retrofit, or the provision of heat-mitigating adaptations to buildings, may change indoor temperature exposures during hot weather (2,14,18,19). There is, however, little data on heat mitigation in lofts other than the aforementioned Skarning study (17).

This paper aims to evaluate the potential overheating risk in a converted loft in Central London. First, the English Housing Survey is analysed to determine the prevalence of converted lofts across the English housing stock. Indoor temperatures are then modelled for a converted loft in a semi-detached dwelling using the dynamic thermal simulation tool Integrated Environmental Solutions Virtual Environment (IES VE) under current and future climate scenarios. A number of passive heat-mitigating adaptations are then modelled and ranked according to their effectiveness and cost. The research questions are:

1) Are converted lofts more likely to overheat than other bedrooms in a house?
2) What are the most effective passive cooling interventions to reduce loft overheating?
3) How do these passive cooling interventions rank according to cost-effectiveness?

2. Methods

2.1. Background

The 2015-2016 English Housing Survey (20) was analysed for the presence of a loft conversion and the year that the conversion was performed. Results indicate a rapid increase in loft conversions in recent years, with the most recent period (2010-2020) on pace to exceed the number of conversions during the previous period (2000-2010) (Figure 1). In London in particular, loft conversions nearly doubled from 2000-2009 compared to the previous decade (72,590 to 141,524). Overall, loft conversions are found in 5.8% of dwellings in England, with the highest rates of conversion found in London (10.8%), Yorkshire and the Humber (8.3%), and the North West (6%). The majority of converted lofts are found in semi-detached dwellings (34.5%), followed by mid terraces (29.1%), detached (18.3%), and end terraces (9.8%). The majority of the dwellings with rooms in the lofts have been built pre 1919 (42.7% of all converted lofts), followed by 1919-1944 (26.5%), 1945-1964 (18.2%), and 1965-1980 (9.2%). The most common household types to have a room in the loft are couples with no dependent children (38%), followed by couples with dependent children (36%), and other multi-person household (8.1%). The most common ages of the household reference person are 45-54 (25%), followed by 35-44 (21%), and 65 or over (20%).

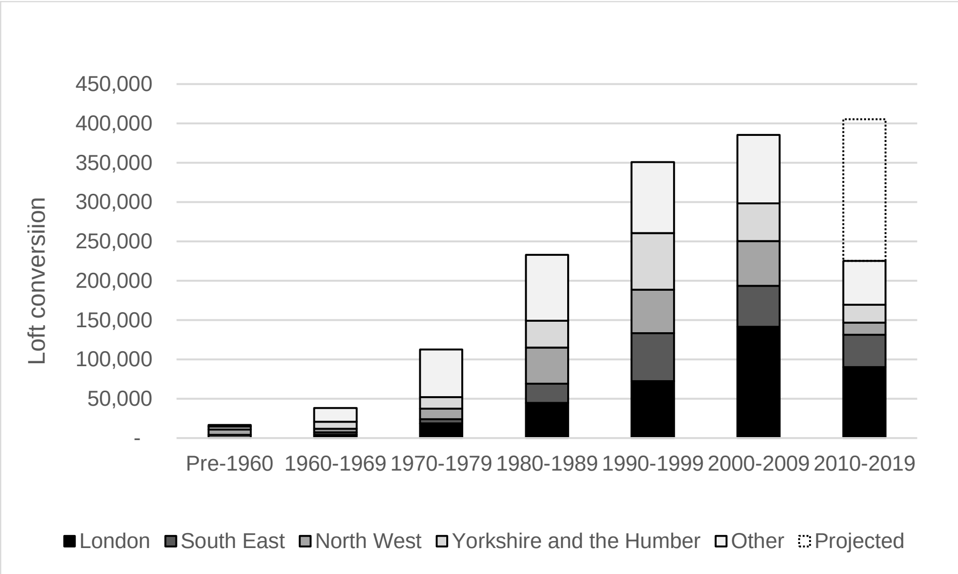

Figure 1. The number of loft conversions by date range conversion occurred, by English regions.

2.2. Building simulation

Based on the analysis of loft conversion in the EHS, we selected the semi-detached dwelling for further analysis, as it is the dwelling variant most commonly found with loft conversions. For the purposes of this modelling, we assume that the loft is occupied and being used as a bedroom. We modelled the dwelling in London due to the high frequency of converted lofts, as well as the additional heat risks due to the UHI. Dynamic thermal simulation was performed using IES VE (21).

2.2.1. Semi-detached built form

The built form for the dwelling was modified from that used by Taylor et al (22) in previous modelling of overheating risk across dwelling variants. The loft height was changed to ensure that the loft had a maximum ceiling height of 2.3m, the minimum requirement for converted lofts (23,24). The dimension of loft room is 5.4m long and 4.3m wide, allowing 1.2m minimum head space along the perimeter as recommended by Mindham (23). For lofts, optimal daylighting can be provided by roof windows with a minimum glazing-to-floor ratio of 6.7% (25). Therefore, two 1.2m by 1.2m roof windows are added to each loft roof (north and south-oriented) to provide daylighting and natural ventilation. The converted loft is accessed from the first-floor corridor through a permanent spiral staircase. English dwellings are predominantly naturally-ventilated and converted dwellings are typically older, so a Mechanical Ventillation Heat Recovery (MVHR) system was not modelled (26). House floorplans and a crosssection of the archetype are shown in Figure 2.

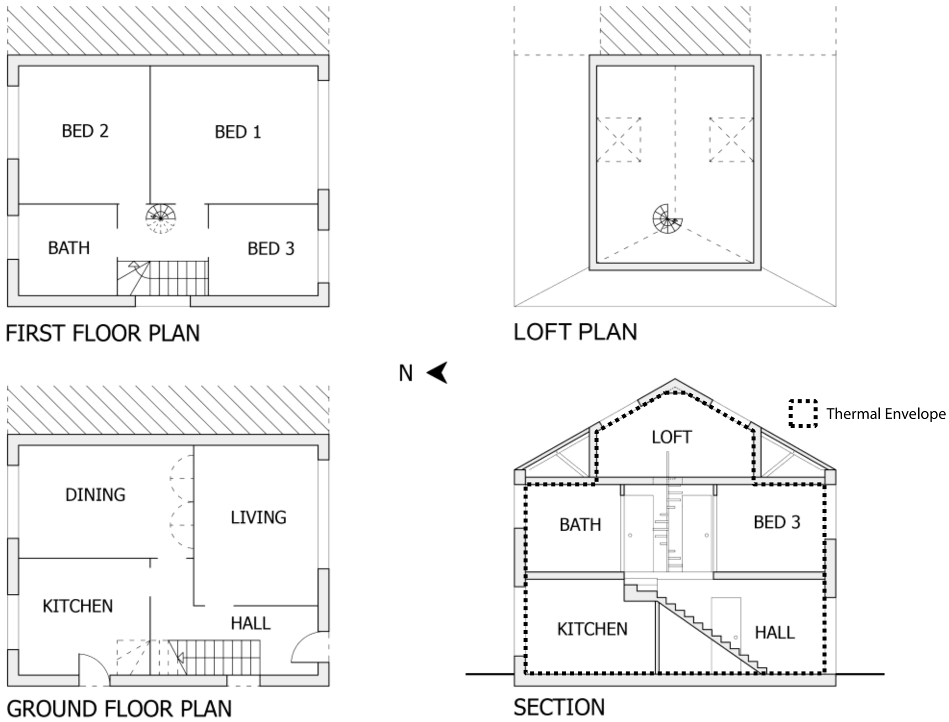

Figure 2. Semi-detached house floorplans of ground floor, first floor and loft and west-facing crosssection. The thermal envelope is indicated with a thick black dotted line.

2.2.2. Building envelope

The building envelope characteristics input into the model can be seen in Table 1. We model the dwelling as having been constructed from 1919-1944 with cavity walls, and assume that the building has undergone an energy efficient retrofit during the loft conversion, including cavity insulation and double glazed windows.

The model was generated assuming that the converted loft is in compliance with current Building Regulations for energy efficiency (27) and ventilation (28), with the design informed by various loft conversion guidelines (24,29). We model the roof as being supported by timber rafters underneath, covered by concrete tiles which represent the dominant roof covering material for converted lofts (20). The roof is assumed to be insulated by 150mm-thick polyurethane (PU) insulating boards installed between rafters and finished internally with 12.5mm plasterboards. There is also a 50mm air cavity between the insulation layer and roof tiles to ensure sufficient roof ventilation. The modelled U-value of insulated roof is 0.16W/m^{2}K, under the 0.18W/m^{2}K requirement of Building Regulations.

The section of roof sheltering the unoccupied part of the loft remains uninsulated as it is outside the thermal envelope. With the exception of the existing party wall, the converted loft room is further enclosed by three newly-built walls, forming part of the thermal envelope. These walls are assumed to be timber-framed, insulated with 150mm PU boards and internally finished with 12.5mm plasterboard, achieving a U-value of 0.25W/m^{2}K. The loft floor of the occupied section in the same as the internal ceiling/floor construction mentioned above, while the unoccupied part is insulated at floor level with 150mm thick PU insulation boards installed between joists (0.16W/m^{2}K) to create an enclosed thermal envelope. The loft is modelled with centre-pivot roof windows, as they are the most commonly utilised product for roof windows (30); these are sized in accordance with Approved Document F (28), with a maximum openable area of 30^o and an openable area percentage of 80%. The two roof windows are double glazed with CO_2 infill, resulting in 1.39 W/m^{2}K thermal transmittance, performing better than the 1.6 W/m^{2}K recommendation by Building Regulations for roof windows (27).

Table 1. Building fabric characteristics of the base case model

Element	Construction detail (external to internal)	U-value (W/m^{2}K)	Solar absorptivity	Solar emissivity
Main house				
External walls	105mm brick + 50mm cavity filled with UF foam insulation + 100mm dense concrete block + 12.5mm plasterboard	0.60	0.8	0.9
Party wall	12.5mm plaster + 215mm brick + 12.5mm plaster	1.43	-	-
Internal walls	12.5mm plaster + 105mm brick + 12.5mm plaster	1.91	-	-
Ground floor	125mm concrete slab + timber battens + 20mm timber flooring	1.74	-	-
Internal floor/ceiling (uninsulated)	20mm softwood flooring + 150mm timber joists + 12.5mm plasterboard	1.55	-	-
Windows	6/12/6 double-glazing (argon filled) + PVC frame	1.57	-	0.85
Doors	40mm plywood	2.06	0.7	0.85
Converted loft				
Loft roof (insulated)	Concrete tiles + 50mm ventilated air space + 150mm PU insulating board between and under rafters + 12.5mm laminated plasterboard	0.16	0.7	0.9
Roof (outside thermal envelope)	Concrete tiles + timber battens + timber rafters	5.71	0.7	0.9

Loft walls (insulated)	Timber frame + 150mm phenolic insulating board + 12.5mm plasterboard	0.25	-	-
Internal floor/ceiling (insulated)	20mm softwood flooring + 150mm PU insulation + 12.5mm plasterboard	0.16	-	-
Roof windows	6/12/6 double-glazing (CO_2 filled) + PVC frame (0.55 g-value)	1.39	-	0.85

2.2.3. Operational settings

Operational settings for the model can be seen in Table 2. Air change rates for each room are set based on typical values provided in Chartered Institution of Building Service Engineers (CIBSE) Guide B1 (31). The unconditioned part of the loft is assumed to have a 5ACH ventilation rate due to the presence of vents. It has been assumed that this house is home to a family of four, with each person sleeping in one bedroom including the converted loft. Internal gains for residents, appliances and lightings are decided based on CIBSE Guide A (32). Except for the corridors, all rooms are heated with radiators during occupied hours in winter months (October to April); set points for turning on radiators differ with function of the rooms, which are determined according to recommended winter indoor air temperatures for dwellings in CIBSE Guide A. The heating system is modelled with a UK-average boiler efficiency of 80% (33).

Window opening in the base case dwelling is modelled to occur above an indoor temperature threshold of 22 °C , as per CIBSE TM59 (34), during occupied awake hours; in the loft, this is limited to fully opening a single roof window. We acknowledge a great deal of uncertainty in window-opening behaviours. A large proportion of London residents prefer to keep windows closed – particularly during sleep - to avoid disturbance from external noise and security hazards (35), while roof windows may not be openable in all weather conditions.

Table 2. House operating settings.

Room	**Infiltration (ACH)**	**Occupied hours**	**Activity**	**People gain (W), Sensible (Latent)**	**Appliances gain (W), Sensible (Latent)**	**Lighting gain (lux)**	**Heating set point (°C)**
Kitchen	1	17:00 – 17:30	Four people cooking	300 (264)	Hob: 3000 Fridge-freezer: 60 all hours	300	19
Dining room	1	17:30 – 18:00	Four people eating meal	328 (216)	-	200	19
Living room	1	18:00 – 22:00	Four people seated	260 (140)	TV: 90 during occupied hours, 7 otherwise.	200	23

Bedroom/loft	0.5	22:00 – 23:00	One person reading	65 (35)	-	100	19
		23:00 – 07:00	One person sleeping	55 (25)	-	-	19
Bathroom	2	07:00 – 08:00	One person bathing	75 (66)	Hot Shower: 400 (200)	150	22
Corridor	1.5	-		-	-	-	-

2.2.4. Adaptations

Housing adaptations were selected to reduce loft overheating risk by minimising solar gains, optimising ventilation strategies or reducing thermal transmittance of the building envelope. Internal gains remain unchanged as occupant behaviours are unpredictable and vary with individuals. Interventions are summarised in Table 3, and are applied to the base model individually. The adaptations are described in further detail, below.

Table 3. Interventions applied to base case dwelling to mitigate loft overheating.

Category	Intervention	Description
Solar control	External shutters	External shutters with no solar transmittance operated from 9am to 5pm during summer
	Internal roller blinds	Internal roller blinds with 0.61 shading coefficient and 0.3 short-wave radiant fraction operated from 9am to 5pm during summer
	Internal curtains	Internal curtains with 0.54 shading coefficient and 0.3 short-wave radiant operated from 9am to 5pm during summer
	Light-colour walls	White exterior wall paint, reducing solar absorptivity to 0.3
	Light-colour roof	White coating on roof tiles, reducing solar absorptivity to 0.25
	Solar control glass film	Reflective silver solar control film to the roof window glazing, lowering g-value to 0.27
Ventilation	Night-purge ventilation	The loft skylight is opened 1 hour before sleep and kept open at night (22pm to 7am) during summer
	Cross ventilation	Reduce opening of roof window 1 from 80% to 40%, and open roof window 2 40% to create cross ventilation from 10-11pm.
	Operating time	Open one roof window in advance (1 or 2 hours) during summer
	Window types	Change centre-pivot roof window to side-hinged, top-hinged or bottom-hinged window without changing any other ventilation settings
Insulation	External wall insulation (EWI)	Add extra 60mm EPS insulation and 12.5mm dense plaster to exterior wall surface resulting in 0.4 solar absorptivity and U-value of 0.30W/m^{2}K
	Internal wall insulation (IWI)	Add extra 60mm EPS insulation to interior wall surface resulting in U-value of 0.30W/m^{2}K

Ground floor insulation (GFI)	Add 90mm PU insulating boards above concrete slab reducing U-value to 0.25W/m^{2}K

Solar control adaptations

Solar control interventions include shading, house paint and solar control glazing. All shading interventions applied to loft roof windows are implemented based on IES shading device settings. Shading devices are added to both roof windows, regardless of their orientation. External shutters, internal roller blinds and white cotton curtains are chosen from IES database for modelling (21). All shading devices are assumed to be fully closed from 9am to 5pm only during summer months, as it is not practicable to rely on occupants to adjust shading level according to real-time solar intensity because the loft is usually not occupied during daytime. For adaptations to building absorptivity, external masonry walls or concrete roof tiles are coated with white paint to achieve surface solar absorptivity of 0.30 and 0.25, respectively (36). For the solar control glazing, reflective silver tint is applied to the outer window pane to reduce g-value to 0.27 from 0.55.

Ventilation adaptations

There are six modelled ventilation adaptations, including three behavioural and three related to window type. Night-time purge ventilation is modelled by keeping a single loft roof window open between 22:00-07:00, May to September. Cross ventilation is modelled in the loft by reducing the opening area of roof window 1 from 80% to 40%, and opening roof window 2 40% between 22:00 and 23:00, thus allowing for cross ventilation without changing the total openable area of the windows. Advance ventilation is modelled by opening a single roof window 1 hour or 2 hours before the occupied period. Roof window opening type may also influence the efficiency of ventilation; therefore side-hinged, top-hinged and bottom hinged windows are tested as independent interventions (30). When modelling the other three window types, the maximum open angle, window proportion, openable area and ventilation control profiles are kept consistent with the base case.

Thermal adaptations

While the base case dwelling has a roof insulated to high standards and the windows are double-glazed, the thermal characteristics of external cavity walls and uninsulated ground floor may be improved further. Cavity walls are improved using either external or internal insulation with 60mm EPS boards. Finally, the solid concrete ground floor is insulated with 90mm PU insulating boards on the internal surface.

2.2.5. Weather

Weather files for modelling were obtained from CIBSE (37). A Design Summer Year (DSY) weather file for the London Weather Centre (baseline 2020s, high emissions) is used to analyse current summer overheating, and a Test Reference Year (TRY) for the same period to calculate winter heating energy consumption. Current weather files are used to create the base case for ranking cooling intervention effectiveness and evaluate interventions to eliminate loft overheating. Moreover, predicted future weather files (50 percentile probability) for the 2050s and 2080s under medium and high carbon emission scenarios are also applied to explore the passive cooling performance of the adapted models in future climates. It has been assumed that there is no external shading from either vegetation or other buildings.

2.3. Overheating analysis

We quantify night time loft overheating risks throughout the entire summer (May – September inclusive) using the adaptive model of thermal comfort described in TM52 (38). This model was selected over the TM59 criteria (34) due to its ability to 1) account for occupant adaptation to heat, 2) to enable different categories of thermal comfort criteria to be considered, and 3) to produce a metric which reflected both the frequency and degree of comfort criteria exceedance, which we felt would lead to an increased ability to distinguish between mitigation effectiveness. However, TM52 is limited by the lack of a night time overheating thresholds – important due to the impacts of high temperatures on sleep. We address this in-part here by applying TM52 for both daily and night time–only hours, although we acknowledge the advantages of TM59 in this area.

The exponentially-weighted running mean outdoor temperature (T_{rm}) is calculated using the series:

$$T_{rm} = (1-\alpha) \times (T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \cdots)$$

Where T_{od-1} is the mean outdoor air (dry-bulb) temperature for 'yesterday' and T_{od-2} for the day before yesterday and so on; and α is a constant smaller than 1, the optimal value for which is 0.8 in Europe (38). The indoor thermal comfort temperature for any one day (T_{comf}) is then calculated as:

$$T_{comf} = 0.33T_{rm} + 18.8$$

We then apply two categories of thermal comfort criteria: Category I, which is a narrow range of comfort for vulnerable individuals (±2 ^{o}C) and Category II, a normal range for renovated dwellings (±3 ^{o}C). The weighted exceedance (W_e) during occupied period is then calculated as:

$$W_e = (\Sigma h_e) \times WF$$

Where the weighting factor (WF) is the temperature difference between the hourly indoor operative temperature and maximum indoor temperature threshold when the threshold is exceeded, and h_e is the number of hours that this exceedance was met. In this case, W_e is calculated for all hours of the day (24-hour), and at night only (22:00 - 07:00). We sum W_e for both thermal comfort categories over the summer period to estimate total 24-hour and night time overheating degree hours. When a nightly W_e exceeds 6 degree-hours it is considered an overheating degree night, which we also sum over the summer period.

2.4. Cost-effectiveness analysis

Marginal Abatement Cost Curves (MACC) are typically used for determining the implementation order of energy efficiency retrofit measures based on cost effectiveness (39). In this case, we apply the same method to overheating reduction. Net present cost (NPC) describes the cost of each intervention through its entire lifecycle. NPC divided by overheating degree-hour reduction provides a MAC value (£/degree-hour), which represents cost-effectiveness; the smaller the value the more cost-effective. The costs for the different adaptations were estimated, including capital cost for the product and any additional expenses due to increased winter space heating demand, accounting for the boiler efficiency. Formulas below are used for calculating MAC and NPC.

$$MAC = \frac{NPV}{|\Delta ADH|}$$

$$NPC = C_{initial} + \sum_{n=1}^{t} \frac{E_{heating} \times P_{gas}}{(1+\varphi)^n}$$

where MAC is the marginal abatement cost (£/degree-hour); NPC is the net present cost (£); ΔADH is the change in loft overheating degree hours following each intervention; $C_{initial}$ is the initial cost of each intervention; $E_{heating}$ is the additional energy consumption for winter space heating in loft per annum (kWh/year); P_{gas} is current UK natural gas price of 0.03 £/kWh (40); φ is a discount rate of 2.5% essential to predict long-term cost considering currency inflation; t is the lifespan of each intervention; and n is the year.

3. Results

3.1. Base case overheating

A comparison of the overheating risks in converted lofts relative to conventional bedrooms under the current climate can be seen in Figure 3. Under current climatic conditions, the converted loft in the base dwelling has 10,799 overheating degree hours (Category II) and 13,028 degree hours (Category I) from May to September; in contrast the overheating degree hours for the other three conventional bedrooms average 624 (Category II) and 1,293 (Category I). Similar results can be seen for night overheating hours, with 1,581 Category II and 2,212 Category I overheating degree hours in the lofts, compared to an average of 108 Category II and 284 Category I degree-hours for the conventional bedrooms. Out of 153 nights in total over 5-month period, 60 nights in the converted loft exceeded the TM52 Category II overheating criteria, and 69 nights exceeded the Category I criteria.

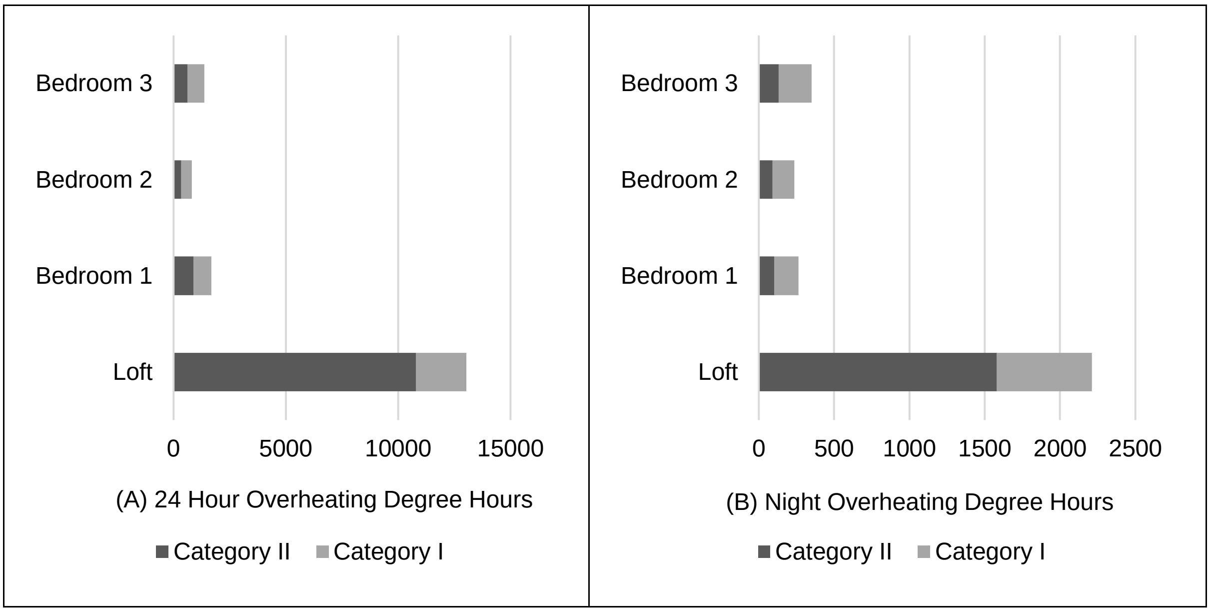

Figure 3. Overheating degree hours for the full day (A) and during night-time (B) for converted lofts compared to conventional bedrooms under current climate conditions.

Overheating risks worsen substantially under future climate scenarios (Figure 4). Category II 24-hour overheating degree hours in lofts are found increase to 13,113 - 13,822 by the 2050s, and 15,275 – 17,495 by the 2080s, depending on the emission scenario; similarly, Category I overheating degree hours increase to 15,550-16,316 in the 2050s and 17,917 – 20,319 in the 2080s. Night-time overheating degree hours are correspondingly smaller, but also show an increase under future climates. Overheating can be seen in conventional bedrooms as well, but such rooms continue to be substantially less vulnerable to overheating relative to the lofts.

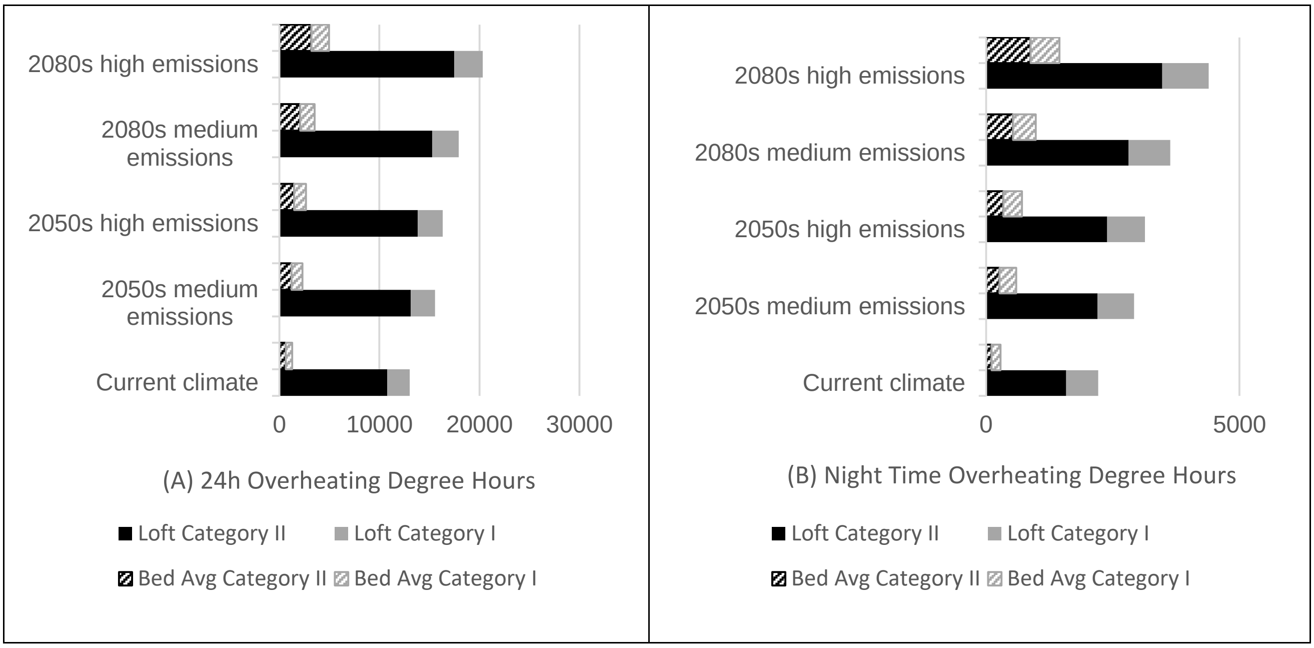

Figure 4. (A) 24-hour Overheating degree hours (Category I and II) for converted lofts compared to the average for the conventional dwellings under future climate scenarios. (B) Night time overheating degree hours (Category I and II) for converted lofts compared to the average for the conventional dwellings under future climate scenarios.

3.2. Passive cooling interventions

Figure 5 shows the ranking of interventions according to the effectiveness in reducing loft night-time overheating degree-hours (A) and overheating nights (B) under the current climate. The order of ranking using both overheating metrics is the same; here we discuss the results for night time degree-hours. Solar control measures are the most effective passive cooling interventions leading to an average degree-hour decrease of 54%, with external shutters able to reduce overheating problems by 96%, reflective solar film reducing overheating degree-hours by 86%, while internal curtains and internal roller blinds are found to be slightly less effective, reducing overheating degree hours by 57% and 50%, respectively. A 34% drop in degree hours is observed after applying white paint to roof tiles, while only 3% decrease is possible by painting walls. Loft annual heating demand increases by 15% after applying reflective solar control film, 3.5% after painting the roof a lighter colour, and 0.2% after installation of external shutters.

Ventilation interventions are also capable of reducing overheating. Night-purge ventilation decreases overheating degree hours dramatically by 89%. Moreover, ventilation in advance reduces overheating degree-hours by 44% (1 hour in advance) and up to 64% (2 hours in advance). In comparison with the base-case centre-pivot windows, the use of bottom-hinged windows for ventilation mitigates overheating by 11%. Change of top-hinged and side-hinged windows are even more influential, leading to 19% and 26% reduction individually. Cross ventilation is much less influential resulting in only 0.3% overheating mitigation. Ventilation related measures have no impact on loft winter heating demand due to only being implemented during the summer.

Insulation interventions may cause a slight decrease in overheating of 0.1% after external wall insulation (EWI), or an increase of 3% following internal insulation. Ground floor insulation (GFI) has a negative impact on loft overheating, increasing the risk by 5% due to the substantial loss of thermal mass.

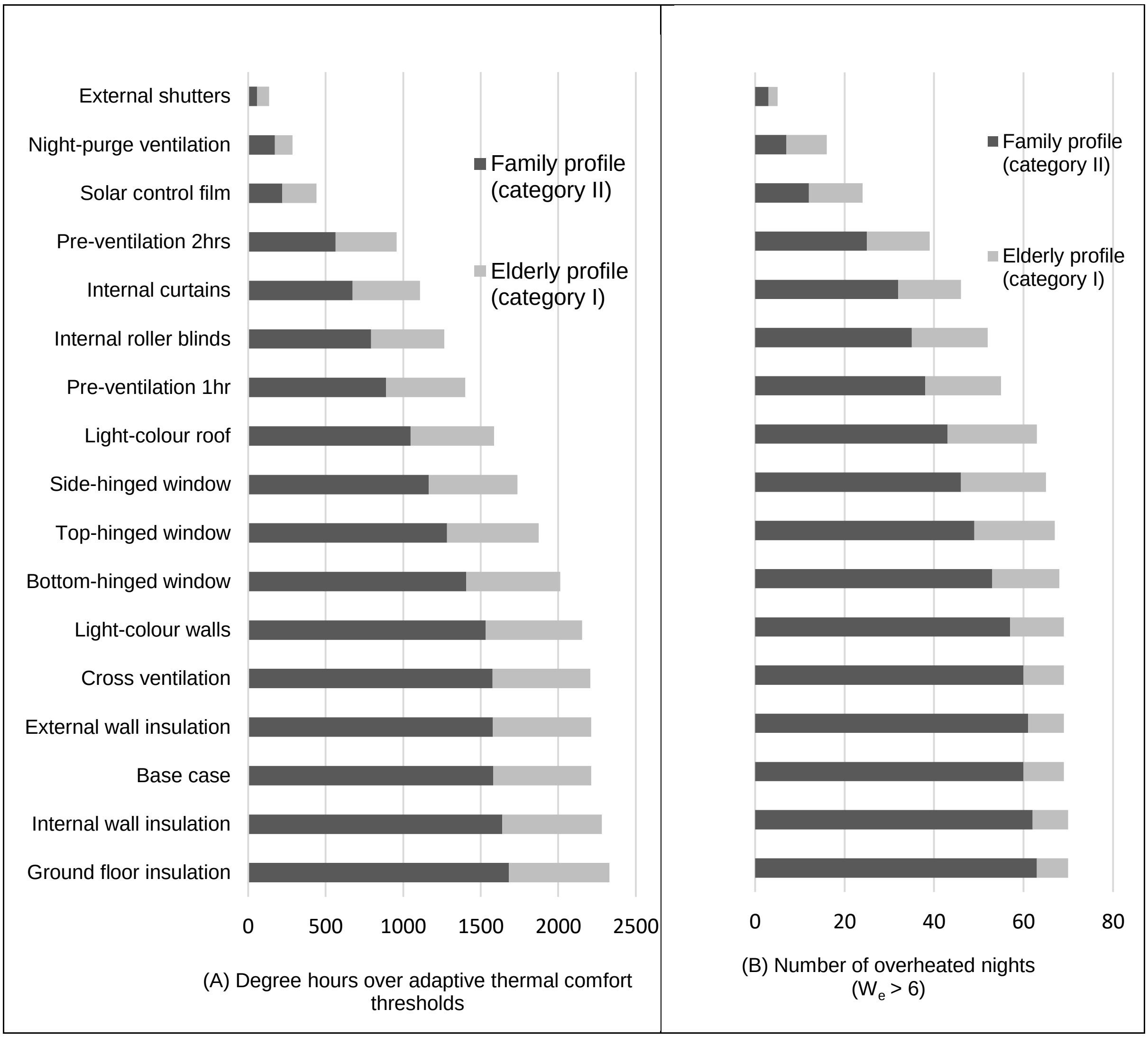

Figure 5. (A) Passive cooling interventions ranking –night time degree hours of loft overheating (B) and the number of overheated nights.

3.3. Analysis of cost effectiveness

Cost-effectiveness is quantified by calculating discounted MAC value, which includes initial costs for the intervention product as well as ongoing expenses for any increased space heating energy consumption in winter. The life expectancy of each intervention is also taken into account as interventions need to be replaced at the end of their lifespan. Calculation variables and results of all interventions are listed in Table 4. Several interventions conflict with others and cannot be implemented simultaneously. Where conflicts occur, the more effective adaptation is selected (highlighted in the table in grey), and applied to the base model cumulatively according to ascending order of their MAC values. Moreover, external wall insulation was found to increase overheating risk (by a likely insignificant 0.05%) when applied alongside light-coloured walls, so is deemed ineffective as an overheating adaptation and is excluded.

Table 4. Intervention cost-effectiveness. Discounted MAC is calculated individually and ranked; these are then modelled cumulatively to identify the most cost-effective adaptations to eliminate overheating. References for capital costs and life expectancy are shown in brackets. Grey rows indicate interventions that have been selected instead of alternative, conflicting interventions.

Interventions	Degree-hour reduction (family profile)	Capital cost (£)	Annual space heating energy increment (kWh/year)	Annual extra cost (£/year)	Intervention lifespan (years)	Discounted MAC (£/degree-hour)
Night-purge ventilation	1408	-	-	-	100	0.000
Pre-ventilation 2hrs	1017	-	-	-	100	0.000
Pre-ventilation 1hr	692	-	-	-	100	0.000
Cross ventilation	5	-	-	-	100	0.000
Internal curtains	907	100 (30)	0.5	0.01	30 (30)	0.005
Internal blinds	787	100 (30)	0.4	0.01	30 (30)	0.006
Solar control film	1362	60 (41)	104.1	2.99	10(41)	0.007
External shutters	1524	400 (30)	1.1	0.03	20 (30)	0.017
Light-colour roof	533	100 (42)	24.3	0.70	10 (43)	0.023
Side-hinged window	415	600 (30)	3.5	0.10	20 (30)	0.093
Top-hinged window	298	760 (30)	2.2	0.06	20 (30)	0.164
Bottom-hinged window	176	520 (30)	1.1	0.03	20 (30)	0.190
Light-colour walls	50	410 (44)	2.1	0.06	10 (43)	0.941
External wall insulation	3	11,800 (45)	-8.0	-0.023	100 (46)	124.050

Even under current climate conditions, overheating degree hours cannot be eliminated comprehensively for either Category with all nine interventions applied simultaneously. However, for Category II, the number of overheating degree hours is reduced to 11 by implementing the first five interventions according to Discounted MAC ranking (night-purge ventilation, advance ventilation for 2 hours, cross ventilation, internal curtains and solar control film), which eliminates overheating nights. For Category I, an additional two interventions (external shutters and light-colour roof) can reduce overheating degree hours to nine, and eliminate overheating degree nights under the current climate. With all nine interventions applied, overheating degree hours can be reduced to 2 for Category II and 7 for Category I. However, implementing all adaptations led to an increase in the heating demand of the whole house of 274 kWh (+3.4%). Among all heated rooms, the loft experienced the largest annual heating demand rise by 138 kWh (19.9%), compared to additional energy use for space heating of other three bedrooms of 38 kWh/year on average (+3.8%) and living room 20 kWh (+0.5%).

The number of overheating degree-hours and overheated nights following installation of all nine interventions under all climate scenarios are shown in Figure 6A and 6B. While loft overheating cannot be completely eliminated even if all nine effective interventions are applied simultaneously, overheating can still be dramatically reduced relative to the base case (Figure 4B). The implementation of all nine passive cooling interventions will be able to successfully limit loft overheating at acceptable levels until the 2080s, after which active cooling interventions may need to be adopted in parallel with passive adaptations to reduce high indoor air temperatures.

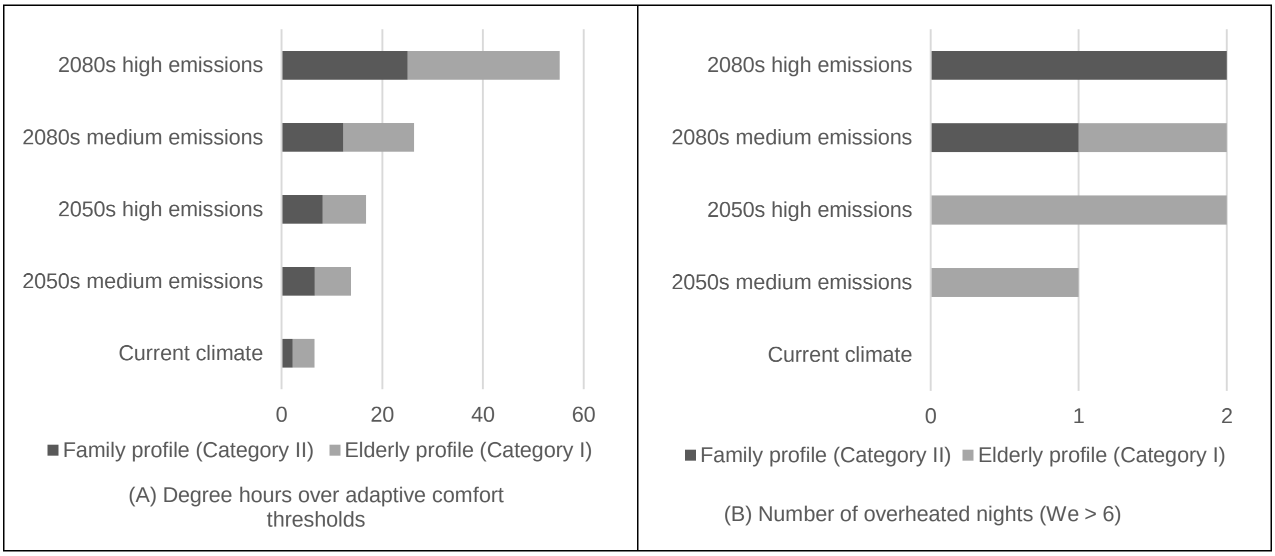

Figure 6. (A) Loft overheating risks under different climate scenarios following all nine adaptation measures; (B) Number of loft overheated nights under different climate scenarios following all nine adaptation measures.

4. Discussion

The overheating potential of converted lofts has been an under-researched topic, and there is little evidence available in the UK to demonstrate the degree of overheating risk relative to conventional rooms, and how to mitigate this risk. The analysis of the EHS shows that dwellings with converted lofts make up a small (5.8%) but rapidly increasing minority of the English housing stock – particularly in London - and one which may increase further in the future due to demand for extra floor space and high house prices. While the predominantly young residents in houses with loft rooms are not typically those that are the most vulnerable to heat-related illnesses and mortality, night-time temperatures will influence the comfort and sleep quality (6), and has been shown to impact on mortality rates across all age groups (7,8).

The results of the modelling described here indicate that converted lofts present a substantial increase in heat exposure risk compared to other bedrooms in a dwelling. We estimate that converted lofts have 10 times more Category I and 17 times more Category II overheating degree hours (24 hour) during current hot summers compared to the average of conventional bedrooms. Future climates increase this risk substantially, adding an additional 2,315 – 3,025 Category I overheating degree hours to lofts by the 2050s and 4,889 – 7,291 by the 2080s. These results are consistent with previous monitoring and modelling studies that found top floor flats with an attic space above are at greater overheating risk than mid or ground floors (2,10,11,15), however the results here are more extreme. This is due to the room being directly below the roof, as well as the relatively small internal volume and low thermal mass of the surrounding room envelope in comparison to more typical English dwelling spaces. We have modelled the dwelling as being well insulated, and dwellings with less roof insulation may in fact be at greater overheating risk that we have shown here (14). We have also assumed that the occupants are able to ventilate the loft and adjacent rooms by opening operable windows; the inability to do so would increase overheating risk in the loft even more. Hot weather that coincides with driving rain or wind may mean that roof windows cannot be opened. The substantial increase in heat exposure risk supports previous epidemiological studies, which show an increased risk to the elderly living in spaces directly under the roof (3). It is therefore advisable that the most heat-vulnerable living or sleeping in lofts are encouraged to find other locations to stay during hot weather episodes.

There is therefore a need to understand the effectiveness of different overheating interventions for converted lofts. The installation of external shutters is the most effective single intervention leading to a 96% reduction in overheating degree hours at the cost of 0.2% winter heating demand increase. It is unclear, however, how practical external shutters on roof windows would be, as they may be difficult to operate and may be damaged by rain, snow, and debris. . The second most effective adaption is night-purge ventilation in loft room, which reduces overheating degree hours by 86% without impacting annual heating demand; however it may not be a good option for residents living in relatively noisy parts of London or in certain weather conditions. The application of reflective solar control film is the third most effective single intervention in terms of overheating mitigation, however such an intervention can cause winter heating demand to increase by 15% for the room. This is consistent with the findings of Porritt et al. (18) and Taylor et al (47) in similar modelling studies of UK dwellings - solar control interventions prevent solar gains from penetrating into the dwelling and being absorbed by building fabric during daytime which is why additional space heating is required to maintain indoor temperatures during winter. Furthermore, ventilation two-hours prior to bedtime and internal curtains are found to be the fourth and fifth most effective intervention, reducing overheating by 64% and 57%, respectively. Various window types have great influence on loft overheating levels due to the differences in maximum ventilation rates between them. Side-hinged window are shown to be the most effective intervention among the three window variants, with maximum air volume flow rate increased from 31.5 L/s to 38.8 L/s, reducing loft overheating by 26%. Internal insulation is found to increase loft overheating risks, in agreement with other findings that internally insulated walls may cause higher dwelling indoor temperatures than external insulated ones due to the loss in thermal mass (2,13,14,48). Similarly overheating degree hours will increase by 5% if the ground floor is internally insulated. Interventions that are effective for average people may not be as effective for vulnerable residents, who may lack mobility or the ability to operate windows, blinds or shutters easily. Therefore, thermal comfort for vulnerable occupants should be considered when designing for sensitive occupants or buildings such as nursing homes.

This study also examines the cost effectiveness of heat mitigating adaptations, through the novel application on MAC values which account for the initial cost, additional expense for space heating, and adaption lifespan. Results indicate the most cost-effective interventions are night purge ventilation, ventilation two hours in advance, cross ventilation and internal curtains. Under both current and future climates, loft overheating cannot be eliminated comprehensively even with all alternative passive cooling interventions applied simultaneously, however risk can still be successfully maintained at acceptable level until the 2080s, beyond which point widely adoption of air-conditioning systems may be inevitable. Overheating can be further reduced by adjusting behavioural interventions to adapt to warmer future climates in manners which have not been modelled here. These could include fullyopening both roof windows, opening loft roof windows 3 to 4 hours in advance of occupied hours, changes to the opening angle of the corridor windows, changes to the hours that shading devices are in operation, and reduction of internal gains.

This modelling study is among the first to focus on overheating and overheating mitigation in converted lofts in England. We model a typical semi-detached house, which represents the most commonly converted dwelling and which may also be generalised to similar dwellings such as end terraces and possibly converted flats, assuming the dwelling is well-insulated. Further research is required to model additional dwelling variants and insulation levels. We also assume static occupancy behaviours, however these are likely to vary from one household to another. We model occupancy based on the profile of a family of four that are out during the day, and estimate overheating degree hours for both Category I and Category II criteria during both 24 hour periods and night hours only. However, as the loft is most likely to be used as a bedroom, we estimate the effectiveness of adaptation on night time overheating degree hours only. Vulnerable individuals are more likely to spend daytime hours at home and – in extreme cases – potentially the loft room. The risk to occupants of heat exposure in such as case would be very high. Furthermore, we have not considered the practicability of some adaptations - for instance, painting walls or the roof in light colours may not be permitted by Building Regulations in conservation areas, while external shutters and some curtain types may not work on roofs of certain pitches. The optimum overheating adaptation scenario may differ depending on dwelling types, individual household properties, and occupants' behaviours. Despite the limitations of this initial investigation, it is clear that lofts are at risk of significant summertime overheating. Consequently, passive cooling measures for lofts should be mandated through building regulations, and vulnerable occupants should be provided alternative sleeping accommodation during periods of hot weather.

5. Conclusions

Dynamic thermal simulation results of a converted loft in a typical semi-detached house found a significantly increased risk of overheating relative to conventional bedrooms, with 11,340 – 12,210 more summertime Category I overheating degree hours under the current climate. Results indicate that the most effective passive cooling intervention for the loft is external shutters, which can lead to a 96% reduction in overheating under the current climate. Other effective interventions include night purge ventilation (89%), solar control film (86%), ventilation two-hours in advance (64%), and internal shading devices (50-57%). When considering capital and ongoing costs, the most cost-effective interventions are night ventilation, advance ventilation, and cross ventilation. The current optimal solution for both cost and heat mitigation is therefore to employ night ventilation, ventilate in advance, and enable cross ventilation, with internal curtains used to limit solar heat gains. It is estimated that such passive cooling strategies alone would be inadequate until the 2080s, after which active cooling systems may become necessary in lofts. This paper recommends that the risks of loft overheating and relevant passive cooling interventions are introduced in Approved Document L1B of the UK Building Regulations.

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Figure 1. The number of loft conversions by date range conversion occurred, by English regions.

Figure 2. Semi-detached house floorplans of ground floor, first floor and loft and west-facing crosssection. The thermal envelope is indicated with a thick black dotted line.

Figure 3. Overheating degree hours for the full day (A) and during night-time (B) for converted lofts compared to conventional bedrooms under current climate conditions.

Figure 4. (A) 24-hour Overheating degree hours (Category I and II) for converted lofts compared to the average for the conventional dwellings under future climate scenarios. (B) Night time overheating degree hours (Category I and II) for converted lofts compared to the average for the conventional dwellings under future climate scenarios.

Figure 5. (A) Passive cooling interventions ranking –night time degree hours of loft overheating (B) and the number of overheated nights.

Figure 6. (A) Loft overheating risks under different climate scenarios following all nine adaptation measures; (B) Number of loft overheated nights under different climate scenarios following all nine adaptation measures.