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Low energy housing retrofit in North England: Overheating risks and possible mitigation strategies

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Abstract

In the drive to reduce space-heating demand and associated CO_2 emissions as well as tackle fuel poverty, dwelling overheating and summer-time occupant thermal discomfort might be the unintended consequences of low-energy building retrofits. This paper presents the findings of a steady-state modelled low energy retrofit dwelling in northern England and its potential current and future climate overheating risks using UK Climate Projections 2009 (UKCP09) scenarios (2050 and 2080 High Emission Scenarios). Predictive findings highlight that retrofitting to low energy standards increases overheating risk over time, unless passive prevention measures are included in the retrofit design. In addition, the steady-state nature of the model might not fully capture the occupants' exposure to actual future overheating risks. Among the most effective individual passive overheating mitigation strategies are temporary internal shading, permanent external shading, and night-time ventilation. Most effective is a combination of these adaptation measures, so that predictive overheating is minimised in a future changing climate, reducing the uptake of active cooling in retrofitted dwellings.

Practical applications: Much research focuses on building overheating risks in the warmer South-east of England. However, this paper highlights how dwelling retrofit in north England (Sheffield) also can lead to increased dwelling overheating risk, unless passive design measures are included in the retrofit design. Among the most effective individual passive overheating mitigation strategies are solar shading devices and increased night-time ventilation, though ideally different measures are combined. Using future climate scenarios highlights that retrofits designed today might not be able to provide occupant thermal comfort in a future warming world.

Keywords Low energy housing, overheating risks, overheating mitigation strategies, retrofit

1.0 Introduction

The residential sector is responsible for around 27% of the UK's CO_2 emissions.[1] In addition, roughly 11 % of people in England live in fuel poverty, with especially older, uninsulated dwellings being harder to heat.[2] Hence retrofitting the existing stock is one of the key strategies towards significant carbon emission reductions in the residential sector [3] and to reduce fuel poverty.[2] As a result, in the UK and in Europe there is a drive towards the implementation of fabric energy efficiency improvements in building retrofit and in the construction of new buildings to more stringent standards. The Passivhaus standard is such a standard for achieving high building energy performance and exceeds most countries' building regulation standards. The standard is increasingly adopted in Europe, including in the UK.[4] However, based on growing evidence of uncomfortable indoor environments of low energy new built dwellings, [5] and retrofits, [6] a more energy-efficient fabric might lead to overheating risks.[6–10] Currently, 20% of homes in England might already experience overheating in summer and this is likely to increase in a warming climate.[11] In southern European countries the proportion of occupants experiencing discomfort in their homes during summer can be nearly as high as 50%.[5] Even in northern countries such as Latvia and Lithuania this was reported as high as 30% to 35% respectively.[5] Additionally, retrofitted homes may be at an increased risk of overheating due to the difficulty and expense to retrofit solar shading.[12] Dwelling overheating might lead to increased active cooling systems being used to ensure occupant comfort, though in colder regions passive measures may be sufficient.[6] Increasingly, overheating prevention measures are identified to enhance summer thermal comfort [7], but many studies suggest that especially in southern UK areas, passive measures and behavioural adaptations will be insufficient to provide summer thermal comfort in a warming world.[12] If active cooling becomes the norm in the future, which has been estimated to increase by about 30% by the 2080's [6], this will lead to an unintended energy burden.[10]

This paper evaluates a retrofit case study in north England (Sheffield) in the current climate and future predicted climate. Different fabric energy-efficiency scenarios are explored to evaluate when overheating risk might occur: i.e. unrefurbished, retrofitted to Zero Carbon standard, EnerPHit or Passivhaus standard. In addition to evaluating predicted overheating risks in the current and a future predicted climate, practical passive adaptation strategies are also explored to understand their impact on overheating risk.

2.0 Predicting Overheating Risks

2.1 Case study: A Sheffield retrofit

The single-family case study dwelling is a retrofitted detached house in Sheffield, located 223.6m above sea level and facing the Peak District at the south. The architects' design strategy was retrofitting to Zero Carbon standard to meet Fabric Energy Efficiency Standards (FEES) of <46kWh/m^{2}a [13] for the space heating demand of a detached house. This was achieved with improved airtightness of about 5.2 m^3/hr.m^2 @50Pa (measured), whole house insulation, high performance windows and the installation of Mechanical Ventilation with Heat Recovery (MVHR) - see Table 1 for retrofit characteristics. Furthermore, the north-south orientation allowed the architect to combine views of the landscape with desirable passive winter solar gains by installation of large south facing windows as part of the retrofit; though this might lead to increased summer overheating risk.

Table 1. Case study house fabric characteristics

Case study characteristics	Pre-retrofit (existing, design values unless stated otherwise)	Post-retrofit (design values unless stated otherwise)
Yearly estimated space heating demand	143 kWh/ m^{2}a	46kWh/m^{2}a

Airtightness	>10 m^3/hr.m^2 @50Pa	5.2 m^3/hr.m^2 @50Pa (measured)
Wall U-values	0.26~0.38 W/m^2K	0.13~0.16 W/m^2K
Ground floor U-value	1.17 W/m^2K	1.17 W/m^2K
Roof U-value	0.3 W/m^2K	0.07 ~0.09 W/m^2K
Windows/doors U-values	1.25 W/m^2K	0.66~0.88 W/m^2K
Glazing U-value	2.70 W/m^2K	0.62 W/m^2K
Glazing g-value	0.77 W/m^2K	0.60 W/m^2K

2.2. Research methods

Passive House Planning Package (PHPP), a steady state energy balance software was used to evaluate the energy performance of the case study house; pre and post-refurbishment. The case study house was modelled in the current and future climate when (a.) unrefurbished, (b.) retrofitted to the Zero-carbon standard and (c.) the EnerPHit and (d.) the Passivhaus standard for comparative purposes. Space heating demand per year [kWh/(m²a)] and frequency of overheating (%) were the main data obtained from the software. The East Pennines current climate dataset in PHPP was used as most representative of the case study location, altitude was adjusted to reflect the actual location.

Future predicted weather data used was obtained from Prometheus, underpinned by the UKCP09 climate model. Two reference years were used: 2050s and 2080s. High emission scenarios were selected to reflect a current trajectory of medium to high emission scenarios.[14] Test Reference Year (TRY) and 50th percentile data were used as the TRY data are more comprehensive and suitable for energy analysis [15] and the 50th percentile is a median estimate and excludes extreme results.[15]

2.3. Overheating benchmarks

The overheating benchmark used to evaluate overheating risks was based on the Passivhaus criteria: the measure of comfort is defined by the frequency in which temperatures rise above the established comfort limit, expressed as the total time of the year. The default maximum temperature used in PHPP is 25°C, which is calculated based on the annual temperature curve without active cooling [16]; the frequency of overheating must not exceed 5% to ensure good summer comfort and if this value exceeds 10%, additional summer heat protection will be necessary.[16]

CIBSE Guide A 2006 [17] has recommended overheating criteria which were also used for further overheating evaluation. For dwellings, overheating is defined as the operative temperature (OT) exceeding 28°C for more than 1% of the annual occupied hours in the living area and exceeding 26°C for more than 1% of the annual occupied hours in bedrooms. CIBSE Guide A 2006 (a single threshold temperature) was used as the case study was under retrofit construction during the production of this paper. Thus, no field survey was possible to understand occupant thermal comfort perception or the actual dwelling performance as recommended in the revised version of CIBSE Guide A 2015.[18] Unlike the 2006 CIBSE single threshold temperature, the 2015 CIBSE Guide A recognises that occupant thermal comfort perception is affected in relation to the outdoor temperature and defines comfort temperatures as a band, based on adaptive comfort theory, rather than a single threshold.

CIBSE has also recently published TM59: 2017, the latest overheating assessment methodology for new and refurbished dwellings. The criteria outlined for predominantly mechanically ventilated homes are that all occupied rooms should not exceed an operative temperature of 26°C for more than 3% of the annual occupied hours and corridors are considered to have significant risk if temperatures exceed 28°C for more than 3% of the annual occupied hours.[19–21] However, a comparison study using this overheating metric was not undertaken in this study as it requires data from dynamic modelling software (i.e each room's daily temperature with the individual room's heat gains), which cannot be extracted from the PHPP steady state model. Another limitation of steady-state models is that they might underestimate the actual overheating risk, as also noted when SAP (Standard Assessment Procedure) was used for regulatory compliance compared to dynamic modelling tool outputs for overheating risk.[22] Additionally, single temperature thresholds do not indicate the severity of the overheating, as temperatures could be significantly higher than the threshold. Further research and more detailed study is required to compare the steady-state model predictions of overheating risk in PHPP with dynamic modelling tools as recommended by Hopfe and McLeod [23]. Additionally, monitoring actual dwelling summer temperatures and perceived occupant comfort is necessary to validate predictive model outputs; a study found that about 70% of in-use new built-Passivhaus dwellings overheated, attributed to user behaviour [24], which was not accounted for in the model.

3.0 Results and discussion: Predicted overheating risks

3.1. Predicted overheating in the current climate

In the current climate, and pre-retrofit, no overheating is anticipated for the existing case study (unrefurbished). However, the case study retrofitted to zero carbon, which is the standard of the actual refurbished house, has a predicted 2% overheating frequency in today's climate and achieved a 79% reduction in space heating demand. As expected, when retrofitted to the Passivhaus standard, the frequency of overheating is predicted to increase (5%), while the space heating demand would further reduce (see Table 2). This suggests that even in today's climate in a northern England city, there is already a small risk of overheating, a finding in line with other research.[6]

Overheating risk for the case study was further evaluated using CIBSE Guide A 2006 single temperature thresholds.[27] The occupied hours were from 5:00pm to 9:00am daily; taking into account the actual homeowners' living patterns. Findings suggest that only the refurbishment to the zero carbon standard in the current climate would provide acceptable summer thermal comfort for the occupants. The other retrofit standards in the current climate would lead to overheating exceeding 2% of annual occupied hours in bedrooms.

Table 2. Summary of case study predicted performance in current climate

Refurbishment	Pre-	Post-	Retrofit to	Retrofit to

standards and energy performance	refurbishment	refurbishment (Zero Carbon)	EnerPHit	PassivHaus
Space Heating Demand [kWh/(m^2/annum)]	143	30	17	8
Frequency of Overheating when temperature rise above 25°C (%)	0	2	4	5
% of reduction space heating demand	-	79%	88%	94%

3.2. Overheating in a predicted future climate

Using the PHPP overheating metric, the Zero Carbon retrofit dwelling might experience up to 8% overheating in the 2050s High Emissions Scenario (HiES) predicted future climate; exceeding the acceptable level of comfort.[16] However, the overheating risk is further exacerbated when retrofitting to EnerPHit and Passivhaus standards of 13% and 15% overheating frequency (OF) respectively providing a poor level of summer thermal comfort.[16] Moreover, as the projected climate is predicted to be warmer in all areas in the UK year by year [25], the 2080s HiES prediction indicated 13% overheating frequency for the Zero Carbon retrofitted dwelling and 19% to 22% overheating frequencies when retrofitted to EnerPHit and Passivhaus standards respectively. This is significantly above the recommended thermal comfort thresholds of maximum 10% and the ideal recommended 5% according to the Passivhaus threshold.[16] These findings highlight that mitigation strategies are required for all refurbishment standards for the future predicted climate (see figure 1). Similar results are indicated in studies by McLeod et al [26], also highlighting that in contrast to falling heating demand, the risk of overheating increased for all studied dwelling in a future warming world. The unrefurbished dwelling is also predicted to create uncomfortable summer-time indoor temperatures, i.e predicted overheating frequency of 1.5% in 2050 and 3.5% in 2080.

[Insert Figure 1]

Furthermore, evaluation using CIBSE Guide A 2006 with single temperature thresholds in the future predicted climate, the Passivhaus retrofitted dwelling was projected to overheat by as much as 11% of the annual occupied hours for bedrooms (> 26ºC) during the 2080s HiES (see figure 2). Additionally, overheating could be even higher if the occupancy hours were to include day temperatures (outside the 5:00pm to 9:00am time frame); and might be as high as 13% > 26ºC during the 2080s (HiES) in the Passivhaus retrofit if weekend daytimes are included (so over a 24 hr timeframe at weekends). Hence, vulnerable people especially might be more affected; while increased future occupancy during the daytime could also be problematic. Figure 2 also highlights that in the current climate and with any of the tested refurbishment standards, the indoor summer temperatures were expected to remain below 28ºC when using the PHPP model. However, from the 2050's, the overheating frequency with temperatures of >28ºC steadily increases to reach 7% in 2080 in the Passivhaus refurbished dwelling.

Due to the steady state nature of the model, the location and extent of more extreme temperatures are more difficult to characterise, though analysis suggests that the occupants in the zero carbon retrofitted house might experience highs of 29ºC (0.7%) in the 2050s, rising to 1.6% overheating frequency above 29ºC in the 2080s with up to 33ºC (0.1%) in the 2080s. The maximum predicted temperatures might increase with the Passivhaus standard retrofit: up to 35ºC (0.13%) in the 2050s, rising to 0.5% in the 2080s, with 0.13% up to 37ºC in the 2080s, significantly above comfort thresholds. More detailed dynamic analysis is recommended as also suggested by others [23], to investigate extreme temperatures as well as zones most at risk; ideally models are also validated with data collection from houses in the current climate.

[Insert Figure 2]

4.0 Results and discussion: Overheating mitigation strategies

All mitigation strategies tested were applied to the Passivhaus retrofitted case study to investigate the efficacy of measures in the worst case scenario, in response to the results summarised in Figure 1, where increased overheating risks were identified. Six main strategies and two combination strategies were used to evaluate the most appropriate overheating mitigation measures in the case study (see Figure 3 and 4).

4.1 Strategy 1: Reducing building fabric energy efficiency

The insulation to the walls and roof were reduced to comply with the maximum recommended U-values in Part L1B 2015 Building Regulations for England. This strategy was carried out to compare the performance of the regulatory recommendations with the Passivhaus standard in a predicted warmer future climate scenario. For the Part L retrofit standard, the space heating demand was projected to now meet the Passivhaus standard in the 2050s and 2080s HiES (see Figure 3 and 4). Additionally, the impact of reducing wall insulation highlighted that overheating could be reduced by 2% both in 2050s and 2080s HiES, however, the overheating frequencies still exceeded 10% with temperatures above 25ºC. Other studies similarly revealed that improved fabric U-values increased the probability of overheating, but the position of insulation can be an important consideration [28], especially relevant in building retrofit where internal insulation can reduce the heat-storing capacity of thermal mass. Furthermore, reducing roof insulation gave no projected improvement to the overheating frequency in the 2050s and just 1% improvement for the 2080s (HiES). Additionally, the reduction in building fabric insulation to Part L standard leads as expected to an expected increase in space heating demand even in a projected warming climate, though still within reasonable limits to support winter thermal comfort (see Figure 3 and 4).

4.2 Strategy 2: Night-time cooling (ventilation)

In the case study model, a base case summer night-time ventilation scenario was modelled with 0.5 ach^{-1} and 3 windows openings. Artmann, Manz, & Heiselberg [29] report that night-time ventilation of 1 to 4 ach^{-1} is sufficient to maintain the limit of thermal comfort and Tillson [30] reported that window ventilation with 4 ach^{-1} could eliminate 99% of overheating occurrences in the housing stock.

However, due to the reported limitations of window ventilation found in various other studies [31–34], further research is required in designing and testing appropriate and realistic window ventilation and usage, while maintaining occupants' privacy and safety and reducing noise ingress at night-time. As such, further adjustments made to window openings were derived from the recommendation of inward opening hopper windows for night-time ventilation [5] : window ventilation with air change rate of 0.8 to 1.5 ach^{-1} was tested and 4 hopper window openings were suggested, which involved 2 windows on the first floor and 2 windows on the upper ground floor. While the modelled 0.8 to 1.5 ach^{-1} is significantly below the above suggested 4 ach^{-1}, this is to reflect a more realistic behaviour expected from occupants in response to overheating while taking other behavioural limitations into account. For example, limitations to maximising night-time ventilation include issues of privacy, security, pollution and noise as well as plants on window sills and other restrictors or obstructions to opening windows and achieving high air-change rates, making night-time cooling a less robust strategy. Additionally, increased ventilation might be associated with worse Indoor Air Quality (IAQ) due to bringing outdoor pollutants inside [12]; though this needs to be balanced with reduce indoor pollutant built-up from increased ventilation rates. Findings based on the opening of hopper windows for night-time ventilation up to 1.5 ach^{-1} suggested overheating frequencies could be within 10% in the 2050s (HiES). However, in the 2080s (HiES), applying the same night-cooling strategy would exceed internal thermal comfort, leading to a 12% projected overheating frequency (see Figure 3 and 4). Note that space heating demands were not affected as this affects summer ventilation only.

4.3 Strategy 3: Internal and external shading

Incorporating appropriate internal or external shading reduces the amount of direct summer solar gain entering internal spaces, reducing overheating risks [34]. This is most effective when using light coloured temporary shading as it is the best solar gain reflector [6], while also maximising winter solar gains. In the case study, internal shading indicated a significant reduction to overheating frequencies in both the 2050s and 2080s HiES scenarios. The overheating frequencies were all predicted within 10%, while maintaining the low space heating demands and < 5% overheating frequency for the 2050s (see Fig. 3 and 4). It is unknown how effective this strategy is in reality nor how accurate the PHPP steady-state model is compared to reality and other models.

Additionally, fixed and permanent external horizontal shading was simulated at 1.0 m from the external window, reflecting a recommended depth of around 50% of the window height and ≤1.5m to allow winter solar gain.[5] Similarly to internal, adjustable and light-coloured shading, comparable overheating frequency reductions were obtained in the 2050s and 2080s, however seasonal space heating demand slightly increased (see Fig. 3 and 4). As such, temporary internal shading appeared to be more beneficial in balancing summer overheating frequency with winter thermal comfort. Though because internal shading is adjustable to maximise winter solar gain [36], occupant behaviour is likely to influence its summer and winter efficacy and daylighting performance, and in real-life this strategy might not be as effective as fixed external shading. Moreover, the operation of adjustable shading might be determined by the visual comfort requirements of the occupants rather than indoor temperatures [26].

4.4 Strategy 4: Reducing glazing area and g-values

Glazing is one of the most important elements in Passivhaus design as it is the aperture of collecting free solar heat gain which is useful for passive heating. However, the window itself can also allow excessive solar gains into living spaces [34] in warmer seasons. Hence, overheating risk might be minimised by reducing the glazing area and reducing glazing g-values for lowering solar energy transmittance. Account must be taken of realistic g-values; below 0.35, windows are often tinted and reduce daylighting, affecting visual comfort. Firstly, a small proportion (7%) of the glazing areas was reduced to 39% of overall glazing ratio on the southern façade. Careful consideration was made on the percentage of reduction area, in order to balance the amount of daylighting and heat gain through the windows to provide winter passive solar heating to meet the Passivhaus standard. Doing so, lead to a reduced overheating frequency of 11% in the 2050s and 17% in the 2080s (HiES), but still above recommended comfort thresholds. Hence, moderate south facing glazing alone is unlikely to act as a sufficient strategy to eliminate the overheating risks as also highlighted by McLeod et al.[37].

However, the reduction of glazing g-values from 0.62 to 0.30 (62 to 30% of solar energy permeability) projected a significant reduction in the overheating frequencies, as suggested by AECOM as an overheating mitigation strategy in London.[38] Doing so reduced overheating frequencies to 2% in the 2050s and 5% in 2080s HiES scenarios, with the space heating demands increased (but still within the Passivhaus standard). For the Sheffield retrofit case study, glazing g-values should not be less than 0.30 (30% of solar energy permeability) to balance winter space heating demand and summer overheating, now and in the future. Nevertheless, lowering g-values usually leads to tinted glass and reduced visibility and daylighting and may cause visual discomfort.[39] Some glazing innovations allowing high level of daylight transmission and low levels of solar transmittance might resolve this [39], but it is unknown if this is a suitable and an affordable solution for dwelling retrofit. Any future glazing replacements would also need to be carefully managed to achieve the appropriate specification.

[Insert Figure 3]

[Insert Figure 4]

4.5 Strategy 5: Combination strategies

It can be argued that a combination of overheating mitigation strategies are more robust in future proofing retrofitted low energy dwellings to provide a good level of occupant comfort, as also suggested elsewhere.[28] This research investigated two combination strategies: increased user defined strategies (combination strategy 1, more reliant on user behaviour and interaction) and non-user adjustable strategies (combination strategy 2, less reliant on user behaviour and interaction).

Combination strategy 1 combined night-time ventilation with up to 1.0 ach^{-1}, temporary internal shading and permanent external shading. This strategy predicted to eliminate overheating frequency entirely in the 2050s and to reduce it to as low as 2% in the 2080s (HiES) (see table 2). Combination strategy 2 included night-time ventilation (1 ach^{-1}), permanent external shading and reduced glazing g-values from 0.62 to 0.30 (62% to 30% solar energy permeability). Overheating frequencies were projected to be 1% in the 2050s and 2% in the 2080s (HiES), values that are within the Passivhaus overheating thresholds (see table 3 and 4). However, space heating demand was projected to be slightly higher in combination strategy 2 compared to strategy 1, but still within the Passivhaus standard. Combining mitigation strategies were also found to be the most effective in reducing new-built dwelling overheating in Gupta & Gregg's study.[28]

Table 3. Overheating mitigation strategy: Combination strategies No 1; combined strategies, results are combined step by step (SHD = Space Heating demand and OF= Overheating Frequency)

PASSIVHAUS (After refurbishment)	Future Climate Data (Hi ES)	BASE CASE (the case study house Passivhaus standard)		*STEP 1: DISPENSE* night-time ventilation with up to 1.0 ach^{-1}		*STEP 2: DEFENSE* Temporary Shading – Internal Roller blind/white		*STEP 3: FUTURE PROOF* Permanent Shading – external, horizontal	
		SHD kWh/(m2/annum)	OF >25 °C (%)	SHD kWh/(m2/annum)	OF >25° C (%)	SHD kWh/(m2/annum)	OF >25° C (%)	SHD kWh/(m2/annum)	OF >25° C (%)
Sheffield case study	2050	6	15	6	9	6	2	8	0
	2080	5	21	5	16	5	5	5	2

Table 4. Overheating mitigation strategy: Combination strategies No 2; combined strategies, results are combined step by step (SHD= Space Heating demand and OF= Overheating Frequency)

PASSIVHAUS (After refurbishment)	Future Climate Data (Hi ES)	BASE CASE (the case study house Passivhaus standard)		*STEP 1: DISPENSE* Night-time ventilation with up to 1.0 ach^{-1}		*STEP 2: DEFENSE* Permanent Shading – external, horizontal		*STEP 3: FUTURE PROOF* Reduction glazing G-value (g-value 0.3)	
		SHD kWh/ (m2/ annum)	OF >25°C (%)	SHD kWh/(m2/ annum)	OF >25°C (%)	SHD kWh/ (m2/ annum)	OF >25°C (%)	SHD kWh/ (m2/ annum)	OF >25°C (%)
Sheffield case study	2050	6	15	6	11	8	2	13	1
	2080	5	21	5	18	5	6	10	2

5.0 Conclusion

Low energy housing standards such as the Passivhaus standard lead to significantly reduced space heating demands as was demonstrated for the retrofit case study dwelling in the north of England. As predicted by the steady-state PHPP model, a higher overheating frequency would occur over time due to a changing climate. However, findings showed that as long as appropriate overheating mitigation strategies were applied, technically low energy housing retrofits could be beneficial in both the current and predicted future climate. This study also verified other research findings that in the more northern England climate, passive overheating mitigation measures might be sufficient to prevent summer-time discomfort now and in the future.[6]

A well-insulated building skin is appropriate in this area's climate, leading to reduced winter energy use (and associated carbon emissions reductions) and enhanced winter occupant thermal comfort. According to the case study modelled results, passive summer overheating mitigation measures were necessary in the current and future projected climate in Sheffield. Aligning building adaptation with carbon emission reduction efforts, it was demonstrated that either permanent external shading, temporary internal shading and night ventilation could significantly reduce dwelling overheating frequency.

Nevertheless, single mitigation measures alone are less robust than multiple strategies combined; the most optimal overheating mitigation strategy tested was a combination of reduced glazing g-values, appropriately designed internal or external shading devices, and good night-time ventilation, though reduced g-values are also likely to affect visual comfort and more research is required to understand its effect in housing. A reduction in glazing areas facing the solar path might also be beneficial in a warming climate. The passive overheating mitigation strategies tested indicated that active solutions might not be necessary in eliminating overheating risks in Sheffield's dwellings now and in the future. However, there may be other effective strategies such as different roof forms, or use of vegetation and landscaping surfaces altering microclimatic conditions to be considered in further studies. Additionally, to better understand overheating risks in more detail (e.g. extreme temperatures, risks in different zones), the steady state PHPP method should be supported by a more detailed dynamic modelling analysis as part of the design process. Furthermore, this study was based on modelling predictions and do not take into account user behaviour, though care was taken to only include realistic user behaviour. Monitoring actual buildings will both help validate modelling tools and support understanding of the effect of users and their practices and impact on overheating risks – further research is necessary in this area.

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Acknowledgements

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Figure Legends

1. **Figure 1: Overheating risks in the current and future climate using PHPP/Passivhaus overheating frequency (OF, % of temperature ≥ 25ºC, wide bars) and reduced space heating demand (kWh/m^{2}a, narrow bars), in 2050 and 2080 HiES (High Emission Scenarios)**
2. **Figure 2: Overheating frequency (%) in the current and future climate using CIBSE Guide A 2006 Overheating Criteria (HiES, High Emission Scenarios), 0% indicates no overheating above 28ºC, the single temperature threshold for living rooms in the current climate.**
3. **Figure 3: Overheating frequency (OF, % of temperature ≥ 25ºC, wide bars) and space-heating demand (SHD, kWh/m^{2}a, narrow bars) in the 2050s HiES after application of mitigation strategies**
4. **Figure 4: Overheating frequency (OF, % of temperature ≥ 25ºC, wide bars) and space-heating demand (SHD, kWh/m^{2}a, narrow bars) in the 2080s HiES after application of mitigation strategies.**

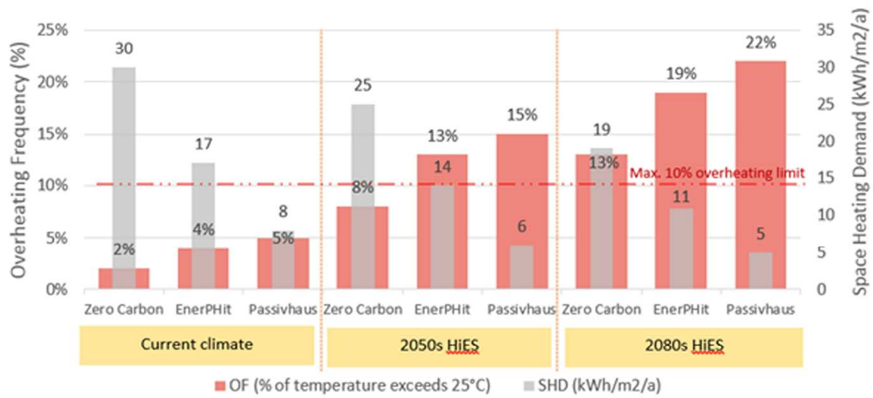


Figure 1: Overheating risks in the current and future climate using PHPP/Passivhaus overheating frequency (OF, % of temperature ≥ 25ºC, wide bars) and reduced space heating demand (kWh/m2a, narrow bars), in 2050 and 2080 HiES (High Emission Scenarios)

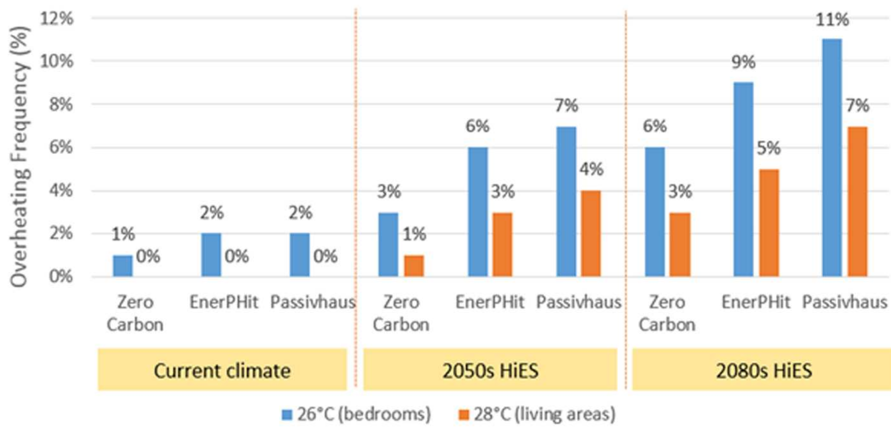
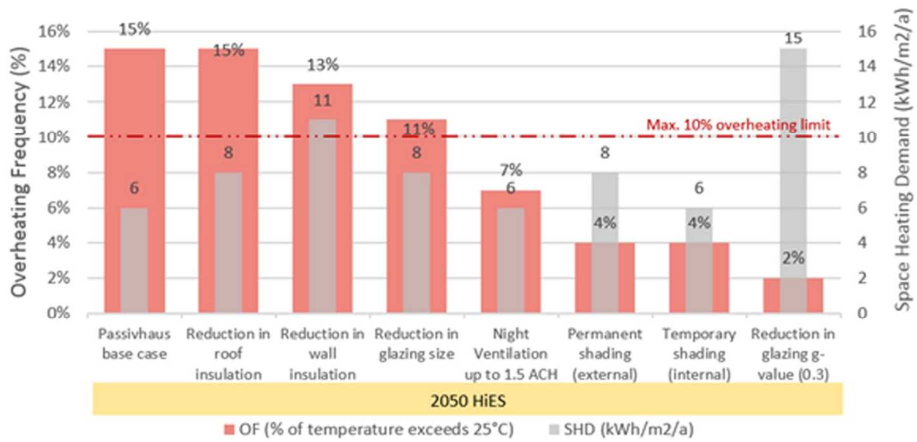


Figure 2: Overheating frequency (%) in the current and future climate using CIBSE Guide A 2006 Overheating Criteria (HiES, High Emission Scenarios), 0% indicates no overheating above 28ºC, the single temperature threshold for livingrooms in the current climate.



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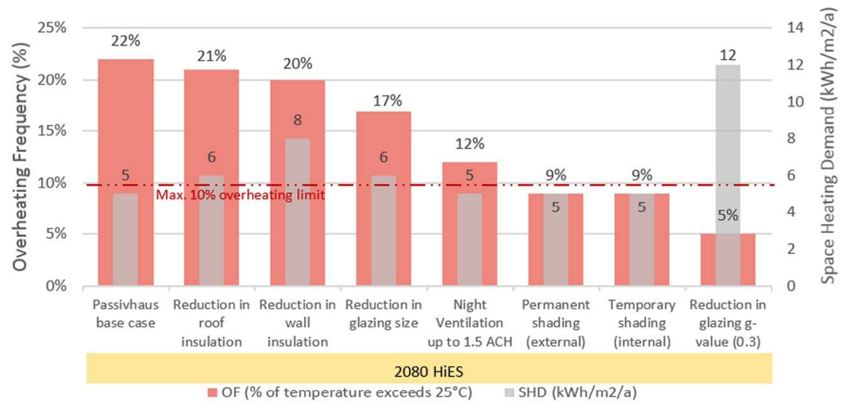

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