Department for
Energy Security
& Net Zero

The effect of energy efficiency measures on summertime overheating in English homes: an evidence review

Overheating in Homes: Further Analysis of EFUS Data

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Contents

Introduction 5

Aims and objectives of the review 5

Terminology **Error! Bookmark not defined.**

Review methodology 6

Content of key articles 7

Evidence synthesis 7

Research methodologies 10

Overheating metrics 12

Weather data 13

Dwelling archetypes 14

Review findings 14

Findings from modelling 14

Modelling assumptions 14

Validation of models 15

Wall insulation 16

Influence of archetype 17

External wall insulation versus internal wall insulation 17

Roof and loft insulation 17

Ground floor insulation 18

Combined measures 18

Impact of geographical location 20

Importance of ventilation 20

Findings from field studies 21

House age as a proxy for energy efficiency levels 21

Influence of roof or loft insulation 22

Influence of EPC rating band 22

Meta-analyses of field study data 23

Conclusions 23

Supplemental files **Error! Bookmark not defined.**

References 25

Appendix A 32
  Search strategy, methods and scope 32
    Definition of search keywords and search strings 32
    Inclusion and exclusion criteria 33
    Sources of evidence 34
    Evidence search and search record 35
  Screening search results 36
    Research Quality Assessment 36
    Extracting evidence from the studies 38
Appendix B 41

Introduction

Context and background

The temperature of a space within a dwelling will increase if the overall heat gains are greater than heat losses. There are concerns that reducing the heat loss of the building fabric through improved insulation measures may lead to excess heat being trapped within the home during summer conditions. This can lead to an overheated dwelling, where temperatures are above a level that can cause thermal discomfort and create health risks for its occupants.

Several monitoring studies have identified that new UK homes built to low-energy standards (i.e., those with high fabric energy-efficiency) are suffering from summertime overheating in the current climate (Tabatabaei Samini et al., 2015; Morgan et al., 2017; Gupta et al., 2019; Mitchell et al., 2019). There are, however, some contradictory findings from both modelling studies and field studies, in which temperatures in actual homes are monitored, as to the effects of improved insulation on overheating risk.

Terminology

Energy-efficiency measures are defined as insulation to walls, loft/roof, ground floor, and double-glazed windows.

Energy Performance Certificate band, also known as the Energy efficiency rating (EER) band (SAP 2012). Bands from A to G that are used in the Energy Performance Certificate for dwellings. ‘A’ is the most efficient and ‘G’ is the least efficient (DBEIS, 2021: 75)

Combined measures are defined as the introduction of a ‘package’ of energy-efficiency measures.

Aims and objectives of the review

Considering the above, the key question to be addressed by this review is ‘*Do measures which reduce home energy demand in the winter increase the risk of overheating in the summer.*’? In the proposed research, energy efficiency as represented by the overall Energy Performance Certificate band rating as well as the presence of individual energy efficiency measures, will be considered. The overall research aim will be achieved through the following objectives:

- Using systematic literature searching techniques, collect all the previous relevant studies.
- Assess the quality of the previous studies using government approved frameworks.

- Synthesise the previous research studies to determine the impact of improved insulation levels on indoor temperatures, overheating or thermal comfort.
- Identify key knowledge gaps.

The review is driven by the following questions:

- Which energy efficiency measures result in a higher summertime indoor temperature?
- Which energy efficiency measures do not result in elevated summertime indoor temperature?
- Which energy efficiency measures might reduce summertime indoor temperature?
- Are there levels of insulation that will lead to unacceptable levels of summertime indoor temperature?

Review methodology

This evidence review was conducted in a manner appropriate for Rapid Evidence Assessments (REAs). "*REAs is a type of evidence review that aims to provide; an informed conclusion on the volume and characteristics of an evidence base, a synthesis of what that evidence indicates and a critical appraisal of that evidence*" (Collins et al., 2015: xi). The conceptual framework for the review is presented in Figure 1 and described in detail in Appendix A. A brief description of the search methodology and outcomes is described below.

Evidence was sought primarily from two databases, Scopus and EI Compendex supplemented by searches of other databases and Google scholar. Keywords were identified and search strings developed. The search protocol discovered 738 studies. After removal of duplicate articles, 311 studies were screened, firstly by reading the abstract and then by reading the full text of the relevant sources. This left just thirty-nine studies which were subject to a quality assessment. Some documents were excluded for not being focussed on UK dwellings, these were documented and stored. At this stage, two extra studies were included from the research team's expert knowledge. Two studies were rejected following the application of a Quality Assurance (QA) framework meaning that thirty-nine articles remained for the evidence synthesis.

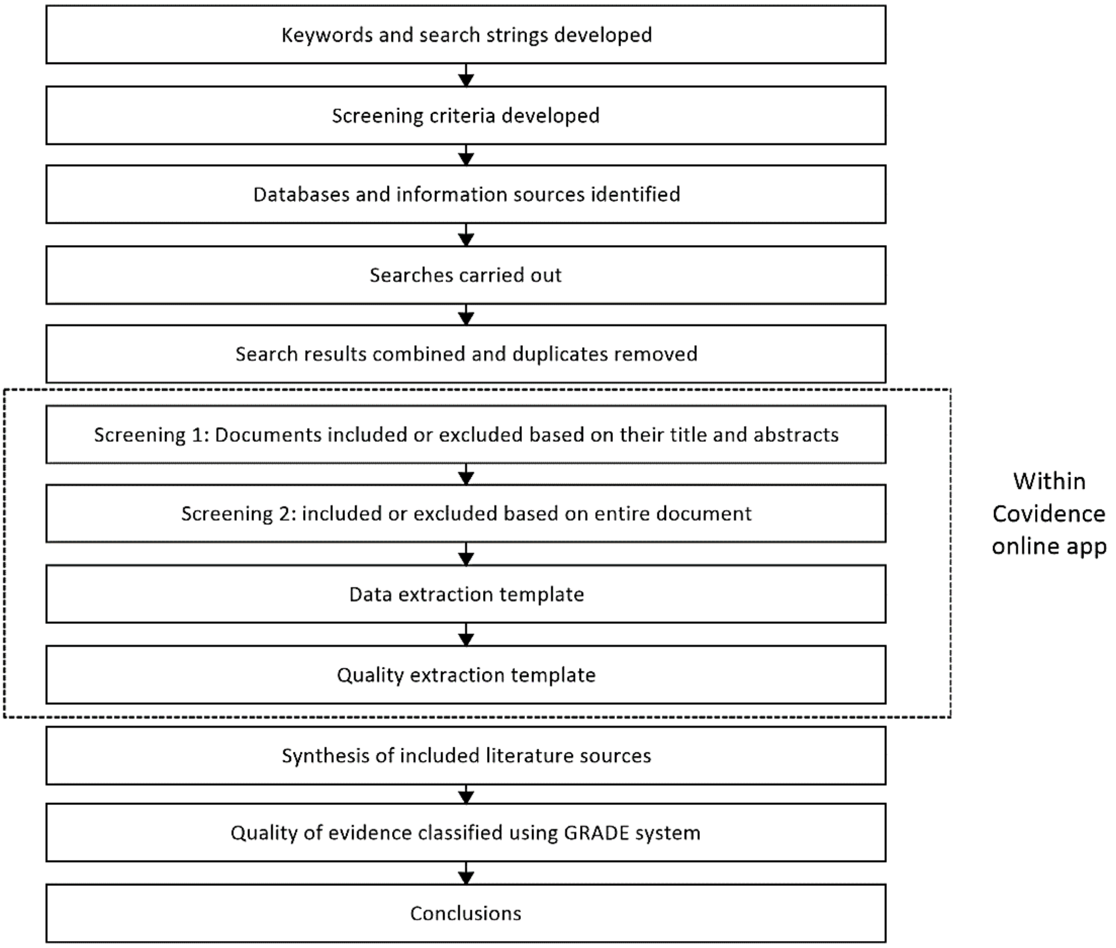

Figure 1 Review conceptual framework.

Content of key articles

Evidence synthesis

For each of the thirty-nine articles included in the evidence synthesis, Table 1 provides information on the energy-efficiency measures studied. The studies in Table 1 are categorised according to the research methodology adopted. Alternative building standards refer to dwellings with improved construction elements (i.e. lower U-values) compared to the regulatory minimums of Part L of the building regulations. Examples include homes built to the voluntary standards of the Code for Sustainable Homes (CfSH) levels 4 and 5 (DCLG, 2010) and the Passive House standard developed by the Passive House Institute (Passive House Institute, 2015). Where field studies have limited information on the insulation levels of dwellings, house age is often used as a proxy indicator for the energy-efficiency of the home, with assumptions that newer-built homes will be more energy-efficient.

Table 1 Classification of the included articles organised by research methodology.

Source	Energy-efficiency measures studied							
	Wall insulation	Roof/loft insulation	Ground floor insulation	Double Glazing	EPC rating band	Combined measures	Alternative building standards	House age as a proxy for energy-efficiency
Dynamic thermal simulation								
Orme & Palmer 2003							✓	
Peacock et al. 2010	✓						✓	
Gupta & Gregg 2012	✓	✓		✓		✓		
Mavrogianni et al. 2012	✓	✓	✓	✓				
Gupta & Gregg 2013						✓		
Mavrogianni et al. 2013	✓	✓		✓				
McLeod et al. 2013							✓	
Porritt et al. 2013	✓	✓						
Ji et al. 2014						✓		
Mavrogianni et al. 2014	✓	✓	✓	✓		✓		
Gupta et al. 2015	✓	✓				✓		
Taylor et al. 2015	✓	✓	✓	✓		✓		

Fosas DePando et al. 2016							✓	
Makantasi & Mavrogianni 2016						✓		
Mulville & Stravoravdis 2016							✓	
Taylor et al. 2016						✓		
Lee & Steemers 2017	✓							
Mavrogianni et al. 2017	✓	✓	✓	✓				
Fosas et al. 2018	✓	✓	✓	✓				
Taylor et al. 2018	✓	✓	✓			✓		
Ji et al. 2019	✓			✓		✓		
Li et al. 2019	✓		✓			✓		
Salem et al. 2019	✓							
Elsharkawy & Zahiri 2020	✓							
Taylor et al. 2021						✓		
Arup 2022	✓	✓				✓		
Large field study								
Beizaee et al. 2013	✓							✓
Pathan et al. 2017								✓
Petrou et al. 2019		✓			✓			✓

Morey et al. 2020	✓				✓			
Lomas et al. 2021	✓	✓		✓	✓			
Meta study								
McGill et al. 2017							✓	
Gupta et al. 2019							✓	
Mitchell & Natarajan 2019							✓	
Jang et al. 2022							✓	
Other								
Ibrahim & Pelsmakers 2018							✓	
Hayles et al. 2022	✓			✓				✓
Small field study								
Gupta & Kapsali 2016							✓	
Field experimental								
Tink et al. 2018	✓							
Totals	22	13	7	10	3	12	11	4

Research methodologies

There are many different research methodologies or strategies used in architectural and built-environment research. After conducting a critique, and subsequent synthesis of research methods from different disciplines, Hazem Rashed-Ali (2021) proposed that building performance research can be classified into four methodological approaches: (1) simulation research, (2) laboratory experimental research, (3) field experimental research, and (4) field studies.

Building performance simulation involves the creation of a mathematical model to represent an actual or archetype building. Simulation-based models for the prediction of temperatures in buildings rely on either steady-state methods or dynamic methods. Steady-state methods calculate the heat balance of the building over sufficiently long periods, such as one month. On the other hand, dynamic methods use short time steps to calculate the heat balance. These latter methods are adopted in commonly used software for building simulation (e.g., EnergyPlus, IES, TAS) and have found widespread use in overheating studies of domestic buildings. The technique has benefits for research into overheating as it, (1) allows for a relatively high level of control over a complex set of variables, thus enabling 'virtual experiments' to be carried out, and (2) buildings can be subject to a wide variety of current and future climates. However, simulation research methods have limitations, which include how accurately the real-world context is represented, and the completeness and accuracy of model data (see Roberts et al., 2019). Dynamic models are more likely to be reliable for making comparisons of indoor temperatures between, for example, dwellings with insulated versus uninsulated walls than predicting whether temperatures exceed overheating thresholds for a given dwelling.

Laboratory experimental research is typically carried out using environmental chambers and climate simulators of various scales. Where full-scale test simulators are available, whole building performance can be analysed. These methodologies provide the potential for full control of all, or nearly all, independent variables, thus making it beneficial for studies which aim to discover causal relationships between variables.

Field experimental research is carried out in realistic situations where one or more independent variables can be modified within the boundary of field conditions. These methodologies are often used in building energy performance research. Typical examples include assessing building performance in situations where changes are made to building materials, components or systems. Simultaneous trials in two or more identical buildings enable one to act as a control whilst in the other energy efficiency measures are installed (e.g., Tink et al., 2018; Roberts et al., 2019).

Field studies are "nonexperimental research designs that aim to use data collected under field conditions to discover or explain relationships and interactions between variables in real-world situations" (Hazem Rashed-Ali, 2021:56). Field studies measuring temperature in actual occupied homes have the advantage of realism as they capture the complex interactions between building, climate and occupants. In this review a distinction is made between large-scale and small-scale field studies. The former are typically carried out across a diverse range of occupied dwellings in multiple locations, whereas small-scale field studies may only focus on a limited number of case study dwellings. For the purposes of this review, large-scale field studies are defined as more than one hundred dwellings.

Meta-studies use data from multiple field studies to increase sample size and allow for comparisons between different dwelling types. For example, between dwellings generally representative of the existing housing stock and those newly built to low-energy building standards (e.g., Passive House). These types of studies can be somewhat biased, if they attempt to directly compare field studies carried out in different years where the experienced weather is likely to be different.

The evidence evaluated in this review is categorised according to the above methodologies (Figure 2). It is evident from this chart that two-thirds of the studies are conducted using dynamic thermal simulation. Studies where the evidence comes from monitoring actual homes (i.e., field studies at various scales and meta studies) make up the next largest category with ten out of thirty-nine studies (25%). It is apparent from Figure 2 that there was only one study discovered from field experiments in actual dwellings. There were two studies categorised as ‘other’ in Figure 2. One study used steady-state modelling (Passivhaus planning package) to simulate indoor temperatures and one study used empirical models developed from monitored data.

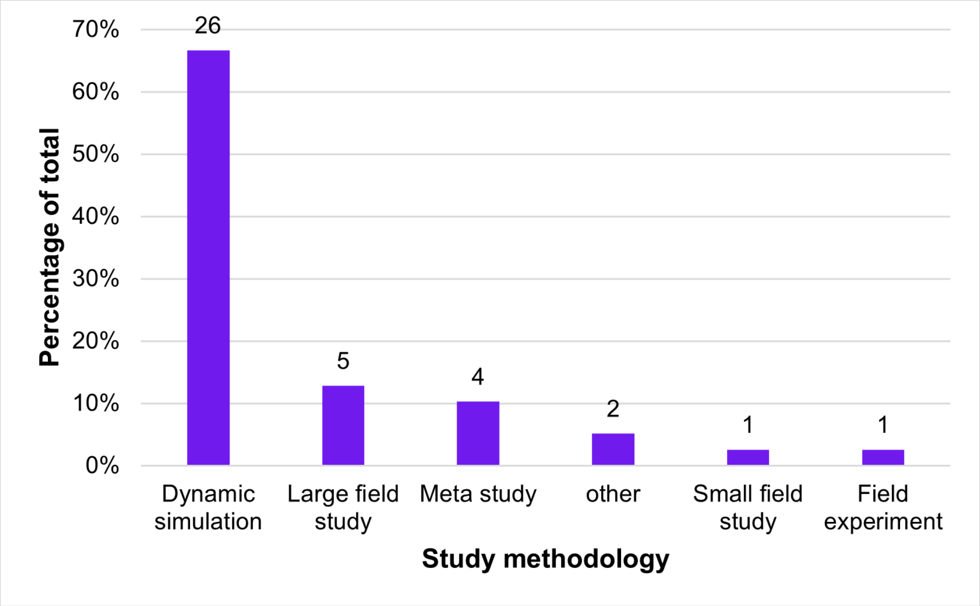

Figure 2 Research methodologies

Overheating metrics

The studies included in this review (Appendix B) adopt a wide variety of metrics to assess overheating. Some studies use the number of hours for which space temperatures exceed a stated threshold temperature over a given period of the year, i.e., the frequency of exceedance, as a measure of overheating. Others calculate a severity of exceedance, expressed as °C.hours (degree-hours) over the threshold temperature over a given period of the year, as a measure of overheating. The chosen period of the year was usually from 1 May to 30 September. However, some studies concentrate on evaluating internal temperatures during short spells of hot outdoor temperature. For example, Mavrogianni et al. (2012) selected the hottest five-day period from the weather file used in modelling.

The threshold temperatures may be fixed, e.g., 25°C and 28°C for living rooms or 24°C and 26°C for bedrooms (CIBSE, 2006), 25°C, Passive House (Mitchell & Natarajan, 2019), or variable, e.g., increasing with the running mean of mean outside temperature as specified by adaptive comfort standards (BSI, 2006; CIBSE, 2013; CIBSE, 2017; ASHRAE, 2010). A number of studies examine the effect of energy efficiency measures on mean or maximum room temperatures and some use other measures of overheating, for example the Passive House standard metric of hours over 25°C. Appendix B details the overheating criteria used in each study.

Several studies identified that when using dynamic thermal models, the choice of overheating metric, and the assumptions made regarding occupancy can influence the overall findings, e.g., Elsharkawy and Zahiri (2020). Similarly, Porritt et al. (2013) discovered that, compared to no insulation, internally insulating a 19th century end-terraced house led to a small reduction of the overheating for an assumed family profile but greater overheating for elderly occupants. Taylor et al. (2016) had similar findings and concluded that the identified dwelling overheating vulnerability was sensitive to the 'overheating' metric used in the analysis. Considering these issues, Ji et al. (2014) suggest that overheating risk assessment should aim to use multiple metrics. Therefore, they propose that degree-hours should be used alongside percentage number of exceedance hours.

Weather data

In building simulation, weather data defines the external conditions to which a building or space is exposed. Studies that adopt dynamic thermal simulation methods have to select a weather file that represents the building location and climate scenario. The dynamic simulation studies identified by the review used a variety of weather files for the present climate and an even greater variety for the future climate – for which assumptions had to be made about carbon emissions pathways, selection methodology (i.e., whether the year is typical, near-extreme, or extreme , and percentile probability of occurrence). This all adds to the challenges of making valid comparisons across the individual studies.

Field studies and experiments monitoring temperature in actual homes are bound by the weather experienced during the monitoring campaign, and as such are indicated in Appendix B, as being conducted under present climate conditions (all seven field studies/experiments identified by the review were conducted post 2010). The ability to use monitored temperature data to predict future overheating risk is a promising research area but, as yet, under-developed. Findings from field studies carried out in ‘average’ summers could fail to account for the effects of insulation in hotter than average summers or during heatwave conditions. The summer of 2018 was the joint hottest on record for England. Studying the monitored temperature of homes in such a year can provide valuable insight on the effects of energy-efficiency measures during summer conditions that will be more common by 2050 (Lomas et al., 2021).

Dwelling archetypes

The selection of a dwelling archetype in simulation studies is driven, in part, by the overall research aim. This can lead to archetypes that are (1), nationally representative (e.g., Arup, 2022; Taylor et al., 2021), (2) generally representative of an area or city (e.g., Gupta et al., 2015; Mavrogianni et al., 2012), (3) most common in the UK housing stock (e.g., the choice of semi-detached dwellings in Mulville & Stravoravdis, 2017), or (4) archetypes that are known to be at a high risk of overheating, such as flats (e.g., Lee & Steemers, 2017). The studies included in this review have covered many of the building archetypes common to the UK housing stock.

Large-scale field studies, such as those by Lomas et al. (2021) and Petrou et al. (2019) used data derived from the Energy Follow Up Survey (EFUS) to the English Housing Survey, which means the study findings can be scaled to the existing English housing stock (DBEIS, 2021).

Review findings

This section describes the findings from the review and is organised based on the research method used. All the results are for dwellings in the UK unless otherwise stated. A summary of the main findings for each study, alongside other relevant information obtained during the data extraction process is presented in Appendix B.

Findings from modelling

Modelling assumptions

To determine the effect of making changes to the building’s construction elements, simulation studies typically create a base case model to act as a reference point. For example, Mavrogianni et al. (2013) modelled the base case dwelling as the assumed current condition of an Edwardian mid-terraced house. Energy-efficiency measures were then implemented to 2010 building regulations with external wall insulation, 2010 building regulations with internal wall insulation, deep retrofit with external wall insulation, and a deep retrofit with internal wall insulation. The existing solid wall was assumed to have a U-value of 2.10 W/m²K. Improvements were then made to the U-value of the wall to building regulations 2010 (0.3 W/m²K) and a deeper retrofit beyond building regulations (0.10 W/m²K).

Where studies are conducted in specific areas of the country, researchers have used building archetypes that are generally representative of the local building stock. For example, Gupta et al. (2015) used three levels of baseline construction representing common build construction in the housing stock: pre-1919 solid wall, 1950s unfilled cavity, and early 2000s filled cavity. Similarly, in the London focussed study by Mavrogianni et al. (2012), the majority of modelled dwellings were solid-walled and had insulation retrofitted internally. In general, the U-values of the walls were reduced from assumed values of 2.10W/m²K to 0.6W/m²K.

Mulville and Stravoravdis (2015) aimed to study the impact of raising building standards on overheating risk. To this end, they simulated a case-study semi-detached house to five different building standards: Part L, (2006 & 2010); Code for Sustainable Homes level 4 and 5; and the Passive House standard. Furthermore, three levels of thermal mass were accounted for with three different construction methods. Peacock et al. (2010) simulated three typical construction methods (timber frame, wall U-value=0.47W/m²K; twin leaf masonry, U-value=0.37W/m²K; pre 1900 solid wall, U-value=1.6W/m²K). Initial simulations were carried out with the windows kept closed to represent a worse-case scenario.

A different approach was taken by Fosas et al. (2018), who conducted an extensive study using 576,000 cases that spanned plausible ranges of wall U-values (0.6 W/m²K to 0.1W/m²K) rather than the actual prevalence in the building stock. The building with the highest risk of overheating was assumed to be a single-sided, top-floor flat. Whereas a detached house was used as the best-case scenario (i.e., with the least overheating risk).

The large-scale modelling study by ARUP (2022) of existing UK housing assumed that uninsulated solid walls had a U-value of 1.35 W/m²K; insulated solid walls, 0.37 W/m²K; uninsulated cavity walls, 1.0 W/m²K; and insulated cavity walls, 0.43 W/m²K. Although the report mentions that sensitivity analysis was carried out on both external and internal wall insulation for solid walls, there are no results presented in the report that compare the two different wall constructions.

Validation of models

Validation of the simulated models with data measured in an actual building is not commonplace in the studies using dynamic thermal simulation. Of the studies that report a validation process, Ji et al. (2014) validated their model using a replica dwelling in a full-scale climate simulator. Fosas et al. (2018) also successfully validated their simulation models with measured data in well-insulated buildings.

Wall insulation

Findings related to the impact of wall insulation on overheating risk are somewhat contradictory. For example, Mavrogianni et al. (2012) showed that wall insulation increased mean daytime temperature by 0.38°C and maximum daytime living room temperatures by 0.61°C. Similarly, Mavrogianni et al. (2017) identified that wall and floor insulation were positively correlated with peak temperature. Wall insulation had the largest impact, perhaps due to the fact that insulation was installed internally for solid walls. Both these studies were conducted in London dwellings. Elsharkawy and Zahiri (2020) simulated the effects of different levels of wall insulation on the overheating of a south facing, mid-storey flat in a 1960s tower block. Their study found that improving the U-value from 0.9W/m²K to 0.3W/m²K led to an increase of mean operative temperature from 19.5°C to 22.6°C in 2050. Furthermore, the base case dwelling (worst insulated) had 38% lower discomfort hours compared to the best insulated walls.

In contrast, the study by Taylor et al. (2006) found that individual energy efficiency retrofits did not, in general, lead to a significant increase in temperature. The exception was for internally insulated solid walls, where there was a slight median temperature increase of 0.1°C (range -0.4°C to 0.9°C).

The study by Arup (2022) also discovered no significant correlation between wall construction and levels of overheating prevalence. However, the study did find a slight negative correlation between wall U-value and overheating severity indicating homes with better insulation were generally better protected from overheating -this was true especially for dwellings with large external wall areas, such as detached.

Lee & Steemers (2017) simulated a south facing bedroom in a flat on the top floor of a three-storey building. They discovered, when assessing night-time hours for the current climate, that cavity masonry constructions, with unfilled and filled cavity showed no overheating when assessed using CIBSE TM52 either Cat.I or Cat.III thresholds[1]. This was true even for the 'worst' window opening schedule[2] and no solar protection. The authors studied four different future climate scenarios, 2030, 2050, and 2080 assuming a medium emissions (A1B) pathway and 2080 assuming a high emissions (A1F1) pathway. Furthermore, each future climate scenario had five

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[1] The category or Cat. thresholds in CIBSE TM52 are for different levels of comfort expectation. They range from Cat. I, recommended for spaces that vulnerable people might occupy, Cat.II with a normal level of comfort expectation for new buildings and renovations, and Cat. III for a moderate level of comfort expectation applicable to existing buildings.

[2] Four window-operation scenarios were considered in the study; two of which were theoretical opposites (‘worst’ and ‘ideal’ scenarios, with respect to facilitating natural ventilation). The worst scenario was one in which the windows were never opened, whereby air exchange was only achieved by infiltration (i.e., through gaps and cracks in the building fabric).

separate files to represent probabilistic percentiles (10th, 33rd, 50th, 66th, and 90th) of the climate signal. The findings revealed that all construction types under future climates would be deemed overheated without window opening or shading of windows. The authors conclude, however, that the increase in overheating due to insulation was generally less than the increase due to climate change.

Influence of archetype

The effects of wall insulation measures differ in different building archetypes. For example, Arup (2022) identified that dwellings with wall insulation were better protected from overheating, but this differed between different archetypes. It was deemed beneficial for homes with significant exterior walls (e.g., detached, end terrace, semi-detached) but less so for flats. Gupta & Gregg (2012) had similar findings whereby external wall insulation was the most effective at reducing overheating (60% fewer overheating hours compared to typical construction) for the detached property compared to other insulation options. However, for mid-terraced houses and flats, the benefit of insulation was reduced to such a degree that it could increase overheating. As an extreme example, Li et al. (2019) studied the temperatures in a converted loft room of a semi-detached dwelling and found very high levels of overheating. Insulation interventions had very little effect on night-time overheating degree hours, with a reduction of 0.1% of night-time degree hours after external wall insulation, an increase of 3% following internal wall insulation, and an increase of 5% after ground floor insulation.

External wall insulation versus internal wall insulation

The contrary findings discussed above possibly relate to the type of wall insulation and where it is installed, as several studies point to the fact that internal wall insulation of solid walled homes can present a greater overheating risk than installing external wall insulation. For example, both Gupta & Gregg (2012) and Porritt et al. (2013) found that external wall insulation reduced overheating more than did other insulation options. For example, in the study by Gupta & Gregg, external wall insulation retrofitted to a detached property led to 60% fewer overheating hours (annual hours where the average whole home temperature is greater than 28°C) in the 2050s compared to the base-case uninsulated cavity wall. These findings are supported by Ji et al. (2019) who discovered that externally insulated walls performed significantly better than the internally insulated walls. The living room and bedroom of the dwelling with external wall insulation experienced 71 hours and 61 hours above 25°C, respectively, compared with 111 hours and 151 hours for the internally insulated dwelling.

Roof and loft insulation

Simulation studies identify that increased loft or roof insulation is generally beneficial for reducing overheating. For example, Mavrogianni et al. (2017) found that roof and window upgrades were generally beneficial for reducing overheating. Similarly, Mavrogianni et al. (2012) identified that roof/loft and window retrofitting reduced average daytime living room temperatures by 0.76°C and maximum daytime temperature by 1.3°C. These findings align with those of Arup (2022) who discovered that roof insulation reduced overheating severity in bedrooms but had no noticeable effect for living rooms. The study by Arup (2022) also revealed that combining solid walled insulation with roof insulation led to fewer bedroom overheated hours than for wall insulation alone.

Although not using existing overheating metrics, Taylor et al. (2018) also identified that loft insulation was beneficial in reducing predicted heat mortality in their modelling study investigating homes in Birmingham, UK.

Ground floor insulation

Although there were seven modelling studies identified in Table 7 that implemented changes to the ground floor insulation, only two studies reported the effect on indoor temperature of this measure alone. In the remaining modelling studies, ground floor insulation was included as a ‘package’ of retrofit measures. It was also apparent, that studies modelling dwellings to different low-energy building codes (e.g., Passive House) would have made improvements to ground floor insulation compared to the current building regulations, but again, this was part of the overall package of insulation measures.

Of the studies reporting the effects of ground floor insulation, Mavrogianni et al. (2017) identified that as the ground floor U-value decreased the living room and bedroom mean temperature increased.

Combined measures

Considering the need to improve the fabric energy efficiency of the UK housing stock, many studies focus on modelling the effect of implementing multiple energy-efficiency measures or building to more stringent building codes (i.e., Passive House standard).

For example, Mcleod et al. (2013) compared a range of typical dwellings built to the Passive House standard to those to the fabric energy efficiency standard (Zero Carbon Hub, 2009). Three different variants of typical Passive House dwellings, to account for different levels of thermal mass, were modelled. The results showed that by 2050, a warmer than average summer could see average internal temperatures in low and ultra-low energy buildings exceeding 25°C for between 5% and 10% of the year. Thermal mass proved beneficial in terms of reducing the frequency of overheating and the amplitude of the maximum internal temperature (by approximately 2°C). However, the beneficial effects of thermal mass for reducing the number of hours over 28°C in the living rooms diminished in the 2080s. The benefit of thermal mass was less obvious for bedrooms and may in some cases lead to more overheating during the night.

Ibrahim & Pelsmakers (2018) also focussed on low and ultra-low energy building standards. They used the Passivhaus planning package (PHPP) steady-state modelling technique to simulate the thermal performance of a case-study detached home in the North of England. The analysis was carried out on the unrefurbished dwelling, and dwellings built to the Zero Carbon standard (Zero Carbon Hub, 2009), EnerPHit standard[3] (Passipedia, 2022), and Passive House standard. These voluntary standards typically prescribe fabric energy-efficiency levels above those of Part L of the building regulations. To provide readers with an overview of these different standards, a useful metric for comparison is kWh/m²/year covering space heating and space cooling energy demand. The target for the Zero Carbon standard, EnerPHit standard and Passive House standard are 46kWh/m²/year, 25kWh/m²/year, and 15 kWh/m²/year respectively.

Overheating was assessed against the Passive House standard which uses the percentage of annual hours exceeding 25°C as a measure of overheating. There was no overheating identified in the current climate for the unrefurbished dwelling. Overheating increased to 2% for the Zero Carbon standard home and 5% for the Passive House standard home. For the 2050s, overheating increased to 13% of annual hours for the EnerPHit standard and 15% for the Passive House standard homes. Reducing wall insulation and roof insulation to 2015 building regulations level did not reduce overheating to any great degree - the percentage of time exceeding 25°C reduced from 15% to 13% in the 2050s and from 22% to 20% in the 2080s.

Mulville & Stravoravdis (2016) found that predicted overheating increased as the fabric energy efficiency improved. For example, in a low mass dwelling, assuming slightly open windows and a north-south orientation, the percentage of overheated hours increased from 0% for a home built to building regulations Part L, 2006, to 11.7% in Code for Sustainable Homes level 5 and 7.8% in a Passive House under the current climate. By the 2080s, these figures had increased to 13%, 61.4% and 58.1% respectively. The authors presented no distinction between living rooms and bedrooms and thus calculated overheated hours by the number of occupied hours exceeding the adaptive comfort threshold relevant to criterion 1 of CIBSE TM52.

Taylor et al. (2015) found that retrofitted dwellings had an increase in overheating hours compared with those that were not retrofitted. The solid walls were insulated internally to represent a ‘worst-case’ scenario. For example, results showed that a mid-terrace dwelling with solid walls had 10.7% of occupied living room hours

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[3] The EnerPHit standard was developed specifically by the Passive House Institute for the retrofit of existing buildings. Compliance can be met by following two approaches: the energy demand method or the building component method.

exceeding 25°C for a future ‘near-extreme’[4] type summer, whereas the same retrofitted variant experienced 14.2% of occupied hours.

Taylor et al. (2021) moved beyond the current overheating standards by focussing on the health impacts of higher indoor temperatures. Indoor temperatures for building archetypes were predicted using meta-models created from the results of dynamic simulation. The authors then used mortality-temperature relationships to determine mortality risk. They found that the current retrofit rate may only lead to an increase of 1 death per million (0.3-0.8% increase). A more ambitious retrofit rate would increase mortality risk by around 12-13 deaths per million (8%) by the 2050s.

Fosas et al. (2018) conducted an extensive simulation study of 576,000 building variants. Their methodology, which entailed validation of the building models and an analysis technique enabling pair-wise comparisons to be made, provides good confidence in their findings. The study simulated the case study dwellings with five different values for the wall construction ranging from 0.6W/m²K to 0.1W/m²K. Reductions to the U-value of other fabric elements such as the roof and ground floor were also made for each step change improvement to wall insulation. Findings showed that the effect of insulation only explained 3.5% of the variance in overheating frequency and 2.9% of the variance of severity. Greater insulation levels increased the overheating duration in three-quarters of dwellings and reduced it in one-quarter. Similarly, for overheating severity, two-thirds of dwellings experienced more severe overheating with increased insulation, whereas one-third saw a reduction.

Impact of geographical location

Modelling studies indicate that the impact of wall insulation can differ for the same building located in different parts of the country. For example, Arup (2022) discovered that wall insulation was more effective at reducing overheating in Manchester than in London. We can speculate that this is due to the different weather experienced in the two locations. The authors inferred that this difference might be explained by higher solar heat gains in London sited dwellings offsetting the beneficial impact of wall insulation. Similarly, Peacock et al. (2010) found that adding insulation to a dwelling in Edinburgh reduced the overheating problem, whereas it made overheating slightly worse in the London dwelling.

Importance of ventilation

Many of the modelling studies point to the importance of ventilation alongside improvements to insulation. For example, Arup (2022) showed that the influence of insulation on overheating was dependent on other factors, particularly the

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[4] In Building performance simulation, a near extreme summer is represented by a Design Summer Year (DSY) weather file which represents the fourth hottest year of a thirty-year period.

effectiveness of ventilation. For example, wall insulation would increase overheating risk for homes where there was limited windows openability and thus ineffective natural ventilation to remove excess heat.

Fosas et al. (2018) also found little evidence that increases in insulation levels also increase overheating unless access to purge ventilation was either severely (purge ventilation during daytime hours only) or unrealistically (no window opening) curtailed. Similarly, Fosas de Pando et al. (2016) revealed that the improvement of the building fabric from 1995 building standards leads to an increase of overheated hours in both current and future climate if purge ventilation is not available. Where purge ventilation was optimised by assuming a 'perfect' occupant, overheating was eliminated in the current climate and overheating was also reduced for dwellings with improved fabric energy-efficiency.

Furthermore, Lee and Steemers (2017) showed that the differences in overheating between insulated and uninsulated or between cavity masonry or timber frame construction became slight when other fabric interventions, such as window shading, and evening ventilation strategies were employed.

Findings from field studies

This section analyses the findings from the six field studies and meta-analyses of field study data. Field studies typically use statistical techniques to identify significant differences in temperature or overheating between sample groups. The sources that adopt meta-analysis methodologies combine the monitored temperature data from multiple field trials. The ultimate aim of these studies being to make comparisons between homes typical of the existing housing and those built to higher energy-efficient standards.

House age as a proxy for energy efficiency levels

The Building Regulations have a direct impact on the insulation and airtightness of new dwellings. Driven by evolutionary changes to these regulations alongside other energy-efficiency policies, the rate homes lose heat during the heating season has, on average, fallen sharply since the 1970s (Palmer & Cooper, 2013). There is evidence from monitoring studies that newer built homes experience more overheating than older homes. For example, the monitoring study reported by Beizaee et al. (2013) discovered that homes built after 1990 had the warmest living rooms and bedrooms on average, with those built prior to 1919 being the coolest. Also, more bedrooms in post 1990 homes exceeded both static 24°C and 26°C thresholds (significant at $p<0.05$). Although not making an identical comparison, Pathan et al. (2017) identified that dwellings built after 1996 (assumptions made that these are to higher energy efficiency standards) had, on average, 6% more summertime occupied hours above 25°C compared to homes built before 1996 (sig. at p<0.05).

It is important to note that there are potentially many other differences between existing housing and new-build housing related to design choices and construction methods (i.e., to more lightweight structures such as timber frame) than just improved insulation levels of the building fabric. Previous work on the topic has noted the influence of the dwelling thermal mass and total area of glazing relative to floor area on overheating risk (Zero Carbon Hub, 2015).

Influence of roof or loft insulation

Petrou et al. (2019) conducted an analysis of temperature data collected in 795 living rooms and 799 bedrooms during the 2011 Energy Follow-Up Survey (EFUS). The authors derived a metric called the standardised internal temperature (SIT) to account for variations in outdoor weather across their study sample. They observed decreasing median bedroom SIT with increased levels of loft insulation, although no such pattern was identified for the living room.

Lomas et al (2021) analysed temperature data from 616 living rooms and 591 bedrooms monitored in the hot summer of 2018 as part of the 2017 EFUS. They found no significant differences in prevalence of overheating related to depth of loft insulation. However, their study also revealed that self-reported overheating by householders was significantly higher in homes with the lowest level of loft insulation. It should be noted that the householder survey which informed the above findings were carried out in the summer of 2017, which had ‘near average’ temperature.

Influence of EPC rating band

Using the SIT metric, Petrou et al. (2019) discovered that the median SIT for living rooms was significantly higher (p<0.05) in properties with an EPC rating greater than 70, Band C (median value 23.8°C) than those with a rating less than 30, Band F (median value 22.5°C). There was no significant difference for this factor discovered for bedrooms.

Similarly, Morey et al. (2020) monitored 122 social housing dwellings across the English Midlands in the summer of 2015 and found that there was a significantly higher mean temperature for bedrooms in B and C rated properties compared to those in Band E. Furthermore, living rooms in D rated properties had the lowest percentage of properties with hours exceeding the 25°C (5% of hours) criteria (significant at p<0.1).

Both the above findings align with those by Lomas et al. (2021) in their study analysing results from the 2017 energy follow up survey. They found that living rooms in EPC rating band A to C experienced more overheating (21%) than those in lower bands D to G (13%). This result was significant at $p<0.05$. However, a significantly higher proportion of Band A to C homes were flats, rather than houses, a dwelling form inherently more likely to overheat.

Meta-analyses of field study data

Gupta et al. (2019) compared monitored temperatures in existing, unmodified homes with those that had been retrofitted or newly-built to low-energy housing standards. Their findings showed that insulated dwellings experienced overheating approximately twice as frequently as those without, which was the case when considering those built to newer standards or retrofitted. However, the summer of monitoring was quite cool, meaning that exceedance hours were low when evaluated against the adaptive criteria in CIBSE TM52-the highest value for a living room was 4.5% of hours over the comfort temperature.

Contrary findings come from the meta-analysis of new-build housing by McGill et al (2017). Although there was a high prevalence of overheating in the monitored low-energy homes, no statistically significant difference (at p values of 0.001, 0.05 or 0.1) in the prevalence of living room overheating related to dwelling type or energy-efficiency standard was discovered.

Conclusions

There is an urgent need to improve the energy efficiency of the UK’s housing stock. A critical method of achieving this is to improve the fabric thermal performance of homes through the retrofit of improved insulation measures. There are concerns, however, that doing so may have “unintended consequences” of increasing summertime overheating risk, which would be detrimental to the health and well-being of people occupying the home.

This report presents a systematic review of the evidence for the impact of energy-efficiency measures on the summertime temperatures in UK dwellings. The review focusses on quantitative evidence of indoor temperatures in dwellings related to the presence of wall insulation, roof/loft insulation, ground floor insulation, double-glazing, combinations of these measures, as well as homes built to low-energy building standards (e.g., Passive House).

The quality of evidence was grouped as high, moderate, low, or very low quality when assessed against the GRADE system. High quality evidence is such that further work is unlikely to change the estimated impact of energy-efficiency measures on summertime indoor temperatures. This was obtained where different studies or those adopting different research methodologies showed consistent findings. Moderate quality evidence is such that further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate. This was obtained from one high quality study or from several studies with some limitations.

From the systematic review, the following conclusions can be drawn:

- There is high quality evidence from parametric modelling studies and nationally representative field studies conducted on the English housing stock, indicating that the prevalence of overheating in living rooms or main bedrooms among dwellings with insulated cavity or solid walls does not exhibit any statistically significant differences from their uninsulated counterparts in current climatic conditions.
- There is high quality evidence from modelling studies, which showed that wall insulation - either to cavity or solid walls - can reduce overheating exceedance in both the living rooms and bedrooms for dwellings with large external wall areas (e.g., detached and semi-detached). Whereas it has little impact or can slightly increase overheating in flats.
- The review provides high-quality evidence obtained from both modelling studies and a field experiment, indicating that insulating solid-walled dwellings internally can lead to a small increase in overheating risk. These findings underscore the importance of careful consideration of retrofit design and materials in the pursuit of energy efficiency and occupant comfort. Further research is necessary to identify the underlying mechanisms driving the observed increase in overheating risk and to inform the development of effective strategies for mitigating this risk while maintaining energy efficiency gains.
- There is high quality evidence from modelling studies that show the quantification of overheating is sensitive to the choice of overheating criterion and the assumptions made about the home occupancy (e.g., occupant vulnerability, and time spent at home). This finding indicates the need to consider the dwelling occupants in developing effective energy-efficient retrofits.
- There is moderate-quality evidence derived from both modelling studies and large-scale field studies, indicating that loft insulation can lower temperatures and reduce hours of overheating in bedrooms during summertime. These findings highlight the potential of loft insulation measures to enhance summer thermal comfort and energy efficiency in residential buildings, while also providing an affordable solution for homeowners seeking to improve their homes' energy performance.

- There is moderate quality evidence from modelling studies which show that the effects of wall insulation can differ for dwellings located in different geographical locations and thus experiencing different weather conditions. For example, in the current climate, solid wall insulation led to a greater reduction in the hours of bedroom overheating for homes in Manchester than homes in London.
- There is moderate quality evidence, derived from a series of modelling studies, indicating that insulation measures could make dwellings less robust to variations in occupant behaviour. Specifically, the findings suggest that insulation improvements could lead to increased temperatures within buildings if occupants fail to adequately ventilate by opening windows. These results underscore the importance of considering the interplay between building insulation and occupant behaviour in the design and implementation of energy efficiency measures.
- There is moderate quality evidence, obtained from meta-analyses of field studies, which contrasts UK homes constructed to low-energy standards, such as Code for Sustainable Homes and Passive House, with dwellings representative of the existing housing stock. The findings consistently reveal a higher prevalence and severity of overheating in the former compared to the latter. Further research is warranted to explore the underlying factors contributing to the observed overheating risks.

This study has some limitations. Firstly, although a systematic process appropriate for rapid evidence assessment was followed, due to the short time constraints, it is always possible that relevant sources of evidence were missed. Secondly, although the introduction of energy-efficiency measures such as insulation and double-glazing will generally improve the airtightness of dwellings, the effect of this was not explicitly evaluated in the study. We can assume, however, that the air exchange due to infiltration will be much less than that through ventilation (i.e., by opening windows or mechanical means). Lastly, research evidence from countries with similar Köppen-Geiger climate classifications was not included in this review. However, the documents discovered through the initial document screening with relevance to the research question were stored for subsequent analysis. Future work should seek to establish whether the findings from these studies are consistent with those discovered in this review.

References

Arup. (2022). Addressing overheating risk in existing UK homes. London: Climate Change Committee.

ASHRAE (2010). ANSI/ASHRAE standard 55-2010 Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

Beizaee, A., Lomas, K. J., & Firth, S. K. (2013). National survey of summertime temperatures and overheating risk in English homes. Building and Environment, 65, 1–17. https://doi.org/10.1016/j.buildenv.2013.03.011

BSI. (2006). BSEN15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality. Thermal environment, lighting and acoustics. Brussels: British Standards Institute.

Brocklehurst, F., Morgan, E., Greer, K., Wade, J., & Killip, G. (2021). Domestic retrofit supply chain initiatives and business innovations: an international review. Buildings and Cities. https://doi.org/10.5334/bc.95

CIBSE. (2006) CIBSE Guide A: Environmental design. 7th edition. London: Chartered Institution of Building Services Engineers.

CIBSE. (2013). TM52 The limits of thermal comfort: avoiding overheating in European buildings. London: Chartered Institution of Building Services Engineers.

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

Collins, A.M., Coughlin, D., Miller, J., Kirk, S. (2015). The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide.

Covidence. (nd). Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia. Available at: http://www.covidence.org

DBEIS. (2021). Energy Follow Up Survey: thermal comfort, damp and ventilation. London: Department for Business, Energy and Industrial Strategy.

DCLG. (2010). Code for Sustainable Homes-Technical Guide. London: Department for Communities and Local Government.

De Pando, D. F., Natarajan, S., Coley, D., Ramallo-Gonzalez, A., & De Pando, M. F. (2016). Influence of overheating criteria in the appraisal of building fabric performance. Proceedings - 9th International Windsor Conference 2016: Making Comfort Relevant, 1078–1098.

Elsharkawy, H., & Zahiri, S. (2020). The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance. Build. Environ., 172(PG-). https://doi.org/10.1016/j.buildenv.2020.106676

Fosas, D., Coley, D. A., Natarajan, S., Herrera, M., Fosas, M., Pando, D., & Ramallo-Gonzalez, A. (2018). Mitigation versus adaptation: Does insulating dwellings increase overheating risk? Building and Environment, 143(May), 740–759. https://doi.org/10.1016/j.buildenv.2018.07.033

Gupta, R., & Gregg, M. (2012). Using UK climate change projections to adapt existing English homes for a warming climate. Building and Environment, 55(PG-20-42), 20–42. https://doi.org/10.1016/j.buildenv.2012.01.014

Gupta, R., & Gregg, M. (2013). Preventing the overheating of English suburban homes in a warming climate. Build Res Inf, 41(3 PG-281–300), 281–300. https://doi.org/10.1080/09613218.2013.772043

Gupta, R., & Kapsali, M. (2016). Empirical assessment of indoor air quality and overheating in low-carbon social housing dwellings in England, UK. Advances in Building Energy Research, 10(1), 46–68. https://doi.org/10.1080/17512549.2015.1014843

Gupta, R., Gregg, M., & Irving, R. (2019). Meta-analysis of summertime indoor temperatures in new-build, retrofitted, and existing UK dwellings. Science and Technology for the Built Environment, 25(9), 1212–1225. https://doi.org/10.1080/23744731.2019.1623585

Gupta, R., Gregg, M., & Williams, K. (2015). Cooling the UK housing stock post-2050s. Build Serv Eng Res Technol, 36(2 PG-196–220), 196–220. https://doi.org/10.1177/0143624414566242

Hayles, C. S., Huddleston, M., Chinowsky, P., & Helman, J. (2022). Summertime impacts of climate change on dwellings in Wales, UK. Build. Environ., 219(PG-). https://doi.org/10.1016/j.buildenv.2022.109185

Hazem Rashed-Ali. (2021). Building Energy Performance Research-Current Approaches and Future Trends. In Rahman Azari, Hazem Rashed-Ali (Eds). *Research Methods in Building Science and Technology*. Cham, Switzerland: Springer Nature.

Ibrahim, A., & Pelsmakers, S. L. J. (2018). Low-energy housing retrofit in North England: Overheating risks and possible mitigation strategies. Build Serv Eng Res Technol, 39(2 PG-161–172), 161–172. https://doi.org/10.1177/0143624418754386

Jang, J., Natarajan, S., Lee, J., & Leigh, S.-B. (2022). Comparative Analysis of Overheating Risk for Typical Dwellings and Passivhaus in the UK. Energies, 15(10 PG-). https://doi.org/10.3390/en15103829

Ji, Y., Fitton, R., Swan, W., & Webster, P. (2014). Assessing overheating of the UK existing dwellings - A case study of replica Victorian end terrace house. Build. Environ., 77(PG-1-11), 1–11. https://doi.org/10.1016/j.buildenv.2014.03.012

Ji, Y., Lee, A., & Swan, W. (2019). Retrofit modelling of existing dwellings in the UK: the Salford Energy House case study. International Journal of Building Pathology and Adaptation, 37(3), 344–360. https://doi.org/10.1108/IJBPA-12-2018-0106

Lee, W. V., & Steemers, K. (2017). Exposure duration in overheating assessments: a retrofit modelling study. Building Research and Information, 45(1–2), 60–82. https://doi.org/10.1080/09613218.2017.1252614

Li, X., Taylor, J., & Symonds, P. (2019). Indoor overheating and mitigation of converted lofts in London, UK. Build Serv Eng Res Technol, 40(4 PG-409–425), 409–425. https://doi.org/10.1177/0143624419842044

Lomas, K. J., Oliveira, S., Warren, P., Haines, V. J., Chatterton, T., Beizaee, A., Prestwood, E., & Gething, B. (2018). Do domestic heating controls save energy? A review of the evidence. Renewable and Sustainable Energy Reviews, 93, 52–75. https://doi.org/10.1016/j.rser.2018.05.002

Lomas, K. J., Watson, S., Allinson, D., Fateh, A., Beaumont, A., Allen, J., Foster, H., & Garrett, H. (2021). Dwelling and household characteristics' influence on reported and measured summertime overheating: A glimpse of a mild climate in the 2050's. Build. Environ., 201(PG-). https://doi.org/10.1016/j.buildenv.2021.107986

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P., & Oikonomou, E. (2012). Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. Build. Environ., 55(PG-117-130), 117–130. https://doi.org/10.1016/j.buildenv.2011.12.003

Mavrogianni, A., Davies, M., Taylor, J., Oikonomou, E., Raslan, R., Biddulph, P., Das, P., Jones, B., & Shrubsole, C. (2013). The unintended consequences of energy efficient retrofit on indoor air pollution and overheating risk in a typical Edwardian mid-terraced house. Conference paper presented at Futurebuild 2013.

Mavrogianni, A., Davies, M., Taylor, J., Chalabi, Z., Biddulph, P., Oikonomou, E., Das, P., & Jones, B. (2014). The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments. Build. Environ., 78(PG-183-198), 183–198. https://doi.org/10.1016/j.buildenv.2014.04.008

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

McGill, G., Sharpe, T., Robertson, L., Gupta, R., & Mawditt, I. (2017). Meta-analysis of indoor temperatures in new-build housing. Building Research and Information, 45(1–2), 19–39. https://doi.org/10.1080/09613218.2016.1226610

McLeod, R. S., Hopfe, C. J., & Kwan, A. (2013). An investigation into future performance and overheating risks in Passivhaus dwellings. Build. Environ., 70(PG-189-209), 189–209. https://doi.org/10.1016/j.buildenv.2013.08.024

Mitchell, R., & Natarajan, S. (2019). Overheating risk in Passivhaus dwellings. Building Services Engineering Research and Technology, 40(4), 446–469. https://doi.org/10.1177/0143624419842006

Morey, J., Beizaee, A., & Wright, A. (2020). An investigation into overheating in social housing dwellings in central England. Building and Environment, 176(March), 106814. https://doi.org/10.1016/j.buildenv.2020.106814

Morgan, C., Foster, J. A., Poston, A., & Sharpe, T. R. (2017). Overheating in Scotland: contributing factors in occupied homes. Building Research & Information, 45(1–2), 143–156. https://doi.org/10.1080/09613218.2017.1241472

Mulville, M., & Stravoravdis, S. (2016). The impact of regulations on overheating risk in dwellings. Building Research and Information, 44(5–6), 520–534. https://doi.org/10.1080/09613218.2016.1153355

Orme, M., & Palmer, J. (2003). Control of overheating in future housing - design guidance for low energy strategies. AECOM

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ, n71. https://doi.org/10.1136/bmj.n71

Palmer, J., & Cooper, I. (2013) *United Kingdom housing energy fact file*. London: Department of Energy & Climate Change. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf (Accessed 08/08/23)

Passipedia. (2022). EnerPHit – the Passive House Certificate for retrofits. Available at: https://passipedia.org/certification/enerphit (Accessed 04/05/23)

Passive House Institute. (2015). Passive House Requirements. Available at: https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm (Accessed 04/05/23)

Pathan, A., Mavrogianni, A., Summerfield, A., Oreszczyn, T., & Davies, M. (2017). Monitoring summer indoor overheating in the London housing stock. Energy and Buildings, 141(PG-361-378), 361–378. https://doi.org/10.1016/j.enbuild.2017.02.049

Peacock, A. D., Jenkins, D. P., & Kane, D. (2010). Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. Energy Policy, 38(7 PG-3277–3288), 3277–3288. https://doi.org/10.1016/j.enpol.2010.01.021

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences. https://doi.org/10.5194/hess-11-1633-2007

Petrou, G., Symonds, P., Symonds, P., Symonds, P., Mavrogianni, A., Mavrogianni, A., Mavrogianni, A., Mylona, A., Davies, M., Davies, M. J., & Davies, M. E. (2019). The summer indoor temperatures of the English housing stock: Exploring the influence of dwelling and household characteristics. Building Services Engineering Research and Technology. https://doi.org/10.1177/0143624419847621

Porritt, S. M., Cropper, P. C., Shao, L., & Goodier, C. I. (2013). Heat wave adaptations for UK dwellings and development of a retrofit toolkit. International Journal of Disaster Resilience in the Built Environment, 4(3), 269–286. https://doi.org/10.1108/IJDRBE-08-2012-0026

Roberts, B. M., Allinson, D., Diamond, S., Abel, B., Bhaumik, C. Das, Khatami, N., & Lomas, K. J. (2019). Predictions of summertime overheating: Comparison of dynamic thermal models and measurements in synthetically occupied test houses. Building Services Engineering Research and Technology, 40(4), 512–552. https://doi.org/10.1177/0143624419847349

Salem, R., Bahadori-Jahromi, A., & Mylona, A. (2019). Investigating the impacts of a changing climate on the risk of overheating and energy performance for a UK retirement village adapted to the nZEB standards. Build Serv Eng Res Technol, 40(4 PG-470–491), 470–491. https://doi.org/10.1177/0143624419844753

Tabatabaei Sameni, S. M., Gaterell, M., Montazami, A., & Ahmed, A. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. Building and Environment, 92, 222–235. https://doi.org/10.1016/j.buildenv.2015.03.030

Taylor, J., Mavrogianni, A., Davies, M., Das, P., Shrubsole, C., Biddulph, P., & Oikonomou, E. (2015). Understanding and mitigating overheating and indoor PM2.5 risks using coupled temperature and indoor air quality models. Build Serv Eng Res Technol, 36(2 PG-275–289), 275–289. https://doi.org/10.1177/0143624414566474

Taylor, J., Davies, M., Mavrogianni, A., Shrubsole, C., Hamilton, I., Das, P., Jones, B., Oikonomou, E., & Biddulph, P. (2016). Mapping indoor overheating and air pollution risk modification across Great Britain: A modelling study. Building and Environment, 99, 1–12. https://doi.org/10.1016/j.buildenv.2016.01.010

Taylor, J., Symonds, P., Wilkinson, P., Heaviside, C., Macintyre, H., Davies, M., Mavrogianni, A., & Hutchinson, E. (2018). Estimating the influence of housing energy efficiency and overheating adaptations on heat-related mortality in the West Midlands, UK. Atmosphere, 9(5). https://doi.org/10.3390/atmos9050190

Taylor, J., Symonds, P., Heaviside, C., Chalabi, Z., Davies, M., & Wilkinson, P. (2021). Projecting the impacts of housing on temperature-related mortality in London during typical future years. Energy Build., 249(PG-). https://doi.org/10.1016/j.enbuild.2021.111233

Tink, V., Porritt, S., Allinson, D., & Loveday, D. (2018). Measuring and mitigating overheating risk in solid wall dwellings retrofitted with internal wall insulation. Building and Environment, 141(June), 247–261. https://doi.org/10.1016/j.buildenv.2018.05.062

Wiley. (2023). Grading of Recommendations Assessment, Development and Evaluation (GRADE). Essential Evidence Plus, John Wiley and Sons. Available at: https://www.essentialevidenceplus.com/product/ebm_loe.cfm?show=grade (Accessed 04/05/23)

Zero Carbon Hub. (2009). Defining a fabric energy efficiency standard for zero carbon homes: Executive Summary of Task Group Recommendations November 2009. London: Zero Carbon Hub. Available at: http://www.carbonconstruct.com/pdf/fees_for_zero_carbon_homes.pdf (Accessed 04/05/23)

Zero Carbon Hub. (2015) *Overheating in homes: the big picture full report*. London: Zero Carbon Hub.

Appendix A

Search strategy, methods and scope

Definition of search keywords and search strings

Keywords for the literature search were developed based on the research question, the research team's knowledge in the field of domestic overheating, and through the analysis of keywords used in peer-reviewed literature investigating overheating. Search terms were developed using the PICO (population, intervention, comparison, outcome) model as used by Brocklehurst et al. (2021) and shown in Table A1.

Simple scoping searches were carried out initially in the research database Scopus using these search terms, synonyms and truncation. The draft strategy was tested using papers that the research team was already aware of and would expect to find given the search terms. If the strategy did not identify them, modifications were made to the search strategy. It was crucial to strike a balance between avoidance of omissions while also considering the practical limitations of manual screening and time constraints.

Once an acceptable search strategy was developed using the Scopus database it was then translated for other databases. This involved adapting the descriptors to match the specific search vocabularies for each database but keeping the free text terms. This iterative process of trialling and refining continued until the search results provided comprehensive coverage of the available evidence.

Table A1 Development of search keywords and terms

PICO elements	Keywords	Example search terms
P (**P**opulation)	Domestic buildings in the UK	Dwelling, domestic, housing, house, residences, flat, apartment, homes
I (**I**ntervention)	Improved insulation or energy efficiency measures	Energy efficiency, energy-efficient, retrofit, Passivhaus, Passive House, insulation, envelope thermal characteristic, EPC rating, low-energy

C (**C**omparison)	Uninsulated homes or those with poor energy-efficiency rating	
O (**O**utcome)	Overheating or high temperature	Thermal comfort, overheating, indoor temperature, heat, heat stress, heat resilience discomfort, thermal performance

Inclusion and exclusion criteria

The research team developed inclusion and exclusion criteria based on the aim and initial scope of this review (Table A2 and Table A3). Documents were selected or excluded on the basis of their abstract (screening one) and then the full text (screening two).

Table A2 Inclusion criteria

Inclusion criteria
Screening one – Abstract
1. Documents that are written in English
2. Documents with a UK context
3. Documents that can be accessed online within the time allocated for the review
4. Documents that the abstract indicates some evidence for the effects of improved insulation levels or energy-efficiency measures on internal temperatures of domestic buildings during the summer
Screening two - Full text
5. Documents that meet points 1 to 4 and provide quantitative evidence for point 4 when reading the full text document

Table A3 Exclusion criteria

Exclusion criteria
Screening one and two
• Studies of non-domestic dwellings • Documents that are a duplicate study (e.g., where a conference paper became a journal paper)

The UK is classified according to the Köppen-Geiger system (Peel et al., 2007) as Cfb, which represents temperate, without a dry season, and warm summer. Of particular interest was countries with similar characteristics, particularly those in Northern and Central Europe (e.g., Denmark, Germany, France, Netherlands, and Belgium). Studies from countries such as Australia, New Zealand, and China were also considered for future investigation as some regions within these countries have similar climate classifications to the UK.

Sources of evidence

Evidence was sought from two peer-reviewed literature databases *Scopus* and *EI Compendex*.

Scopus is an abstract and citation database that offers the most comprehensive coverage across various disciplines. It gathers content from over 7,000 publishers, which undergoes a rigorous selection process by an independent Content Selection and Advisory Board.

EI Compendex is an engineering-focused database by Elsevier that offers reliable content to enhance research outcomes and increase the impact of engineering research. It contains a vast amount of global scholarly and technical literature, ranging from the newest findings to historical research and innovations.

Evidence was also sought from other research databases, including Google scholar, and supplemented by searching institutional databases relevant to the research question (e.g., Construction Information Service (CIS) and the UK Government website gov.uk).

Google Scholar is an open access tool for broadly searching scholarly literature across various fields and sources. Its archive comprises peer-reviewed papers, theses, books, articles, and abstracts from academic publishers, universities, scholarly societies, pre-print repositories, and other scholarly organizations.

Evidence search and search record

Example search strings used for searching in the Scopus and EI Compendex databases are shown below.

Scopus

(TITLE-ABS-KEY (overheating OR "thermal comfort" OR "hot temperature") AND TITLE-ABS-KEY (insulation OR "energy efficien*" OR energy-efficien* OR "low energy" OR retrofit) AND TITLE-ABS-KEY (dwelling OR home* OR house* OR residential OR domestic OR housing OR flat OR apartment) AND TITLE-ABS-KEY (uk OR "united kingdom"))

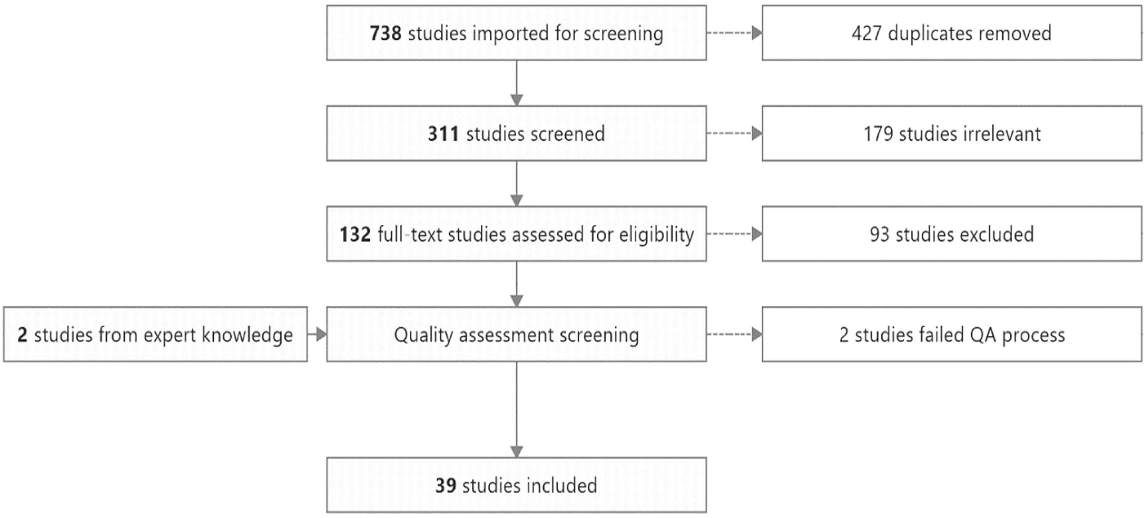
Compendex

(((overheating OR "thermal comfort" OR "hot temperature") AND (insulation OR "energy efficien*" OR energy-efficien* OR "low energy" OR retrofit) AND (dwelling OR home* OR house* OR residential OR domestic OR housing OR flat OR apartment) AND (uk OR "united kingdom")) WN KY)

Google scholar does not allow for complex Boolean searching of their database meaning that the search strategy had to be slightly modified. Thus, separate searches were carried out using combinations of the terms from the search strings used for the literature databases and searching in the title field only. The same approach was used for the other institutional databases.

The search terms, the date, the database and the number of hits for each search was recorded. Databases were searched between 30th January 2023 and 3rd February 2023. After searching in each database, the individual results were combined using Mendeley reference management software and duplicate records removed. The PRISMA (Page et al., 2021) flowchart of this process is shown in Figure A1. The full list of sources was then exported to Covidence software, which is a “web-based collaboration software platform that streamlines the production of systematic and other literature reviews” (Covidence, n.d.)

Figure A1 PRISMA protocol flow diagram with outcomes



Screening search results

The inclusion and exclusion criteria were used to identify the most relevant evidence from the search results. Evidence was assessed in two stages. The first stage of screening involved reading the title and abstract of the search results and judging it against the inclusion/exclusion criteria. A rating of “relevant” or “irrelevant” was applied and the full text was then gathered for all evidence that was labelled as “relevant”. The second stage of screening involved reading the full text of the evidence and evaluating it against the defined inclusion/exclusion criteria. A total of ninety-three sources of evidence were excluded at this stage for a variety of reasons including: no effects of insulation or energy efficiency measures presented (forty-two), not a UK context (twenty-two), or study design of a qualitative nature (eight). Forty-one sources met the inclusion criteria and passed to the quality assessment screening stage.

Research Quality Assessment

The quality of the included sources was judged against the same framework, which was used in a previous scoping review by Lomas et al. (2018). Table A4 shows the scores available for each question in the assessment. Each source was scored out of a total of nine and those that scored six or above were used for the evidence synthesis. The number of studies achieving each quality assessment score is shown in Figure A2, which indicates that two studies failed to meet the requisite threshold of six points.

Table A4 Research quality assessment scales

Points Score	Quality assessment question
Reporting Quality	
0 or 1	Does the author or publishing organisation have a credible track record in the area?
0, 1 or 2	Are the rationale and research questions clear and justified?
0, 1 or 2	Does the document acknowledge funding sources, project contributors and advisors, and list possible conflicts of interest?
0 or 1	Are the methods used suitable for the aims of the study?
Research Quality	
0, 1 or 2	Has the document been peer reviewed or independently verified by one or more reputable experts?
0 or 1	Do the conclusions match the data presented?

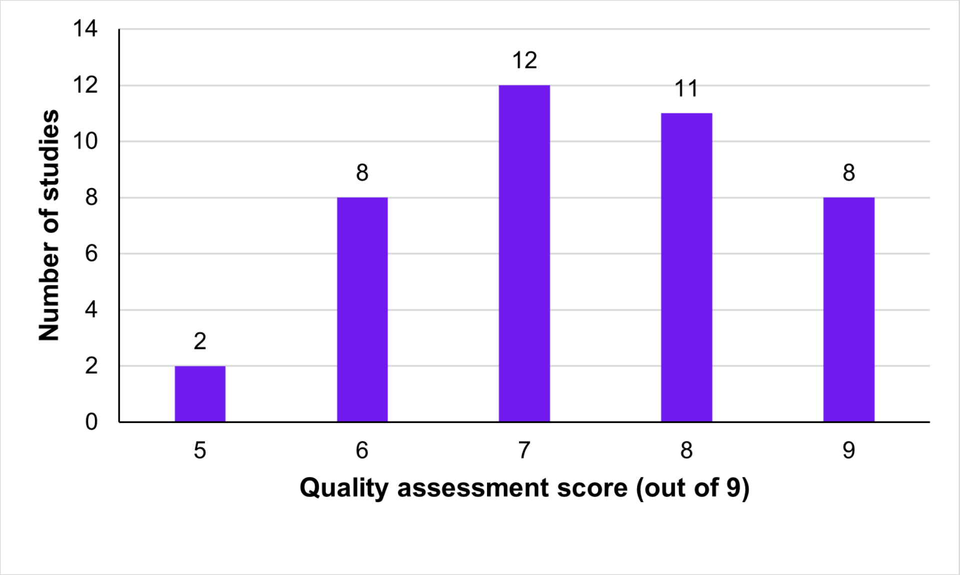


Figure A2 Quality assessment scores

Extracting evidence from the studies

The thirty-nine studies included in the review were read in detail to extract information relevant to answering the research questions. A data extraction template and quality assessment template were produced in the Covidence online software app to enable consistent data extraction. Table A5 presents a list of the information that was extracted from each source.

Table A5 Data extraction template

Citation details	
Authors	
Year of publication	
Title of paper	
Title of publication	
Volume, issue, pages	
DOI	
Data extraction template	
Country context	
Building archetype	
Aim of study	
Study design	
Overheating (OH) assessment	

Notes on OH metric	
Weather data	
Notes on weather data	
Main findings	

Subsequent analysis and synthesis of the included documents aimed to identify and categorise the quality of any evidence. The use of evidence-based assessment is most prevalent in the medical field, and the GRADE system (Grading of Recommendations Assessment, Development, and Evaluation) is used here. The four quality of evidence classifications ranging from high to very low are presented in Table A6.

Table A6 Quality of evidence classification (after Wiley, 2023)

Code	Quality of Evidence	Definition
A	High	Further research is very unlikely to change our confidence in the estimate of effect.
		• Several high-quality studies with consistent results • In special cases: one large, high-quality multi-centre trial
B	Moderate	Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate.
		• One high-quality study • Several studies with some limitations
C	Low	Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate.

		• One or more studies with severe limitations
D	Very Low	Any estimate of effect is very uncertain.
		• Expert opinion • No direct research evidence • One or more studies with very severe limitations

Appendix B

Author and year	Key findings related to overheating and insulation/energy efficiency	Building archetype	Location	Method	Overheating assessment	Notes on overheating metric	Weather data
Orme & Palmer 2003	There was a 16% increase in overheating for a semi-detached house with improved insulation compared to the base case (676Kh cf. 582Kh)	Semi-Detached, Detached, top-floor flat, town house	London	Dynamic simulation	Fixed	Degree hours above 27°C	Present
Peacock et al. 2010	The high thermal mass dwelling had significantly less overheating. Adding insulation to the Edinburgh dwelling reduced the overheating problem, whereas it made overheating slightly worse in the London dwelling.	Detached	London, Edinburgh	Dynamic simulation	Fixed: Other	CIBSE guide A (2006)-hours>25°C representing the average of the entire house (area weighted)	Present; Future

Gupta & Gregg 2012	External wall insulation was the most effective at reducing overheating for the detached property compared to other insulation options (60% fewer overheating hours compared to the base case uninsulated cavity walls). For mid-terraced dwellings and flats, the benefit of wall insulation was reduced to such a degree that it could increase overheating.	Semi-detached, detached, mid-terraced, purpose built flat	Oxford	Dynamic simulation	Fixed	Number of hours where average whole house temperature exceeded a threshold of 28°C	Present; Future
Mavrogianni et al. 2012	Roof/loft and window retrofitting reduced average daytime living room temperature by 0.76°C and the max. daytime temperature by 1.3 °C. Wall insulation appropriate to the dwelling archetype (i.e., internal wall insulation retrofitted to solid walls, and cavity wall insulation to cavity walls) increased mean daytime temperature by 0.38°C and max. daytime living room temperatures by 0.61°C.	Various	London	Dynamic simulation	Temperature	Maximum and average LR temperature for the hottest five-day period. Seasonal mean temperature.	Present; Future

Gupta & Gregg 2013	External wall retrofit, which included external wall insulation and a high albedo render coating was the most successful package for reducing overheating in the living room across the different dwelling archetypes. Internal insulation, on the other hand, was least effective in reducing overheating and was projected in most cases to lead to more overheating.	Various	Oxford, Bristol, Stockport	Dynamic simulation	Adaptive	5% of occupied hours above EN15251 Cat.II threshold for LR and BR	Present; Future
Mavrogianni et al. 2013	Decreased number of hours of overheating in 2050 for retrofit to 2010 regulations with external wall insulation cf. base case (53% reduction in living room, and 41% in bedroom)	Mid-terrace	London	Dynamic simulation	Fixed	LR hours above 28° C, BR hours above 26°C. May to August	Present; Future
McLeod et al. 2013	By 2050 a warmer than average summer could see average internal temperatures in low and ultra-low energy buildings exceeding 25°C for between 5% and 10% of the	Two bed end terrace	Greater London	Dynamic simulation	Fixed; Temperature	LR hours greater than 25°C and 28°C. Maximum internal	Present; Future

	year. Thermal mass proved beneficial, reducing the frequency of overheating and the maximum internal temperature (by approximately 2°C).					temperature. BR hours>26°C	
Porritt et al. 2013	Wall insulation can, in some cases, lead to increased overheating. External insulation performed better than internal for overheating reduction.	Various	London and Southeast	Dynamic simulation	Fixed; Other	Degree hours over 28°C for living rooms and 26°C for bedrooms.	Present & 2003 heatwave
Ji et al. 2014	For the living room, using the adaptive approach, overheating might not occur until 2080s. For bedrooms, overheating could occur by the 2020s. Authors suggest that overheating risk assessment should aim to use Degree hours alongside percentage number of exceedance hours.	Pre-1919 solid wall end terrace	Manchester	Dynamic simulation	Fixed; Adaptive	CIBSE guide A(2006) 28°C LR, 26°C BR. Degree hours. BSEN15251	Present; Future
Mavrogianni et al. 2014	An increase of insulation tended to increase temperature and overheating overall for the specific set of	Various	London	Dynamic simulation	Temperature	18 different temperature related	Present

	behaviour and retrofit assumptions for living rooms and bedrooms. This was much more pronounced when windows were kept closed compared to the different window opening schedules.					metrics (9 for LR, 9 for BR).	
Gupta et al. 2015	Overheating was prevalent in most of the archetypes located in Oxford by the 2080s. Implementation of Green Deal retrofit measures can, in a large majority of cases, result in homes with less overheating than the baseline construction.	Detached, Semi-Detached, Mid-terraced	Oxford, Bristol, Stockport	Dynamic simulation	Adaptive	TM52 (Cat.II occupancy)	Future
Taylor et al. 2015	Archetypes at greatest risk of overheating included top-floor flats, bungalows, and top-floor flats in converted buildings. Dwellings that were retrofitted had an increase in overheating risk compared with those that were non-retrofitted.	Various	Plymouth	Dynamic simulation	Fixed; Adaptive	CIBSE guide A (2006) for LR only. Adaptive method to EN15251 (Cat.II) for LR only	Present; Future

Fosas DePando et al. 2016	Improvement of the building fabric from 1995 building standards leads to an increase of overheated hours for all criteria in both current and future climate if purge ventilation is not available.	Mid-terrace	London	Dynamic simulation	Fixed; Adaptive; Other: Passive House	LR 28°C 1%, BR 25°C, 1%	Future
Makantasi & Mavrogianni 2016	For the worst-case scenario of future climate change (high emissions, 90th percentile, 2050s) cavity wall insulation increased overheating hours by 15.2% cf. base case. Internal wall insulation almost doubled overheating hours	17 storey tower block (ground floor, 7th floor & 15th floor flat)	London	Dynamic simulation	Fixed; Adaptive	CIBSE Guide A (2006) and CIBSE TM52	Present; Future
Mulville & Stravoravdis 2016	Predicted overheating increased as the fabric energy efficiency improved. For example, in a low mass dwelling, assuming slightly open windows and a north south orientation, the percentage of overheated hours increased from 0% for Part L, 2006, to 11.7% for Code for Sustainable Homes level 5 and 7.8% for Passive	Semi-detached	London, Edinburgh	Dynamic simulation	Fixed; Adaptive	CIBSE TM52 and CIBSE Guide A static (1% of hours above 25°C, 1% of hours above 28°C)	Present; Future

	House under the current climate.						
Taylor et al. 2016	Bungalows and top-floor flats were more vulnerable to overheating alongside more modern airtight terraced dwellings. The identified dwelling vulnerability was sensitive to the 'overheating' metric used in the analysis.	Various	London, Plymouth, Edinburgh	Dynamic simulation	Temperature	Ten different metrics related to temperature.	Present
Lee & Steemers 2017	The increase in overheating due to insulation was generally less than the increase due to climate change. Differences between insulated and uninsulated or between cavity masonry or timber frame became slight when other fabric interventions, such as window shading, and evening ventilation strategies were employed.	Typical London mid-terrace	Central London	Dynamic simulation	Adaptive; Other: new metric known as continually overheated intervals	CIBSE TM52	Present; Future
Mavrogianni et al. 2017	Wall and floor insulation were positively correlated with maximum temperature in LR and BR. Wall insulation had	Various (27 variants)	London	Dynamic simulation	Fixed; Temperature	CIBSE guide A (2006). Average temperature,	Present

	the largest impact, perhaps due to the fact that insulation was installed internally for solid walls. Roof and window upgrades were generally beneficial for reducing overheating.					maximum temperature, minimum temperature.	
Fosas et al. 2018	U-value of walls only explains 3.5% of the variance in overheating duration and 2.9% of the variance of severity. Greater insulation levels increased the overheating duration in 3/4 of dwellings and reduced it in 1/4. Similarly, for overheating severity, 2/3 of dwellings experienced more overheating with increased insulation, whereas 1/3 saw a reduction. Overall, the findings indicate that increases in insulation levels don't also increase overheating.	Naturally ventilated domestic properties	Eight global locations including London	Dynamic simulation	Fixed; Adaptive	Different adaptive thresholds for Europe and elsewhere	Present
Taylor et al. 2018	Individual energy efficiency retrofits did not, in general, lead to a significant increase in temperature. The exception	Various	Birmingham	Dynamic simulation	Temperature	Mean maximum daytime living	Future

	was for internally insulated solid walls, where there was a median temperature increase of 0.1°C (range -0.4 to 0.9).					room temperature	
Ji et al. 2019	When considering the number of hours exceeding 25°C for the living room and main bedroom, externally insulated walls performed better than internally insulated. Living rooms experienced 72 exceedance hours and 111 hours respectively. For bedrooms, these figures were 61 hours and 151 hours respectively.	Pre 1919 end-terrace	Manchester	Dynamic simulation	Fixed; Adaptive	EN15251 (Cat.I, II and III)	Present; Future
Li et al. 2019	Loft rooms experienced very high levels of overheating compared to conventional bedrooms under current climate conditions (10,799 overheating degree-hours for Cat.II-24hrs, cf. an average of 624 for other bedrooms). Insulation had very little effect on night-time overheating degree hours, with a reduction	Converted loft in semi-detached dwelling	London	Dynamic simulation	Adaptive	TM52 applied for both the day (24h) and night only hours. Degree hours calculated for Cat.I and Cat.II	Present; Future

	of 0.1% after external wall insulation, an increase of 3% following internal wall insulation, and an increase of 5% after ground floor insulation						
Salem et al. 2019	Severe overheating was experienced in the 2050s and 2080s for the nZEB scenario compared to the base case. However, the base case scenario also had notable levels of overheating by the 2050s and 2080s according to criterion 1a and 1b of TM59.	Flats	London	Dynamic simulation	Adaptive	CIBSE TM59, Cat.I for vulnerable occupants	Present; Future
Elsharkawy & Zahiri 2020	Improving the wall U-value from 0.9W/m²K to 0.3W/m²K led to an increase of mean operative temperature from 19.5° C to 22.6° C in 2050. The base case had 38% lower ‘discomfort’ hours compared to the best insulated wall case. Although, not made explicitly clear in the study, it is assumed by this review that the ‘discomfort hours’ are a combination of living room and	1960s tower block	London	Dynamic simulation	Adaptive; Temperature	Annual operative temperature. CIBSE TM59	Present; Future

	bedroom threshold exceedance hours.						
Taylor et al. 2021	By the 2050s without any adaptation of the housing stock, there is predicted to be a 4-to-5-fold increase in heat-related mortality. The current retrofit rate may lead to an increase of 1 death per million (0.3-0.8% increase). A more ambitious retrofit rate of the housing stock would increase mortality risk by around 12-13 deaths per million (8%).	Various	London	Dynamic simulation	Temperature	Daily maximum indoor temperature.	Present; Future
Arup 2022	Dwellings with improved wall insulation were better protected from overheating, but this differed between different archetypes. It was beneficial for homes with significant exterior walls (e.g., detached, end terrace, semi-detached). Roof insulation reduced overheating severity in the bedrooms but had no	Six archetypes .	Swindon, Manchester, Birmingham , Glasgow, London	Dynamic simulation	Fixed; Adaptive	CIBSE TM59	Present; Future

	noticeable effect for living rooms.						
Beizaee et al. 2013	Homes built after 1990 had the warmest living rooms and bedrooms on average with those built pre-1919 being the coolest. More bedrooms in post 1990 homes exceeded both static 24°C and 26°C criteria ($p<0.05$)	Various	England	Field study large	Fixed; Adaptive; Temperature	CIBSE guide A (2006), BS EN15251	Present (2007)
Pathan et al. 2017	Dwellings built after 1996 (assumptions made that these are to higher energy efficiency standards) had 6% additional summertime occupied living room hours on average above 25°C compared to those pre-1996 (sig. at $p<0.05$)	Various (broadly represents greater London housing census 2011)	London	Field study large	Fixed; Adaptive	CIBSE guide A (LR 1% of hrs>28°C, BR 1% of hrs>26°C). ASHRAE 55 (2013) with thresholds for 90% acceptability. Dwelling with more than 1% of occupied hours above comfort temp	Present (2009 & 2010)

						+ 2.5°C was considered overheated	
Petrou et al. 2019	The median standardised temperature for the living room was significantly higher ($p<0.05$) in properties with a SAP rating greater than 70 (median value 23.8°C) than those with a rating less than 30 (median value 22.5°C). There was no significant difference for this factor discovered for bedrooms or for the presence of greater loft insulation in either room.	Various	England	Field study large	Adaptive; Temperature; Other: Standardised internal temperature	CIBSE TM59.	Present (2011)
Morey et al. 2020	There was a significantly higher mean temperature for bedrooms in B and C properties compared to those in Band E. Living rooms in D rated properties had the lowest percentage of properties with hours exceeding the 25°C (5%) criteria (significant at $p<0.1$)	Various (122)	Central England	Field study large	Fixed; Adaptive	CIBSE fixed LR 5% hrs>25°C, 1% hrs>28°C; BR 5% hrs>24°C, 1% hrs>26°C;	Present (2015)

						CIBSE TM52 and TM59	
Lomas et al. 2021	No significant differences identified in the measured prevalence of overheating in either living rooms or bedrooms for any energy efficiency related measures. However, living rooms in homes with SAP rating band A to C experienced more overheating (21%) than those in lower bands D to G (13%). This result was only significant at $p<0.05$.	Various	England	Field study large	Fixed; Adaptive; Other: reported by occupants	CIBSE TM52 Cat.**II** but Cat.**I** for vulnerable occupants	Present year 2018
McGill et al. 2017	30% of living rooms exceeded 3% of occupied hours above adaptive comfort thresholds. There was a significantly higher summertime average temperature in homes with MVHR systems than those without. No significant differences were discovered regarding prevalence of overheating related to dwelling type, Passive House	Various (53)	UK	Meta study	Fixed; Adaptive; Temperature	CIBSE static (5% annual occupied hours>25°C). Passive House (10% occupied hours>25°C). CIBSE TM52	Present

	certification, ventilation type or region.						
Gupta et al. 2019	Insulated dwellings experience overheating approximately twice as frequently as those without. This was the case when considering those built to newer standards or retrofitted. However, the exceedance hours were very low, the highest value for a living room was approx. 4.5% over comfort temperature. Higher temperatures were observed in bedrooms than living rooms.	Various (63)	UK	Meta study	Fixed; Adaptive	CIBSE guide A 2006 and CIBSE TM52 criterion 1	Present (2013)
Mitchell & Natarajan 2019	Meeting criterion 1b of TM59 was more difficult to achieve than 1a for both houses and flats built to the Passive House standard - 55% of all bedrooms failed criterion 1b.	Various (62 houses, 20 flats)	UK	Meta study	Fixed; Adaptive	Passive House (annual hours>25°C) and TM59.	Present (2011-2017)
Jang et al. 2022	Using criterion 1a of TM59, 5.3% of typical dwelling bedrooms exceeded the threshold and 16% of Passive House bedrooms. Using	Various (113 existing dwellings plus 82	England	Meta study	Adaptive	TM52 and TM59 assuming Cat.II. Data	Present (2011-2018)

	criterion 1b, 43% of typical bedrooms overheated cf. 65% of Passive House dwellings. There were statistically significantly more hours for which bedrooms exceeded the threshold in the Passive House dwellings compared to typical dwellings (19% cf. 12%).	Passive House standard)				from June to September.	
Ibrahim & Pelsmakers 2018	No overheating in current climate for un-refurbished dwelling. Overheating Increased to 2% for upgrade to zero carbon standard and 5% for Passive House. For the 2050s overheating risk increased to 13% for Enerphit and 15% for Passive House. Reducing the wall insulation and roof insulation to 2015 building regs did not reduce overheating to any great degree.	Detached	Sheffield	Steady state simulation	Fixed	PHPP annual hrs greater than 25°C	Present, Future

Hayles et al. 2022	Dwellings suffering more overheating were post 1990 dwellings, flats and properties with internal wall insulation.	Various - 12 different archetypes	Wales	Other: empirical modelling	Fixed	Whole house av.>26°C	Present; Future
Gupta & Kapsali 2016	The majority of homes (living room and bedroom) were found to overheat according to fixed criterion, but none when applying the adaptive comfort criteria. Contextual factors, such as occupant window opening, and heating system operation appeared to be influential on levels of overheating.	End-Terraced (1 home), Mid-Terraced (5 homes), Detached (1 home)	England	Field study small	Fixed; Adaptive	LR-28°C, BR-26°C, CIBSE TM52	Present (2013)
Tink et al. 2018	Operative temperatures were higher in the living room and bedroom of the insulated house compared to the uninsulated. The mean absolute difference between the insulated and uninsulated house was 2.2°C (living room) and 1.5°C (bedroom).	Semi-detached (2 matched-pair dwellings)	Loughbor'gh	Field experiment	Fixed; Adaptive; Temperature	CIBSE TM52 (Cat.I) for LR. 3% of hrs over 26°C for BR	Present (2015) Future
Abbreviations: LR=living room, BR=bedroom							