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RESEARCH PAPER

Assessing impacts of summertime overheating: some adaptation strategies

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The UK is predicted to experience warmer summers in the future, but the domestic building stock in England was not designed to cope with this change. The Standard Assessment Procedure (SAP) 2009 is used to assess the current state of the English building stock in terms of its vulnerability to overheating. The English Housing Survey 2009 provided data for 16 150 dwellings which are weighted to represent the housing stock. SAP predicts 82% of dwellings are currently at 'slight' risk of overheating and 41% at medium to high risk. If summer temperatures become 1.4°C warmer, then 99% of properties are predicted to have a medium to high risk of overheating. Several potential adaptations to the housing stock were considered to reduce overheating. Although ventilation strategies had the largest positive effect, the use of solar shading and shutters which allow secure ventilation could reduce vulnerability to overheating in the current climate. In a warmer climate, although some dwellings would still be at slight risk, the results suggest that solar shading strategies could reduce the percentage of those at medium to high risk to 6%. Future energy efficiency programmes will need to include adaptation measures to prevent overheating.

Keywords: adaptation, building stock, climate change, housing, overheating, ventilation, vulnerability

Il est prévu que le Royaume-Uni connaisse à l'avenir des étés plus chauds, mais le parc bâti résidentiel en Angleterre n'a pas été conçu pour faire face à ce changement. La Procédure d'Evaluation Normalisée (SAP) 2009 est utilisée pour évaluer l'état actuel du parc bâti anglais quant à sa vulnérabilité à la surchauffe. L'Enquête 2009 sur le Logement en Angleterre a fourni des données concernant 16 150 logements qui sont pondérés de façon à représenter le parc de logements. La procédure SAP prévoit que 82 % des habitations courent actuellement un risque « léger » de surchauffe et que 41 % courent un risque moyen à élevé. Si les températures estivales devenaient plus chaudes de 1,4 °C, la prévision est que 99 % des biens immobiliers courraient alors un risque de surchauffe moyen à élevé. Plusieurs adaptations possibles du parc de logements ont été envisagées pour réduire la surchauffe. Bien que les stratégies d'aération aient eu l'effet positif le plus important, l'utilisation de dispositifs d'occultation solaire et de volets qui permettent une aération sécurisée pourrait réduire la vulnérabilité à la surchauffe dans le climat actuel. Dans un climat plus chaud, bien que certains logements courraient encore un léger risque, les résultats suggèrent que les stratégies d'occultation solaire pourraient réduire à 6 % le pourcentage de ceux présentant un risque moyen à élevé. Les futurs programmes d'efficacité énergétique devront inclure des mesures d'adaptation destinées à prévenir la surchauffe.

Mots clés: adaptation, parc bâti, changement climatique, logement, surchauffe, aération, vulnérabilité

Introduction

The threat of climate change induced by human the emissions of greenhouse gases (GHG) is recognized at a global level. Even the most optimistic predictions suggest at least a 1.8°C rise in temperature by the end of the 21st century (Intergovernmental Panel on Climate Change (IPCC), 2007). In the UK, climate predictions have been made by the United Kingdom

Climate Impacts Programme (UKCIP) which indicates that the climate is likely to continue to become warmer, with a likely increase of 1.4°C by 2080 (Department for Environment, Food and Rural Affairs (DEFRA), 2010). Increased internal temperatures in domestic buildings have the potential to raise mortality rates and adversely affect thermal comfort (Mavrogianni *et al.*, 2009). Mavrogianni *et al.* showed a strong link between urban built form in London and excess summer deaths caused by the heatwave of 2006, highlighting the importance of further work into the vulnerability of domestic buildings to summer overheating.

Whilst it is crucial to make every attempt to limit GHG emissions from the built environment to reduce the warming effect, the likelihood of an increase in average temperatures implies that it is important simultaneously to adapt for this change in ways that will not contribute further to CO_2 emissions. In the domestic sector, policy-making has focused on the overheating aspect of adaptation, with the review of Part L of the Building Regulations in England (Conservation of Fuel and Power) stating that changes to the regulations should ensure that there are no unintended overheating consequences (Department for Communities and Local Government (DCLG), 2010a). The domestic building stock is not well suited to cope with overheating, which is shown by finding from the Chartered Institution of Building Services Engineers (CIBSE) that some buildings are already failing to meet basic comfort criteria (CIBSE, 2005). The current study used the CIBSE overheating definitions which state that a building is considered to overheat if the internal temperature reaches 28°C for 1% of occupied hours. It was found that according to this definition, many domestic buildings were already experiencing overheating problems.

There are two main ways in which thermal comfort has been defined and quantified: deterministic and adaptive. Deterministic methods take a set of known conditions and use this to predict likely comfort levels. Adaptive methods use surveys of occupant experiences to account for comfort expectation in different contexts and provide the occupant with a more active role in attaining comfort. The current Building Regulations (in England) require every new home to be assessed for potential overheating risk using a deterministic model: the government's Standard Assessment Procedure (SAP 2009) Appendix P.

SAP was developed for the former UK Department of the Environment in 1992 by the BRE to be used as a tool to deliver energy policy. The methodology used is based on BREDEM (the Building Research Establishment's Domestic Energy Model), and provides a framework for simulating and quantifying a dwelling's energy efficiency and CO_2 emissions. Since 1994, it has been part of compliance of Part L of the Building Regulations for a new dwelling to achieve an acceptable SAP rating, putting it at the heart of government domestic built environment policy-making. It is the chosen model for implementing the European Union Energy Performance of Building Directive, as well as being used to calculate and produce Energy Performance Certificates for dwellings. It will also be key to delivering new government initiative such as the Green Deal and the Renewable Heat Incentive.

SAP ratings are calculated by trained energy assessors who measure and record a building's characteristics and measurements. Necessary parameters include the surface area of all walls, floor, roof and windows, the materials from which these are constructed, and relevant details about the heating systems. Calculations are then performed using this information as well as exterior temperatures and the desired interior temperature. SAP quantifies a dwelling's performance and produces several outputs: energy use per unit floor area, a fuel–cost-based energy efficiency rating from 0 to 100 (known as the SAP rating); and its CO_2 emissions. The overheating algorithm was added in 2006, but it does not feed into the rating given to the building.

When SAP was created in the 1990s it was important that it could be calculated manually. This excluded the use of fully dynamic simulation modelling, which would ideally be used to calculate overheating. Although it was known that occupant behaviour impacted on energy use, the purpose of SAP was to assess the energy performance of one house against legislative requirements, independent of occupant behaviour. Although SAP will not accurately predict a building's energy use, it can compare the energy use of different dwellings for a set occupant behaviour. The overheating calculation is not designed to predict actual temperatures but can identify which homes are most prone to overheating. In contrast, a dynamic model would be able to predict the likelihood of a building to overheat, the frequency and duration of the overheating periods, and the indoor temperature.

A prerequisite to understanding any adaptation strategy for overheating risk is an assessment of the vulnerability of the existing stock. However, to date, research into overheating in the domestic sector has focused on a small number of dwellings (Hacker, Connell, & Belcher, 2005; Orme, Palmer, & Irving, 2003) One study (Porritt *et al.*, 2011) showed that temperatures in the living rooms of typical Victorian terraces could be maintained below the CIBSE overheating thresholds in 2080 (with a Medium–High Emissions scenario) with a combination of interventions such as exterior shutters and ventilation strategies. A similar modelling study (Gupta & Gregg, 2012) investigated the potential for adaptation of several typical English dwellings, but found that no combination of measures was entirely able to eliminate overheating risk into the 2080s. Both of these studies were limited to a small number of dwellings, and do not make comments about the vulnerability of the housing stock as a whole.

A study by CIBSE – 'Climate Change and the Internal Environment' (CIBSE, 2005) – aimed to assess the limitations of passive cooling strategies to alleviate overheating across a range of naturally ventilated domestic buildings: a 19th-century house, a modern house, a 1960s' flat and a modern flat, as well as some non-domestic archetypes. Three locations (London, Manchester and Edinburgh) were used, and three future scenarios. Whilst London was found to be likely to struggle to meet comfort targets by the 2050s without some assistance from mechanical cooling, Manchester and Edinburgh would suffer only minor overheating. The small number of archetypes and locations was a limitation in terms of understanding vulnerability but provided useful insights into the propensity to overheat of some widespread domestic building types in a range of locations.

Coley & Kershaw (2010) investigated the relationship between exterior and interior temperatures for 400 variants of four naturally ventilated building archetypes. They found a linear relationship between the two, with some buildings moderating the exterior temperature and some increasing it. However, this project used virtual rather than real buildings, with no attempt to replicate or represent the UK building stock.

The current study uses SAP 2009 to assess the domestic housing stock in England, as represented by the English Housing Survey (EHS). Using data from the EHS, the vulnerability of the stock to overheating is investigated and the impact of several simple adaptations compared to understand what effect these would have on the propensity of the housing stock to overheat. This study also shows what the key factors are to which the SAP overheating algorithm is sensitive. Note that unlike the main SAP calculations, the overheating appendix is regionally dependent on the external temperature and solar gains.

Table 1 (SAP 2009 Appendix P) table showing the level of overheating predicted by the threshold temperature

$T_{\text{threshold}}$ (°C)	Likelihood of high internal temperature during hot weather
<20.5	Not significant
≥ 20.5 and <22.0	Slight
≥ 22.0 and <23.5	Medium
≥ 23.5	High

Method

SAP 2009 is a simple, monthly model, unlike complex dynamic models such as Energy Plus, which model hourly changes in internal environment. As a static simulation, the model has its limitations (notably in performing monthly internal temperature calculations which provide no information on the duration of overheating episodes, and no capability to model the temperature of internal surfaces or individual rooms). However, the fact that it is static means that it is feasible to examine a very large number of properties with this calculation. More importantly, SAP 2009 requires fewer inputs than more complex simulation models. As SAP 2009 is the UK government's tool for compliance and policy-making, it is important to understand the scale of overheating risk which it predicts.

The input data for this paper come from the 2009 EHS, which includes data for 16 150 sample dwellings, representing the English housing stock. The survey is carried out annually by the Department for Communities and Local Government (DCLG). Each sample dwelling is weighted to stand for a certain number of actual dwellings. The process by which this weighting is undertaken is described in some detail in the Technical Notes produced by the DCLG (2010b), and involves a complex multi-stage process. The survey dwellings used are sampled from the Royal Mail's postcode database, drawn as a systematic random sample to ensure that the distribution of the sample across local authorities is close to that occurring in the postal address file. Firstly, the sample households are weighted against population data derived from the census and then the next step is to weight the dwellings (taking into account the unoccupied ones). Essentially the approach is first to weigh up the dwellings data for the current year to estimated dwelling controls by tenure, then to adjust this weighting so that the number of weighted households that result from it is consistent, within tenure and region, with the weighted full household sample. There are limitations to using this dataset, particularly because the buildings are weighted using socio-economic controls such as tenure and occupancy rather than physical ones, but it is currently the best representation of the English housing stock.

> [SAP 2009] provides a method for assessing the propensity of a house to have high internal temperature in hot weather. It does not provide an estimate of cooling needs. The procedure is not integral to SAP and does not affect the calculated SAP rating or CO_2 emissions.
>
> (Department of Energy & Climate Change (DECC), 2010)

It outputs a threshold temperature representing the average monthly temperature for each of the summer months – June, July and August – indicating the likelihood of high internal temperature during hot weather according to Table 1.

The threshold temperature is calculated for the dwelling using equation (1):

$$T_{\text{threshold}} = T_e^{\text{summer}} + \frac{G}{H} + \Delta T_{\text{mass}} \tag{1}$$

where T_e^{summer} (°C) is the external summer temperature. It is a monthly mean for the region in which the dwelling is located. These mean external temperatures are recent long-term averages provided by the Met Office and updated for the SAP 2009 calculations, and are dependent on location (see Appendix Table 3 in SAP 2009).

The output threshold temperature is the addition of the external temperature, the additional temperature value found by dividing the heat gains by the losses and an increment related to the thermal mass parameter of the dwelling. Dividing the heat gains by the losses gives a gain to load ratio, which is a measure of the usefulness of the gains. Overheating is caused by heat gains that occur when the building is already sufficiently warm, so that any further gains are not useful. The greater the gains compared with the losses the lower the usefulness of the gains (Anderson *et al.*, 2001).

Essentially the threshold temperature is the extent to which the building fabric modifies the average external temperature for that month. However, the implication of the threshold temperature in terms of defining overheating risk is based on a set of assumptions about defining discomfort in domestic buildings.

The summer gains, G (W), are found by adding the summer solar gains to the internal gains calculated in the main SAP calculations. The calculation of internal gains from water heating, cooking, human activity (metabolic) and appliance use is based on the number of occupants in the dwelling, which is assumed from the number of bedrooms. It is also assumed that the heating will not be used throughout the summer period, so the space heating gains are not included. The summer solar gains are calculated according to equation (2):

$$G_{\text{solar}}^{\text{summer}} = \sum (0.9 \times A_w \times S \times g_{\perp} \times FF \times Z_{\text{summer}}) \tag{2}$$

where 0.9 is the average transmittance ratio to that at normal incidence. A set of factors moderates the total solar energy that passes through the window according to how much they obscure the total window area in different ways. A_w is the area (m^2) of the opening in question; S is the solar flux (radiation from the sun; W/m^2) on the window for the summer months, for the latitude of the dwelling's region (138–225 W/m^2; see Appendix Table 5 in SAP 2009); $g_{\perp}$ is the total solar energy transmittance factor (0.57–0.85) of the glazing at normal incidence; FF is the frame factor (the proportion of the window that is glazed not obscured by frames or mullions, 0.7–0.8); and Z_{summer} is the summer solar access factor and takes into account the window overhangs and shading from blinds or curtains according to equation (3):

$$Z_{\text{summer}} = Z_{\text{blinds}}(Z + Z_{\text{overhangs}} - 1) \tag{3}$$

The heat loss factor, H (W/m^2), is the sum of the fabric heat loss and the ventilation heat loss of the dwelling. The total fabric heat loss is calculated in the main SAP model using what is known about the size and construction of the dwelling. The ventilation heat loss is calculated by multiplying the volume of the dwelling by the air change rate (see equation 4). In the summer the rate is dependent on the number of storeys, the extent of window opening and whether or not it is possible to cross-ventilate the dwelling:

$$H_v^{\text{summer}} = 0.33 \times n \times V \tag{4}$$

A thermal mass parameter, TMP (kJ/m^{2}K), is also calculated by dividing the heat capacity of the dwelling by its floor area. As it is not a dynamic model, SAP cannot simulate the effect of thermal mass on temperature, so a formula is used to compensate for this. If TMP is less than 285 kJ/m^{2}K (*i.e.* it has moderate to high thermal mass), then no increment is added to the threshold temperature, *i.e.* $\Delta T_{\text{mass}} = 0°\text{C}$. For dwellings with low thermal mass, the threshold temperature will be up to 2°C higher.

The building physics behind these calculations is the same as that used on other models to analyse overheating, but the difference occurs in the way the data are used. In a dynamic model such as Energy Plus, the calculations are performed at much more frequent time intervals such that the effects of thermal mass over the course of the day and night can be taken into account. This means that the number of hours per day, and days per month when the building is likely to overheat, can be calculated. Another commonly used model for assessing a building's vulnerability to overheating is the Passivhaus Planning Package (Cotterell & Dadeby, 2012). Like SAP, calculations are carried out for monthly time-steps and a heat balance method is used. Similar to SAP's equation (1), where the heat gains are divided by the losses, the Passive House Planning Package compares the heat gains with the heat lost through the fabric.

Instead of calculating a ratio, the difference between the two is found. If the gains are much larger than the losses, this indicates a need for a strategy to increase the losses to match the gains using passive ventilation.

Microsoft Excel was used to create a model of these calculations. Using a macro, the overheating calculations were performed for all EHS properties (Department for Communities and Local Government (CLG), 2011). The raw EHS data were first cleaned and then run through a converter created by Cambridge Architectural Research Ltd to bring it in line with the inputs needed for SAP calculations (Department of Energy & Climate Change (DECC), 2012). The cleaning process involved ensuring that all the relevant data points fell within the defined ranges given, and that any anomalous or obviously incorrect data were removed or altered.

The EHS data contain most of the information needed to undertake an SAP overheating calculation. However, there are a few parameters that are not known. This includes if the windows are opened during the day, as well as details about the window shading (using curtains and blinds) and overhang shading. These details are not picked up in the EHS, but are significant in determining whether or not a dwelling will overheat (see equation 4, which calculates the summer ventilation heat loss using the air change rate of the dwelling). It would be possible to retrofit or control these factors in existing buildings and so the analysis of the results will focus on these adaptation techniques and how implementing then would affect the building stock's vulnerability to overheating.

For all the variables investigated, the percentage of dwellings at risk of overheating was noted and plotted against the variable altered to show trends in the effects on the building stock. 'Dwellings at risk of overheating' are defined as those where the threshold temperature is greater than or equal to 20.5°C, *i.e.* at slight risk and above. As temperatures rise, even those currently at 'slight' risk are likely to be vulnerable, hence their inclusion.

It is assumed that all the dwellings have typical ventilation rates (0.8–1.0 air changes per hour – ACH) – this is taken from Appendix Table 3 in the SAP 2009 calculation and is the air change rate with the windows slightly open as well as being the suggested minimum required air change rate set out in Building Research Establishment's (BRE) *Good Practice Guide 155: Energy Efficient Refurbishment of Existing Housing* (BRE, 2003), window overhang shading of 0.2m – a typical window reveal depth based on the wall thickness of a masonry building using standard details (University of the West of England Faculty for the Built Environment, 2006), dark coloured blinds and no shutters. Future temperature and wind speed changes may impact on ventilation rates, but this has not been a consideration within the current study.

Results

The following histograms show the proportion of the housing stock that would be at risk of 'slight' overheating using the SAP 2009 current climate and for a future climate with a 1.4°C average summer temperature increase, as per the UKCIP future climate predictions for the UK (DEFRA, 2010).

It is clear that in the current climate (Figure 1), the majority of dwellings are at least 'slightly' vulnerable to overly high internal temperatures. If the average external summer temperature were to rise by 1.4°C (Figure 2), then the problem is extended to almost all dwellings (99%), indicating a serious risk. Given the evident need for adaptation measures, if the housing stock is to become more resilient to a warming

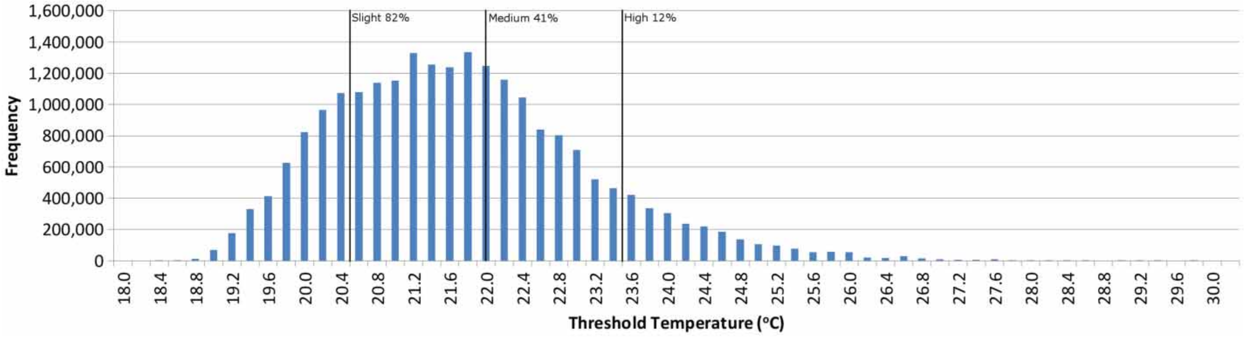

Figure 1 English housing stock – vulnerability to overheating in the current climate. Threshold temperatures predicted by the Standard Assessment Procedure (SAP) indicate the likelihood of the housing stock to overheat in the current climate. The vertical lines show the threshold temperatures that indicate a slight, medium and high risk of overheating, according to SAP 2009, and the cumulative percentages are also shown

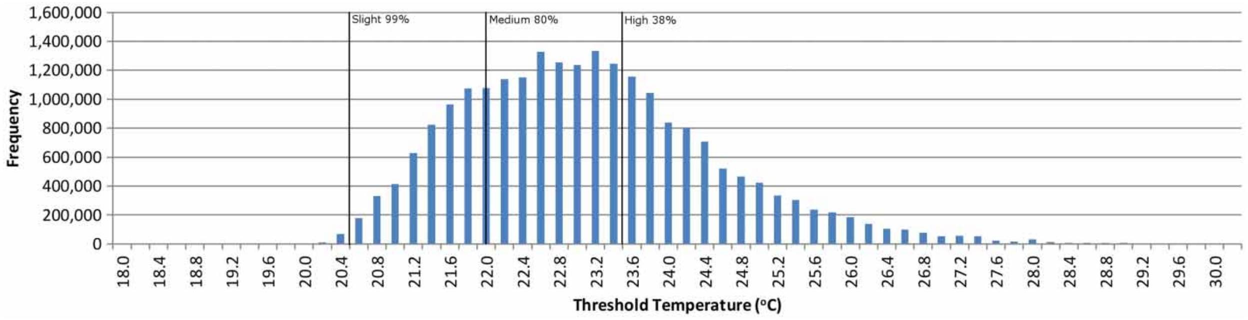

Figure 2 English housing stock – vulnerability to overheating in a climate scenario 1.4°C above the current summer average. Threshold temperatures predicted by SAP indicate an increased overall vulnerability

climate, then the following results show which measures are most effective.

Ventilation

In SAP 2009, dwellings are assigned air change rates based on the number of storeys, window opening and cross-ventilation options. With all the other unknown variables set to typical values, the risk of overheating could be removed for 99% of the building stock, if the air change rate were increased to four ACH, as indicated by Figure 3. The SAP 2009 tables suggest that an air change rate of four ACH is achievable only if the windows are fully open all the time. However, even if the air change rate were increased to two ACH, the percentage of the stock at risk could be reduced to 32%.

It would difficult to achieve four ACH due to reasons of security and outside noise. Inhabitants would not wish to leave their windows open to the required extent for the length of time necessary to achieve the cooling effect. However, if combined with shutters that allowed a flow of air through them, then higher air change rates could be achieved with no loss of security.

Interior window covering (curtains and blinds)

In order to compare directly the effects of the different window treatments, the windows were considered to be 50 mm open, resulting in an input air change rate fixed at 0.8–1.0 ACH depending on the number of storeys in the dwelling. Lighter coloured blinds and curtains were more effective in reducing overheating as they reflect the solar radiation rather than transferring it into the dwelling (Figure 4). There was a 9% difference in the number of vulnerable dwellings between the light curtain/roller blind and the venetian (slatted) blind options. However, if the blinds were dark, there was no difference between them. The colour of the shading is important, as well as the type of shade, because pale colours have a higher albedo and therefore reflect more heat than darker ones. The fabric used for the curtain also affected the heat gain; 16% more dwellings were vulnerable with the radiation-permeable net curtain than with an opaque pale-coloured curtain.

Exterior window covering (shutters)

Adding shading to the outside of the building proved to be more effective than even the best performing

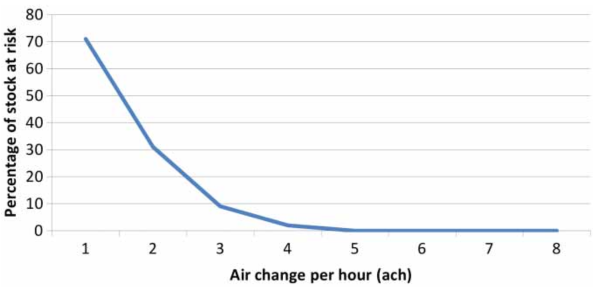

Figure 3 Effect of ventilation on vulnerability to overheating: percentage of dwellings that SAP predicts to be vulnerable to overheating

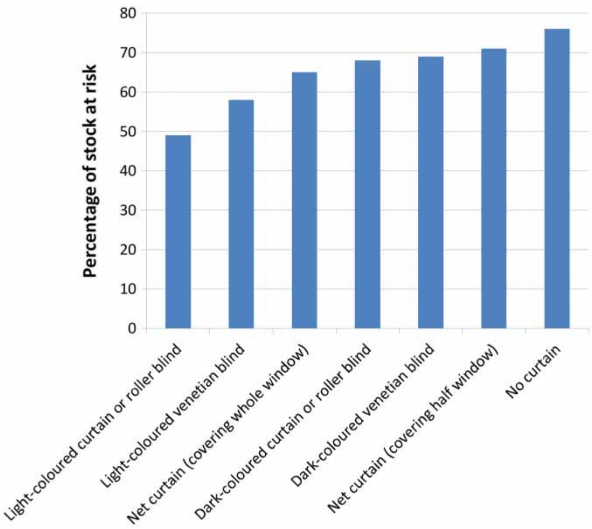

Figure 4 Effect of interior window shading on vulnerability to overheating, based on SAP predictions

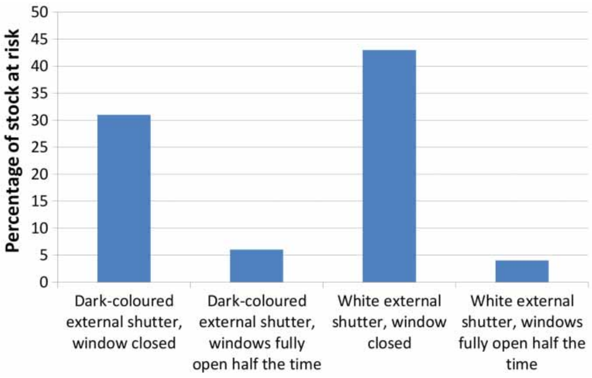

Figure 5 Effect of exterior window shading on vulnerability to overheating, based on SAP predictions

blind or curtain, even with the windows closed (Figure 5). Light-coloured shutters were more effective than dark ones due to their reflective properties. If the windows were opened as well as leaving the shutters closed (this assumes a louvered shutter construction which allows air to pass through), this reduced overheating to only being an issue in 4% of the stock.

Exterior window covering (overhangs)

Adding external overhangs to windows reduced vulnerability to 42% with a 1.2 m overhang, from 75% with no overhang (Figure 6). This is more effective than internal window coverings, but not quite as effective as the addition of shutters, and could be more difficult to retrofit.

Thermal mass

Thermally massive buildings are able to moderate the effects of high external temperatures because of their capacity for thermal storage, effectively absorbing excess heat during the day and releasing warmth outside at night. The results confirm this and show that if the average thermal mass parameter in the building stock was increased (up to the point at a thermal mass parameter of 285 kJ/m^{2}K, at which the SAP assumes no additional benefit from the increase in thermal mass) then the vulnerability to overheating would be reduced (Figure 7). The thermal mass parameter is the ratio of the dwelling's heat capacity to its floor area.

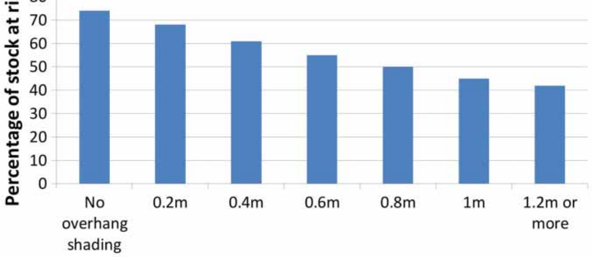

Figure 6 Effect of window overhang shading on vulnerability to overheating, based on SAP predictions

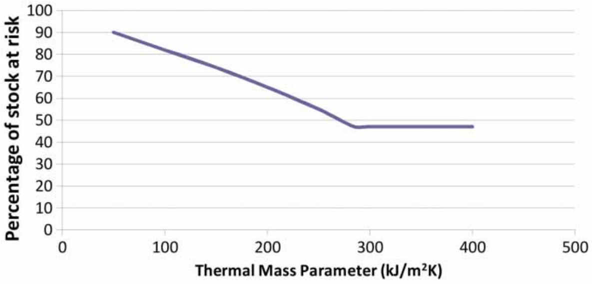

Figure 7 Effect of thermal mass on vulnerability to overheating, based on SAP predictions

Bringing together the most effective adaptations, the following histograms were created to assess the extent of possible improvement. These graphs show how the housing stock could become more resilient if changes were made.

There are two adaptations modelled that are both used for the 'adapted' stock:

- A 0.6 m overhang – an additional 0.4 m shading beyond the 0.2 m modelled in the first set of histograms. This size overhang was chosen as it is the midpoint on the graph and would provide significant shading yet still practicable for many homes.
- White shutters on the windows. It was assumed that these shutters are louvered, so that windows could be open half the time, leaving the shutters closed for security.

The vulnerability of dwellings to overheating varies with age and type. Newer dwellings and flats are most vulnerable to overheating. Dwellings using older, more traditional construction materials such as stone have a higher thermal mass, making them more able to moderate high external temperatures. Whilst adapting houses reduces the percentage of vulnerability to below 5%, even with these adaptations in place SAP shows the flats as still particularly vulnerable to overheating, especially purpose-built flats. The increased vulnerability of flats to overheating is in accordance with another study (Mavrogianni, Wilkinson, Davies, Biddulph, & Oikonomou, 2012) which has found that top-floor flats in particular are more likely to overheat.

Table 2 The vulnerability of dwellings by type and age showing the percentage of buildings with what the Standard Assessment Procedure (SAP) defines as 'slight' vulnerability or above. The top table is for unadapted dwellings; the bottom table for the adapted stock (with overhands and shutters). Darker shading indicates an increased risk of overheating

	Age										
Type	Before 1900	1900-1929	1930-1949	1950-1966	1976-1975	1976-1982	1983-1990	1991-1995	1996-2002	2003-2006	
End Terrace	18%	43%	58%	73%	74%	85%	94%	94%	97%	97%	4,914,347
Mid Terrace	34%	44%	72%	86%	87%	89%	97%	99%	99%	99%	6,392,587
Semi-Detatched	52%	60%	83%	91%	91%	96%	100%	100%	100%	98%	4,305,399
Detached	28%	29%	64%	79%	80%	91%	97%	100%	99%	100%	2,415,588
Flat (purpose-built)	63%	66%	81%	87%	91%	95%	100%	99%	100%	99%	3,406,911
Flat (converted)	64%	64%	76%	77%	0%	100%	n/a	n/a	n/a	100%	871,330
Non-Residential	80%	52%	100%	0%	100%	n/a	n/a	n/a	n/a	n/a	28,536
Total	2,813,961	1,980,308	3,688,835	4,503,948	3,199,871	1,431,593	1,981,379	763,875	1,029,980	940,948	22,334,698

	Age										
Type	Before 1900	1900-1929	1930-1949	1950-1966	1976-1975	1976-1982	1983-1990	1991-1995	1996-2002	2003-2006	
End Terrace	0%	0%	1%	3%	1%	5%	2%	0%	1%	3%	4,914,347
Mid Terrace	0%	0%	1%	2%	3%	3%	6%	3%	2%	1%	6,392,587
Semi-Detatched	1%	1%	2%	3%	3%	4%	6%	0%	3%	4%	4,305,399
Detached	0%	0%	1%	2%	3%	2%	3%	5%	5%	3%	2,415,588
Flat (purpose-built)	9%	20%	18%	13%	21%	24%	38%	32%	30%	21%	3,406,911
Flat (converted)	10%	9%	13%	15%	0%	0%	n/a	n/a	n/a	43%	871,330
Non-Residential	9%	11%	0%	0%	40%	n/a	n/a	n/a	n/a	n/a	28,536
Total	2,813,961	1,980,308	3,688,835	4,503,948	3,199,871	1,431,593	1,981,379	763,875	1,029,980	940,948	22,334,698

Discussion

The extent of the potential for overheating in the English housing stock was considered using SAP 2009 calculations. Past studies have assessed the overheating risk in dwellings, but they have been limited to small numbers of typical dwellings or to a restricted area. The results show that in the present climate 82% of the housing stock is at 'slight' risk of overheating, as defined by SAP 2009, assuming that no adaptation measures are being taken. However, if certain adaptive measures are taken then it would be possible to improve significantly the resilience of the stock and reduce vulnerability to a warming climate. This must be considered in conjunction with attempts to mitigate GHG emissions from dwellings, as it has been shown that improving the insulation and airtightness of buildings can make them more likely to overheat (Mavrogianni *et al.* 2012).

It should be noted that, as a static simulation, the SAP model has significant limitations: it calculates internal temperatures on a monthly basis, which means it is not possible to look at diurnal (day–night) temperature variations, or the duration of overheating episodes. SAP does not attempt to model the temperature of individual rooms, which precludes looking at the extent of overheating, or whether overheating is confined to specific rooms only.

Another limitation of this work is that future temperature and wind speed changes may affect ventilation rates, but this has not been a consideration within the current study.

The SAP model does not take into account the additional burden placed on urban dwellings due to the urban heat island effect: the external temperature in London can be 3°C higher than a rural reference

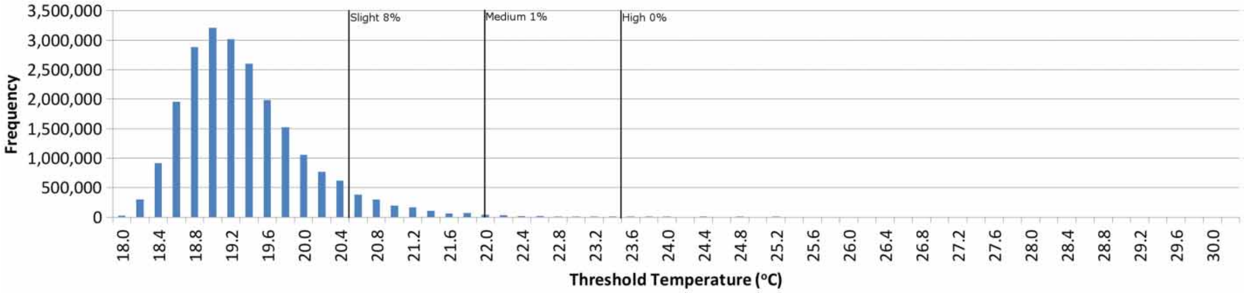

Figure 8 Adapted housing stock – vulnerability to overheating in current climate, as predicted by SAP 2009. The vertical lines show the threshold temperatures that indicate a slight, medium and high risk of overheating, and the cumulative percentages

point in periods of high temperatures (Mavrogianni, Davies, Wilkinson, & Pathan, 2010), putting even more dwellings at risk. Neither does it account for external factors such as proximity to trees or other buildings that can provide shading, or for the cooling effect of green spaces. Nonetheless, this work begins to identify the scale of the potential problem, and possible interventions to reduce overheating risks. More modelling and detailed assessment is needed to validate the extent of ventilation and shading required, but indications from this work are that the interventions needed are relatively modest, with running costs of the interventions close to zero.

However, even a 1.4°C rise in average summer temperatures appears to put the majority of existing buildings at some risk of overheating. If the average temperature were to rise more, to 2.4°C, for example, the histograms would shift 1°C higher, with a corresponding increase in the number of homes at risk and may require additional strategies such as mechanical ventilation for adequate mitigation. This is consistent with the findings of other studies that suggest that adaptation of the housing stock over the coming years will be necessary if the adverse effects of overheating are to be avoided in future (Gupta & Gregg, 2012; Porritt *et al.*, 2011).

The results tend to highlight the importance of a good ventilation strategy and shading devices in adapting dwellings to a warming climate and suggest that it may be possible to reduce overheating risks by designing efficient ventilation. However, there are limitations to this, as occupants may not use and open the windows in the optimum configurations, or use shutters when appropriate, thus reducing the effectiveness of both window ventilation and shading. Concerns about security and noise, particularly for those living at ground level, may mean that they will not open some windows at all, and certainly would not leave them open while they were away. Flats that only have a limited window area would also struggle to achieve the higher ventilation rates required. The effectiveness of ventilation in reducing vulnerability to overheating indicates that unless policy is brought into control it, Britain could turn to air-conditioning as a solution (Collins, Natarajan, & Levermore, 2010).

This study suggests that adapting the building stock using retrofitted shading devices, while not having the same effect as improved ventilation strategies, may offer potential to improve the stock's ability to cope with a warming climate. Altering the thermal mass much harder in older buildings, but adding shading to the exterior of buildings seems to be an effective way to prevent overheating in existing buildings without resorting to air-conditioning. The results suggest that shutters are particularly effective and not only prevent solar gain, but also provide a level of security combined with ventilation that is not possible with windows. This is consistent with recent research on designing for comfort that suggests that a policy of retrofitting of shading devices would be desirable (Gething, 2010).

If the widespread retrofitting of solar shading of various forms were encouraged through public policy, this would help improve the resilience of the English housing stock to a warming climate. It may also reduce reliance on air-conditioning. The Building Regulations could be used to encourage developers to provide secure night-time ventilation in new homes, using either opening louvers or other devices to allow air to enter without the risk of crime.

Two break-points in the chronology of house-building were identified that have a bearing on overheating risks. The year 1930 appears to be significant. Dwellings built before 1930 are significantly less likely to be at slight or greater risk of summer overheating (due to their solid wall construction) than dwellings built afterwards (due to the change to cavity wall construction). The second, less pronounced, breakpoint is 1983, coinciding with efforts aimed at conserving energy used in dwellings in the Building Regulations, which prompted higher levels of insulation. Nearly all dwellings built since 1983, of all types, suffer at least a slight risk of overheating.

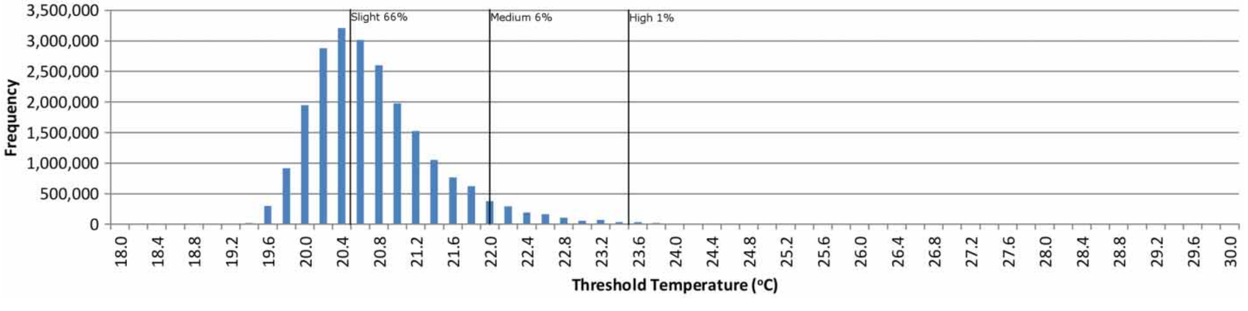

Figure 9 Adapted housing stock – vulnerability to overheating in a climate scenario 1.4°C above the current summer average. The vertical lines show the threshold temperatures that indicate a slight, medium and high risk of overheating, and the cumulative percentages

Flats built before 1983 also offer more potential for adaptation measures, which, according to the SAP calculation, will almost remove the risk of summer overheating. More recent flats are harder to treat effectively, and the modelling indicates that around one-third of purpose-built flats since 1983 cannot eliminate a slight overheating risk even if they use overhangs and shutters.

As described, building physics modelling tools exist to assess the overheating vulnerability of individual buildings, given enough quality data about the building fabric and the behaviour of occupants. However, there is a need for the standardization and validation of models used to assess dwellings for overheating risk. This need has been identified by government, and along with the need for better quality data about the building stock it is one of the aims set out in its recent publication analysing the gaps in overheating research (DCLG, 2012). Further research is being undertaken at Cambridge Architectural Research Ltd to compare the SAP calculations against dynamic simulation models and against empirical data.

Additional work is in progress in collaboration with other researchers at University College London (UCL), who have created a set of archetypes to represent the housing stock. This project will make a comparison between the SAP 2009 overheating model and a dynamic model, Energy Plus.

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