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The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in London: Direct and indirect effects in current and future climates

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Abstract

Mitigating summertime overheating is increasingly viewed as a key issue in urban planning – a warming climate and increasing urbanisation will exacerbate the problem. The effectiveness of green and cool roofs at reducing summertime overheating was assessed for a naturally ventilated, poorly insulated office roof in London. This was contrasted to the application of retrofitting traditional insulation. The new Chartered Institute of Building Service Engineers overheating criteria was used to assess the level of overheating as predicted by a whole building thermal simulation model. The impacts of the roofing strategies were split into the direct and indirect effects. The indirect effects of the roofs were modelled using microclimatic modelling software. The results indicate the direct effects of green and cool roofs at reducing overheating are much greater than the indirect cooling effect. A non-insulated cool roof was found to be the most effective strategy. By insulating the roof, the level of overheating was slightly reduced. Non-insulated green and cool roofs were more effective than insulated roofs at reducing levels of overheating. When using a 2050 weather file, the building frequently overheated without the use of green or cool roof.

Keywords

Green roofs, Cool roofs, Overheating, Urban Heat Island mitigation, Retrofit, Natural ventilation, Climate change adaptation, CIBSE overheating criteria

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Introduction

The Urban Heat Island (UHI) effect is a well-documented phenomenon in which urban areas experience higher average air temperatures than their rural surroundings. The main factors that contribute to UHIs are the morphology and fabrics of a city, resulting in inadvertent changes to the local climate. These factors include increased storage of solar radiation in building fabric due to reduced albedo of artificial surfaces and increased thermal conductivity of building materials, decreased radiant cooling at night due to lower sky view factors in street canyons, decreased wind speeds, reduction of evapotranspiration from soil and vegetation and heat gains from anthropogenic sources.[1]

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In London, extensive monitoring of air temperatures across the city found the average UHI Intensity, the difference between mean summer (June to August) urban and rural temperatures, to be 2.5°C at night.[2] High UHI intensities are likely to occur in specific conditions: clear skies, low wind speeds and dry weather such as those experienced in heatwaves. During the heatwave of August 2003, the UHI intensity reached highs of 9°C during the night.[3] UHI will tend to reduce exposure to winter cold but increase exposure to summer heat. The 2003 heatwave resulted in 2139 excess deaths in England and Wales with the highest incidence of excess deaths occurring in London.[4]

Due to increasing urbanisation and projected climate change scenarios such as those presented by the current UK Climate Projections (UKCP09),[5] urban warming and its potential adverse implications will be exacerbated. UKCP09 projections suggest that by the 2050 s, London's summers will be 1.1–5.2°C warmer (10th–90th probability percentile).[5] Mitigating summertime overheating is increasingly being recognised by national and local government as key to the continued sustainability and resilience of UK cities. This has been highlighted in the UK Government's Climate Change Risk Assessment,[6] the Mayor of London's Climate Change Adaptation Plan[7] and the latest Heatwave Plan for England.[8]

The aim of this study is to assess the effectiveness of two overheating mitigation strategies, green (vegetated/living) and cool (high albedo) roofs for a naturally ventilated office in London. These strategies are compared to adding simple insulation to a roof, thus assessing if green and cool roofs can be useful alternatives to more traditional approaches.

Strategies to reduce summertime overheating

A number of strategies have been proposed for reducing summertime overheating including shading of building envelope and façades; passive and low carbon ventilation; and measures that reduce the summertime UHI.[9] Internal and external insulation have also been proposed as mitigation strategies, but only when used appropriately – in certain cases, it can increase overheating.[10] UHI mitigation measures include introducing vegetation into cities (green roofs and walls, trees and other vegetation); increasing the albedo of surfaces (cool roofs, walls and pavements); reducing anthropogenic heat gains; as well as urban design strategies involving orientation, form and layout, which affect the sky view factor and ventilation corridors. It has been suggested for some time that the net effect of both direct and indirect changes to buildings and their local environment is the most effective mechanism at mitigating UHI effects for both vegetated and cool mitigation strategies.[11] Green and cool roofs are just one of many mitigation strategies that can be retrofitted to existing buildings.

Policy documents such as the London Plan[12] and Climate Change Adaptation Strategy[7] have recognised that roofing strategies could play a part in adapting cities to warmer climates and green roofs seen as a 'low cost, quick win' option when refurbishing commercial buildings.[13] In order to justify how effective roofing strategies could be in London and how they could be a more effective option than traditional insulation, their impact at varying temporal and spatial scales needs to be understood.

Direct and indirect effects of green and cool roofs

The impact of the roofs can be split into direct and indirect effects. Direct effects impact the immediate heat transfer into the building, subsequently affecting energy use and the comfort and health of occupants. Indirect effects impact the heat transfer to local microclimate; a standard flat asphalt roof will absorb solar radiation during the day and consequently emit it at night, adding to the UHI effect. Increasing the insulation in a building is limited to only directly affecting heat transfer through the fabric of the building.

Green roofs cool the local environment by increasing the latent heat flux due to evapotranspiration from their vegetated surfaces. They also reduce the sensible heat flux at the roof surface, although a greater amount of net radiation is absorbed compared to cool roofs due to green roofs' added thermal mass.[14] Cool roofs reduce the sensible heat flux due to their higher albedo, which reduces amount of net radiation absorbed by surface. There has been some evidence linking increased albedo of urban surfaces to an increase in global temperatures[15] and potentially increasing the energy use of surrounding buildings.[16] However, other studies have shown that the large-scale increases in albedo of surfaces can offset CO_2 emissions.[17] In turn, they can reduce the air temperature of urban areas[18] due to increased negative radiative forcing (the difference in radiation received by the earth and the amount radiated back to space), resulting in less radiation absorbed by the earth. A simple schematic of some of these processes is shown in Figure 1.

The performance of green and cool roofs is affected by a variety of physical and environmental parameters. The type of climate particularly impacts their relative effectiveness.[19] Cool roofs perform better in hotter, lower latitude climates, where solar intensity and gains are highest. Green roofs perform better in more

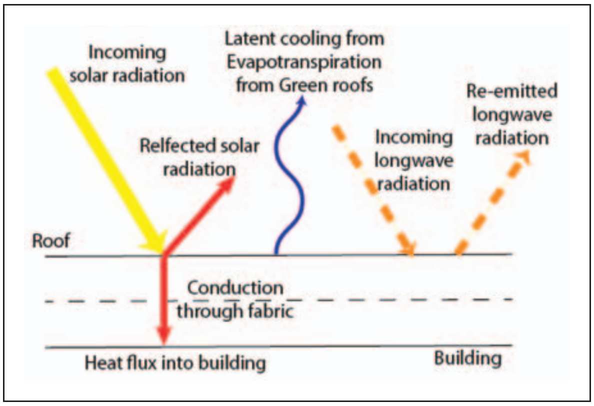

Figure 1. Examples of heat transfer in roof system.

temperate climates as their cooling ability is reliant on the level of irrigation.[20]

Green roofs mitigation potential

Green roofs' passive cooling performance is affected by the foliage density, represented by the leaf area index (LAI), soil layer thickness, foliage height, type of plant, amount of building insulation and climatic conditions such as ambient temperature, relative humidity and wind speed.[21] Niachou et al.[22] measured how green roofs impact internal air temperatures for a non-residential building near Athens. The roof reduced the number of hours the internal air temperatures exceeded 30°C by 13%. When naturally ventilated, the percentage of hours exceeding 30°C was reduced from 68% to 15%. The study also found that green roofs impact surface temperatures to a greater extent on non-insulated roofs compared to well-insulated roofs. Jaffal et al.[23] modelled a green roof in TRNSYS and varied the LAI and the amount of insulation for a family dwelling. The application of a green roof reduced mean indoor temperatures for a typical hot summer period by 2°C. By increasing the level of insulation, the impact of the green roof on reducing internal temperatures decreased, whilst changes to the LAI had less of an impact. Parizotto and Lamberts[24] compared the thermal performance of green roofs to ceramic and metallic roofs for a temperate climate in Brazil. The green roof reduced internal temperatures by 0.5–1°C during a warm week. The extra thermal mass provided by the green roof was the most important characteristic that helped improve the thermal performance. Sfakianaki et al.[25] found that green roofs reduce summer surface temperatures by 0.4–0.6°C when simulating Greek residential buildings and were most effective at increasing indoor thermal comfort when installed onto naturally ventilated buildings. Zinzi and Agnoli[26] compared the impact of green and cool roofs on residential buildings in three Mediterranean climates and varied amount of insulation. The non-insulated buildings had greater number of hours where the operative temperature exceeded 28°C and only in the most extreme climate were there a significant number of hours where the operative temperatures exceeded 30°C. Cool roofs were the most effective at reducing operative temperatures, whilst green roofs performed slightly less well. Green roof performance was affected by the amount of irrigation provided.

Cool roofs mitigation potential

Cool roofs increase the albedo of roof surfaces, varying the optical and thermal properties. Kolokotroni et al.[27] monitored the effect of cool roofs on an office building in London, and then used these measurements to calibrate a TRNSYS model of the building. The painted cool roof resulted in the surface temperature of the roof always being at a lower temperature than the internal ceiling. Comfort was significantly increased by increasing the albedo of the roof, the number of hours above 28°C is almost halved when varying the albedo from 0.1 to 0.7. Synnefa et al.[28] simulated the impact of cool roofs on residential buildings for a wide variety of climates. When increasing the albedo to 0.65, there were resulting reductions in the number of discomfort hours across all climates. Cool roofs also resulted in decreases in indoor temperatures by up to a maximum of 3.7°C. Romeo and Zinzi[29] measured the impact of cool roof on a school in Sicily. Internal summer temperatures were reduced by 2.3°C on average. Using a calibrated TRNSYS model, in rooms with lower solar gains, there was a significant reduction in the number of hours; the operative temperature was higher than 27°C and 29°C, with some rooms seeing a reduction of 25%. Higher insulation levels were found to decrease the impact of cool roofs at reducing the hours of discomfort.

From the evidence in the literature, green and cool roofs have been shown to increase thermal comfort when installed on a variety of buildings and in a variety of climates, they are just one option that a planner or designer could use to mitigate the effects of urban warming to reduce overheating within buildings. The aim of this study is to assess how effective a design option using green and cool roofs in London could potentially be. The thermal performance of both roofs is affected by the existing building insulation levels, performing less effectively when installed onto well-insulated roofs. This study models the impact of retrofitting the roofs on an existing, poorly insulated roof and alternatively assesses how increasing the insulation level will impact the level of overheating and the performance of the roofs.

Materials and methods

This study uses microclimatic modelling software and building simulation software to analyse the direct and indirect impacts of installing green and cool roofs in an area of central London, around Victoria Station. The microclimatic model was originally developed to analyse the impact of green and cool roofs on local temperature perturbations.[30] This current study uses the microclimatic outputs for the summer months from the previous work to analyse the direct and indirect effects of the roofs on overheating using the new Chartered Institute of Building Service Engineers (CIBSE) overheating criteria.[31]

Background: Victoria Business Improvement District

An audit was undertaken by the Land Use Consultants and the Green Roofs Consultancy,[32] which assessed all flat roofs within the Victoria Business Improvement District (BID; www.victoria-partnership.co.uk) boundary for their suitability for supporting a green roof. The audit concluded that 25 hectares out of the total 29 hectares of roof area could potentially support a green roof. For this study, the selection of roofs that were assumed to be able to support a green roof, or be painted with 'cool roof' paint were based on results from that audit.

Microclimatic modelling: ADMS

ADMS 4 Temperature and Humidity (ADMS) is a neighbourhood scale temperature and humidity model developed by Cambridge Environmental Research Consultants (CERC) as part of the LUCID (The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities) Project.[33] The model calculates perturbations of temperature and humidity (T&H) due to land use changes. The model has a domain range of 1–50 km^2 and can calculate perturbations at variable resolutions. Hamilton et al.[34] recently applied the model to the London Olympic Parkland, to analyse the impact of the development on local air temperatures.

ADMS is based on the meteorological pre-processing module of the standard Atmospheric Dispersion Modelling System[35] and the flow field and turbulence model FLOWSTAR. CERC developed the FLOWSTAR model to calculate profiles of the mean airflow and turbulence in the atmospheric boundary layer.[36] ADMS uses hourly values of the upwind surface sensible heat flux to satisfy the surface energy balance equation. The sum of the surface and latent heat fluxes is equal to the difference between the net radiation and the ground heat flux. As the local temperature depends on the sensible surface heat flux, it will be affected by local changes in the surface properties. Any changes to these surface properties will result in perturbations to the temperature and humidity profiles. Carruthers and Weng[37] outlines the theory for calculating how temperature and humidity vary with changing surface moisture, whilst the theory from Raupach et al.[38] outlines the effect of shear stress perturbation due to changes in local surface roughness. The particular version of ADMS used in this work did not account for anthropogenic heat emissions as this was not required for this comparative study. However, another version of ADMS can be used to incorporate the impact of anthropogenic heat and was used in Hamilton et al.[34]

ADMS defines the upwind boundary layer profile using its estimates of the upwind heat flux terms. It then uses its estimates of the local heat flux terms to define the perturbations to the upwind boundary layer profile. ADMS estimates the heat flux terms in the following ways:

- The upwind heat flux terms are estimated from upwind meteorological data (air temperature (°C), specific (kg/kg) or relative humidity (%), wind speed (m/s) and direction (degrees) and cloud cover (oktas)) along with an estimation of the minimum Monin-Obukhov length (a parameter that represents the stability of the atmosphere and is affected by the heat production in cities),[39] the height at which the meteorological data has been collected and the ratio of ground heat flux to net radiation (G/Q^*).
- The local heat flux terms are estimated by ADMS from inputs of the spatial variation of land use characteristics (albedo, surface resistance to evaporation and thermal admittance) and urban morphology (normalised building volume and surface roughness) across the domain. The normalised building volume (the total built volume within a given area, divided by that area) is calculated using the method outlined in Hamilton et al.[40] The model does not explicitly model the geometry of buildings; rather, the 3D urban morphology is represented using the normalised building volume and surface roughness.

Details of how to create the input files and run ADMS are included in the ADMS 4 Temperature and Humidity User Guide.[41]

Data required to define the upwind heat flux terms

The air temperature and relative humidity data were taken directly from a CIBSE Test Reference Year file

(TRY) for London.[42] Overheating is usually assessed using a 'Design Summer Year'. However, the outputs used in this study also related to the roofs' impact on annual energy consumption; hence, the use of a TRY. The use of a TRY will potentially mean that the extent of overheating will be underestimated, and this was noted when analysing the results. The use of a TRY should not significantly affect the assessment of the relative impact of the roofs.

The wind speed and direction were taken from the TRY weather file and were adjusted to reflect the fact that the case study site is in the city centre rather than the outskirts of London, where the Heathrow weather station is situated. The calculated wind speeds were on average 40% lower than the original TRY wind speeds. The process uses the methodologies included in the CERC Meteorological Input Module technical specification[43] and CERC Boundary-Layer Structure technical specification.[44] The cloud cover data were retrieved from the Met Office Integrated Data Archive System (MIDAS)[45] from the Heathrow weather station.

For the future climate scenario, the meteorological data were generated using the existing TRY and the most recent UK Climate Projections (UKCP09) (UKCP09 2010). This study has used the monthly climate projections provided for the 2050 s time period, for the 25 km grid square that encompasses central London, under the medium emissions scenario and for the 50th probability percentile, which was assumed to be a reasonable approximation for a central estimate. The predicted changes were accessed from the UKCP09 User Interface.[46] The current TRY for Heathrow was 'morphed' using the previously described climate projections as described in Belcher et al.[47] This methodology was also used with the previous UK Climate Projections (UKCIP02) to produce the CIBSE Future Weather Years.[48]

The upwind Monin-Obukhov length was assumed to be $L_{MOmin} = 100$ for large conurbations such as central London as suggested by CERC.[41] ADMS also requires an estimate of the ratio of ground heat flux (G) to net radiation (Q^*) in order to estimate the upwind heat flux terms which are in turn used to define the upwind temperature and humidity profiles. A number of empirical studies have shown the relationship of G with net radiation (Q^*) to be non-linear, exhibiting hysteresis loop behaviour.[49–51] Camuffo and Bernardi[52] described the hysteresis behaviour, which expresses G as a function of Q^* and the rate and direction of the change in Q^*, with three coefficients.

This study uses the outputs from the University of Reading's LondUM model[53] to estimate G/Q^* for the case study site, reflecting the diurnal (hysteresis loop behaviour) and annual variation as accurately as possible. The LondUM model uses the Met Office Unified Model combined with the urban surface energy-balance parameterisation scheme MORUSES (Met Office Reading Urban Surface Energy Scheme).[54,55] LondUM output data at 1 km^2 resolution across the whole of London for May, June, July and December of 2006. Modelled hourly heat flux data for the square kilometre containing London Victoria were used to estimate the Camuffo and Bernardi coefficients for the four months available. A sinusoidal trend was assumed for the coefficients, which was then used to predict coefficient values for the rest of the year. A value for G could then be estimated using Q^* outputs from ADMS and the monthly coefficients. These values were then used as upwind G/Q^* profiles input into the ADMS. The estimated flux variations are consistent with those observed by Anandakumar.[51] Further details of the methodology developed are outlined in greater detail in a forthcoming study.[56]

Data required to define the local heat flux terms

The land use input data required by ADMS are gridded, and a value is assigned to each grid point. The following are the required parameters:

- Surface resistance to evaporation (sm^{-1});
- Thermal admittance ($Jm^{-2} s^{-1/2} K^{-1}$);
- Albedo (–);
- Normalised building volume (m);
- Surface roughness length for momentum transfer (m).

The existing land use across the site was established using the Cities Revealed Land Use database[57] which assigns one of 19 land use descriptions categories (including building, road, rail) to each Ordnance Survey topography[58] polygon. Each land use description was then placed into groups that would have similar ADMS land use parameters. Proposed values of albedo, thermal admittance and surface resistance to evaporation for each land use category are summarised in Table 1. The Cities Revealed Land Use GIS files were combined with the Victoria BID Green Infrastructure Green Roofs GIS files[32] to establish the variation in land use parameters across the site for each of the modelling runs.

The normalised building volume and surface roughness length represent the urban morphology inputs. Values of surface roughness length (Z_o) were estimated as 1/30 times the canopy height, a simplified methodology mentioned in the ADMS 4 Meteorological Input Module technical specification. The canopy height was taken to be the average building height within each

Table 1. Albedo, surface resistance to evaporation and thermal admittance assumed for each land use category.

ADMS land use parameter group	Albedo (–)	Thermal admittance ($JK^{-1}m^{-2}s^{-1/2}$)	Surface resistance to evaporation (sm^{-1})
Water	0.8	1545	0
Path	0.8	1096	200
Cool roof	0.7[a]	1505	200
Green roof – dry	0.3[b]	620[c]	200
Domestic gardens	0.19	600	60
Green roofs	0.157[d]	620[c]	100[d]
Public green space	0.157	600	100
Buildings (normal roof)	0.12	1505	200
Road	0.08	1205	200
Rail	0.08	1150	200
Pavement/hard standing	0.05	1205	200

Sources:
[a]Albedo of a cool roof was taken from Hogenhout.[60]
[b]The albedo of a dry green roof was assumed to similar to values quoted for 'light dry soil' (0.2–0.45) as given by Oke.[59]
[c]Thermal admittance for green roofs was assumed to be similar to 'dry sandy soil' as given by Oke.[59]
[d]Albedo and surface resistance to evaporation was assumed to be similar to that for the green space category.
All other parameters are from a study using ADMS to assess the impact of the London Olympic Parkland on the urban heat island.[34]

15 m × 15 m grid square. A minimum value of 0.5 was used throughout the site; a figure of surface roughness for an urban parkland.[59] The Normalised Building Volume was calculated for each 15 m × 15 m grid square. Buildings' heights and volumes were established using the Cities Revealed LiDAR database[57] which contains height data for each Ordnance Survey topography polygons. Further details, including graphical representations of all input files, can be found in of Jansz.[30]

In this study, an area representing the Victoria BID was modelled in ADMS. The following scenarios were modelled:

- Basecase – represents the existing land use,
- Green roof – models 90% of the roofs as green roofs which are irrigated,
- Dry green roofs – as per the green roof scenario but assumed to be dry from June to August,
- Cool roof – models 90% of roofs as cool roofs painted with high albedo paint.

Hourly outputs of air temperature and relative humidity at a height of 1.5 m (chosen to represent near surface temperatures of the roofs) were generated for each modelling run at 50 m intervals of an output area sized 250 m × 250 m. These outputs were averaged for the whole area and used to edit a weather file to be input into a building model, details of which are outlined next. The outputs from a single rooftop point were also generated in order to assess the magnitude and timing of the microclimatic perturbations.

As outlined before, two climate scenarios are used: current and morphed 2050 for medium emissions under UKCP09 (UKCP09 2010). As the upwind weather file used in the modelling was based on a CIBSE TRY, the basecase roofing scenario also used a standard TRY. In order to assess the impact of the indirect effects of roofs on a building, the TRY was edited using the outputs from ADMS. Once the T&H profiles had been edited in the TRY .CSV file, it was converted to an .EPW file using the EnergyPlus Weather and Statistics Conversions utility. In the results, the TRY will be referenced as the weather file used to analyse the direct effects and a perturbed weather file will refer to the weather file which includes the results from the microclimatic modelling.

Building simulation model

This study used Design Builder 3.0.0.105 to model a naturally ventilated office building. Design Builder is an interface for the dynamic thermal simulation software EnergyPlus (version 7.0.0.036). Design Builder was chosen as it includes a validated green roof module, where a green roof is added as an extra layer of construction. The EnergyPlus green roof module 'Ecoroof' was developed and validated by Sailor[61] and is based on the FASST vegetation models.[62]

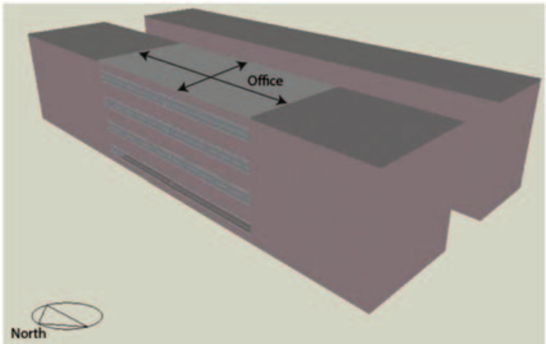

Figure 2. 3D representation of Design Builder building model.

Table 2. Construction details of model.

Layers	Thickness (m)	Area per surface (m^2)	U Value (W/m^2K)
Basecase roof	0.209	499.5	2.76
Single external wall surface	0.363	133.2	0.32
Internal floor	0.3545	499.5	0.22
Glazing	0.016	65	1.98

Figure 2 shows a visual representation of the office building. The model is based on modifications to work carried out by Demanuele et al.,[63] The model is orientated north to south and consists of four zones each sized 33 × 4 × 15 m, with a total floor area of 2000 m^2. Details of the construction are outlined in Table 2. The glazing ratio is 50% on all facades of which 20% can be opened and has a *g*-value of 0.7. The internal shading consists of internal blinds with high reflectivity slats.

The building is naturally ventilated, the level of ventilation was modelled to vary with occupation schedule and the maximum outside air change rate was set at 3 ACH. The building is occupied from 09:00 to 17:00 on weekdays. The following internal gains are based on an Open Plan Office template from the UK National Calculation Methodology[64]:

- Metabolic Rate = 120 W/person,
- Occupancy Density = 0.11 person/m^2,
- Lighting Density = 15 W/m^2,
- Equipment Density = 15 W/m^2.

The roof of the basecase model was varied to a green, dry green and cool roof. The basecase roof was then altered by increasing the insulation levels to meet current Part L regulations.[65] This new insulated basecase was then varied in the same way to the non-insulated roof. To model a green roof in Design Builder, the outer layer of construction is removed and the green roof is added as an extra layer. To model a cool roof, the physical characteristics of the basecase model are varied. Details of the modelled roof variations are outlined below:

- Basecase roof consists of an outer layer of black asphalt with an albedo of 0.1.
- Green roof with soil thickness of 0.15 m is added to the roof instead of black asphalt. The green roof has a LAI of 2. The normal green roof is irrigated throughout the summer period using Design Builder 'Smart' schedule. The green roof has a *U*-value of 1.36 W/m^2K.
- Dry green roof was modelled by using the exact same green roof model without any irrigation for the summer period.
- Cool roof uses the same model as a basecase roof, with an albedo of 0.7.
- Insulated basecase roof has the same construction as the basecase roof, but with an added layer of 0.2-m-thick mineral wool insulation. The *U*-value for the insulated roof is 0.18 W/m^2K.
- Insulated green and cool roofs, which use the same constructions as the insulated basecase, but varies the outer layer of the roofs as per the non-insulated scenarios.

Design Builder can output a wide range of environmental parameters. For this study, the internal operative temperature and the outdoor dry bulb temperature are needed to assess the level of comfort in the building. The next section briefly outlines the theory and methodology behind the new CIBSE overheating criteria, detailing the required inputs and calculations.

CIBSE overheating criteria

The CIBSE Guide A[66] previously provided guidance to assess summertime overheating for free-running buildings. Guide A recommended a criterion where operative temperatures should not exceed 28°C for 1% of occupied hours. Following a review by the CIBSE Overheating Taskforce, the new overheating criteria use the adaptive approach to thermal comfort. Technical Memorandum 52[31] outlines the new criteria which are based on BS EN 15251.[67] The adaptive equation for comfort used in BS EN 15251 relates the indoor comfort temperature to the outdoor air temperature and is defined as

$$T_{comf} = 0.33T_{rm} + 18.8°C$$

where T_{comf} is the internal comfort temperature and T_{rm} is the exponentially weighted running mean of the daily-mean outdoor air temperature as outlined in CIBSE Guide A.[66] The new guidance suggests acceptable temperature ranges in relation to T_{comf}, which define the maximum allowable difference between the operative temperature and T_{comf} for the building being simulated. The guidance recommends that new and renovated buildings should be designed to fall within category 2 limits for naturally ventilated buildings. The maximum acceptable temperature T_{max} for these buildings is consequently defined as

$$T_{max} = 0.33T_{rm} + 21.8^{\circ}\mathrm{C}$$

Using this maximum temperature threshold, all the new criteria are based on the following temperature difference

$$\Delta T = T_{op} - T_{max}(^{\circ}\mathrm{C})$$

where T_{op} is the internal operative temperature and T_{max} is the upper limit of the acceptable comfort temperature. The guide[31] uses ΔT to define the three criteria. Criterion 1 assesses the frequency of overheating within the building. Criterion 2 assesses the severity of repeated overheating, by using a daily weighted exceedance. Finally, criterion 3 sets an absolute maximum value (T_{upp} – the upper temperature limit) for the indoor operative temperature, for any period where there is excessive overheating. If a building fails two of the criteria for occupied hours, it is classed as overheating. As outlined above, in order to calculate whether the building is overheating, only the operative temperature and outdoor running mean are needed from the simulations. The results from the building simulations are analysed based on the following performance criteria:

- Which is the most effective roofing strategy at reducing overheating in the building in current and future climate scenarios?
- How effective is the indirect capacity of the roofs at reducing overheating in current and future climate scenarios?

Results

Mean summer microclimatic perturbations in current climate

This study uses the area averaged temperature and humidity outputs for the summer months June to August, to assess the impact of indirect cooling of the roofs at reducing overheating. The results from the single rooftop point within the output area are analysed first, to assess the magnitude and timings of the perturbations and the impact of summer weather conditions.

Table 3. Definition of type of day according to cloud cover for the summer period June to August.

Type of day	Average daily cloud cover (cc) (Oktas)	No. of summer days of this type
Cloudy days	≥ 7	10
Partly cloudy days	$4 < cc < 7$	54
Clear-sky days	$cc \leq 4$	28

The results from the single rooftop point have been split into different day types. This is in order to interrogate and understand the impact of different meteorological conditions on hourly roof level temperature perturbations for the summer period. These conditions were categorised by defining each day within the weather files into one of three cloud cover categories: cloudy days, partly cloudy days and clear-sky days. These classifications are based on a system used in a study into the impacts of physical characteristics on outdoor air temperatures by Kolokotroni and Giridharan.[68] Definitions of each of the day types, including the number of days of that type are shown in Table 3 in the year, whilst the mean meteorological parameters are shown in Table 4.

Table 5 presents the following three temperature perturbation characteristics for each day type:

1. The largest temperature perturbation that occurs in the day;
2. The hours within which the largest temperature perturbation occurs;
3. The mean daily temperature perturbation.

The largest temperature perturbations resulting from the installation of green and cool roofs occur on clear summer days (−1.05°C and −1.27°C, respectively). This day type has the highest average levels of solar radiation, the highest average temperatures and some of the lowest relative humidity values (averages of 285 W/m^2, 17.9°C and 71%). Dry green roofs do still exhibit a cooling effect, exhibiting similar behaviour on each of the summer day (0.34°C, 0.38°C and 0.38°C for each summer day, respectively).

The timings of the largest temperature perturbation vary considerably depending on the type of roof. The maximum temperature perturbations for green roofs occur in the evening; varying between 19:45 and 24:00. Dry green roofs also exhibit their comparatively lower peak temperature perturbations in the late

Table 4. Daily mean climatic values for each summer day type.

Type of day	Cloud cover (Oktas)	Solar radiation (W/m^2)	Temp (°C)	Wind speed (m/s)	RH (%)
Cloudy days	7.4	127	16.7	1.9	74
Partly cloudy days	5.5	200	17.4	1.7	71
Clear-sky days	2.6	285	17.9	1.6	71

Table 5. Diurnal temperature perturbations and the time they occur for each day type for three roofing scenarios.

	Green	Green Dry	Cool
Largest temperature perturbation (°C)			
Cloudy days	–0.96	–0.34	–0.58
Partly cloudy days	–1.01	–0.38	–1
Clear-sky days	–1.05	–0.38	–1.27
Period of largest perturbation			
Cloudy days	18:15–23:15	21:00–24:00	09:15–13:45
Partly cloudy days	19:00–21:00	21:00–01:00	08:30–13:00
Clear-sky days	19:45–24:00	24:00–03:00	09:00–11:00
Mean daily perturbation (°C)			
Cloudy days	–0.45	–0.14	–0.2
Partly cloudy days	–0.49	–0.15	–0.33
Clear-sky days	–0.48	–0.16	–0.44

evening, between 21:00 and 01:00. The peak temperature perturbations for cool roofs, however, occur between morning and midday, varying between 9:00 and 11:00.

The average daily temperature perturbations for cool roofs exhibit the same relationship with meteorological conditions as the maximum daily temperature perturbations, with the highest average values occurring on the clear summer days (–0.44°C). Green roofs show very similar average performance, on both the clear and partly cloudy summer days (0.48°C and 0.49°C respectively). In terms of daily average temperature perturbations, green roofs are modelled to outperform cool roofs on every day type. However, when the green roofs are modelled as dry, they are outperformed by the cool roofs on each of the summer days.

The modelling undertaken in this study indicates that green roofs are slightly more effective at reducing the maximum daily rooftop air temperatures than cool roofs.

Overheating criteria

Direct effects. To assess the direct effects of each roofing scenario, only the results using the TRY weather file (rather than the perturbed weather file) will be analysed in terms of their performance for each overheating criteria. Table 6 shows the percentage of occupied hours for which each roofing scenario exceeded the three criteria. The results are split into current and future climate scenarios and include the perturbed results, which will be discussed in the next section. All results refer to percentage of occupied hours that the three criteria are exceeded.

In the current climate, the building overheats under all roofing scenarios according to the new criteria. They all fail due to not meeting two of the three criteria. The basecase overheats for 8% of occupied hours. Green roofs reduce the likelihood of exceeding criterion 1 by 5%. They also reduce the severity of overheating by reducing the percentage of hours criterion 2 is exceeded by 6%. In current climates, dry green roofs are as effective as irrigated green roofs. Cool roofs are the most effective at reducing overheating within the building. The building only overheats 1% for criterion 1 and 2% of the time for criterion 2. All roofing scenarios do not exceed criterion 3 in the current climate.

For future climate scenarios, the building overheats to a much greater extent for all roofing scenarios. The basecase fails all three criteria and overheats frequently and severely, failing criterion 1 for 28% and criterion 2 for 24% of occupied hours. Criterion 3 is not met for

Table 6. Percentage of occupied hours that the models exceed the CIBSE overheating criteria.

		Percentage of occupied hours exceeding criteria		
Scenario	Roof type	Criterion 1	Criterion 2	Criterion 3
TRY	Base	8	11	0
	Green	3	5	0
	GreenDry	3	5	0
	Cool	1	2	0
Perturbed	Base	9	11	0
	Green	3	5	0
	GreenDry	3	5	0
	Cool	1	2	0
TRY 2050	Base	28	24	2
	Green	14	14	0
	GreenDry	14	14	0
	Cool	8	11	0
Perturbed 2050	Base	29	26	2
	Green	13	12	0
	GreenDry	15	17	0
	Cool	7	11	0

2% of occupied hours. The addition of a green roof reduces the number of hours criterion 1 is exceeded by half, while reducing the hours of exceedance for criterion 2 by 10%. Irrigated green roofs perform the same as dry green roofs. However, even though there is a comparative reduction in the number of hours of overheating, both scenarios exceed criteria 1 and 2 for 14% of occupied hours. Cool roofs are again the most effective at reducing the number of hours and severity of overheating. Both criteria 1 and 2 are exceeded for 11% or less of occupied hours. Only the basecase exceeds criterion 3.

The direct impacts of the roofs can be visualised by analysing the temperature profiles for a typical hot week during the summer period for the TRY results. Figures 3 and 4 show the effect of the roofing strategies for a week in July. The variable T_{out} represents the outdoor dry bulb temperature, T_{max} is the maximum comfort temperature and T_{upp} is the upper limit temperature as defined earlier for a category 2 building.

In the current climate, the operative temperature exceeds the T_{max} as the week progresses but does not exceed the T_{upp} for any scenario. The basecase exceeds this temperature for almost all of the occupied hours for days 3 to 5. The addition of a green or cool roof reduces the number of hours of overheating. In the future climate, by day 4 and 5, all the roofing scenarios are overheating for the majority of the day by exceeding T_{max}. However, only the basecase exceeds T_{upp} during hours of peak solar gain.

Indirect effects.

The indirect effects of the roofing scenarios can be assessed by analysing how the perturbed weather files impact the indoor temperatures compared to the TRY weather file. The perturbed results represent the combined effect of the direct and indirect impacts of the roofs. As the perturbations represent area averaged air temperatures 1.5 m above the roof surface for the output area, the indirect effects of the roofs are the impacts these air temperature perturbations have on the indoor environment.

The indirect effects are calculated by taking the difference between the perturbed and the TRY results for the percentage of occupied hours each comfort criterion is exceeded in Table 6. The impact of the microclimatic modelling, which subsequently altered the temperature and relative humidity in the weather file has little impact on the level of overheating within the building. This is evident in Table 6 where in the current climate scenario, the perturbed results all differ from the TRY results by less than 1%. In the future climate scenario, the impact of the microclimate is slightly greater. The differences in Table 6 show the perturbed basecase model overheats by 1% more than the basecase TRY model for criterion 1 and 2% for criterion 2. The difference between the irrigated green roof and dry green

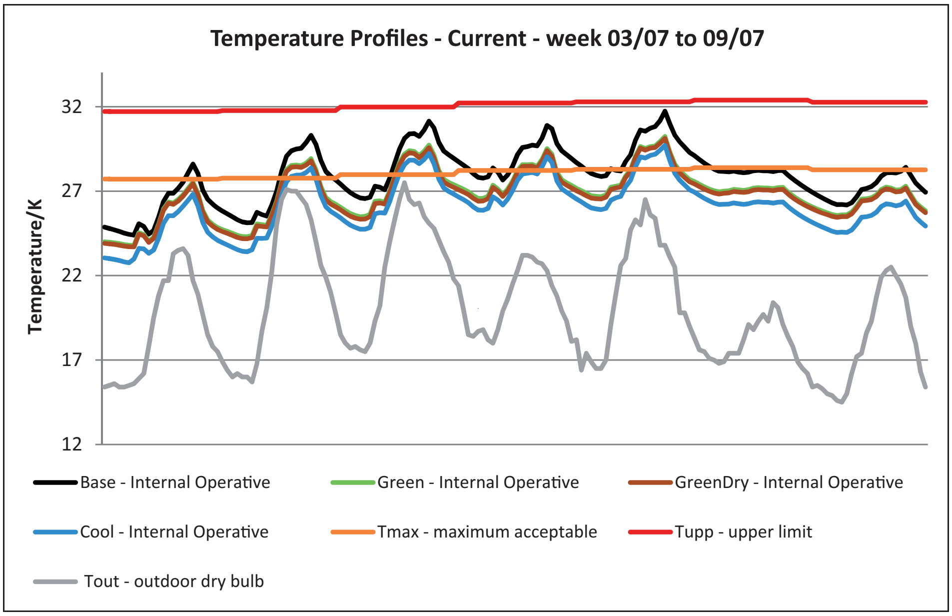

Figure 3. Operative temperature profiles for a typical week for each roofing scenario in the current climate.

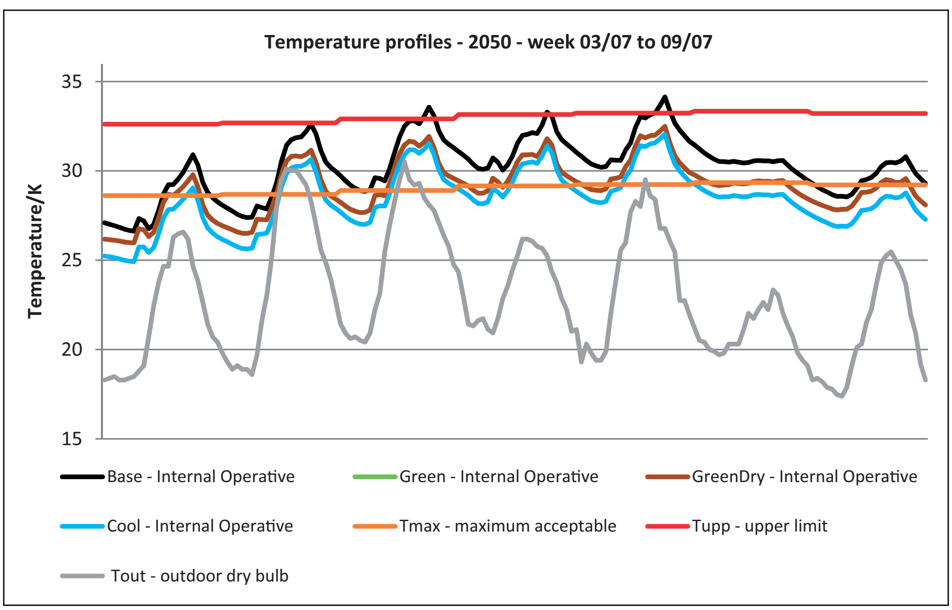

Figure 4. Operative temperature profiles for a typical week for each roofing scenario in the future climate.

roof is more evident when the microclimatic perturbations are included in the weather file. For criterion 2, the change from the basecase for irrigated green roofs is a reduction of 4% for criterion 2 and 1% increase for dry green roofs. The microclimatic effect of the cool roof impacts the results less than the green roof.

Impact of insulation. The results for insulated roofing scenarios are shown in Table 7. This analysis is only concerned with how the added insulation would impact internal comfort and also the effectiveness of the roofing strategies. Therefore, only the TRY weather file was used and the dry green roof was not modelled with added insulation.

Comparing the results from Tables 6 and 7, the added insulation reduces the number of hours of overheating for the basecase. In the current climate, the insulation decreases the percentage of hours of exceedance for criterion 1 by 1% and criterion 2 by 2%. In the future climate, exceedance of criteria 1 and 2 are

Table 7. Percentage of occupied hours that the insulated models exceed the CIBSE overheating criteria.

		Percentage of occupied hours exceeding criteria		
Scenario	Roof type	Criterion 1	Criterion 2	Criterion 3
Insulated TRY	Base	7	9	0
	Green	5	8	0
	Cool	5	8	0
Insulated TRY 2050	Base	26	23	1
	Green	25	21	1
	Cool	24	21	1

reduced by 2% and criterion 3 by 1%. The added insulation also reduces the effectiveness of both green and cool roofs in both climate scenarios. In the current climate scenario, both green and cool roofs now overheat for the same amount of time. Green roofs now exceed criteria 1 and 2 by an added 2% and 3%, respectively. Cool roofs have exceeded criteria 1 and 2 by an increase of 4% and 6%, respectively.

In the future climate scenario, the impact of the added insulation is even greater. For the basecase, the added insulation has a positive impact and reduces the exceedance of criteria 1, 2 and 3 by 3%, 5% and 1%, respectively. Green roofs now exceed the criteria 1, 2 and 3 by 12%, 9% and 1%. Cool roofs are affected the most by the added insulation and now see an increase in exceedance of 17%, 10% and 1% for criteria 1, 2 and 3. In the future climate scenario, cool roofs are still slightly more effective than green roofs.

Discussion

This study used the new CIBSE overheating criteria to assess the effectiveness of green and cool roofs at reducing overheating in a naturally ventilated office building. The roofs were modelled as being retrofitted onto an existing building, which currently has a poorly insulated roof. The analysis of the impact of the roofs can be split into direct and indirect effects. This is followed by the analysis of the insulated roofs.

Direct effects

Even with the addition of green and cool roofs, all modelling scenarios show a period of occupied hours where the building is overheating according to the new criteria. However, in the current climate, the basecase is the only scenario that overheats for more than 3% of the time. The addition of green or cool roof does reduce the percentage of hours that the building overheats. Cool roofs are the most effective option at reducing overheating within the building. Green roofs also reduce the level of overheating within the building, but to a lesser extent than cool roofs.

Drying green roofs only affect the results in the future climate scenario. Green roofs reduce air temperatures primarily by increasing the latent heat flux away from the roof, by increasing evaporation. As evaporation is proportional to temperature, this mechanism will be most efficient in the summer when the air temperatures are highest. If, however, the green roofs are assumed to dry out, their cooling effect will be reduced. A small cooling effect does remain however, resulting from the assumed marginally higher albedo of dry earth compared to a typical roof and also the lower thermal admittance. Hence, the difference between the irrigated and dry green roofs is more apparent in 2050.

In the future climate scenario, the basecase overheats for almost a quarter of occupied hours, making the building frequently an uncomfortable environment to work in. The input weather files used for 2050 were medium emissions (50th percentile). There could potentially be even larger increases in air temperatures, which would only exacerbate the level of overheating within office buildings.

This study concentrates on overheating within the building and thus only the summer period was evaluated. The results show that the reflective surface properties of cool roofs are more effective than green roofs at directly reducing heat transfer into the building and improving thermal comfort. As shown in Figure 5, the heat flux away from the building is greatest for cool roofs. This increased albedo is a more effective cooling mechanism than the latent cooling due to evapotranspiration of a green roof. However, when choosing what type of roof will be the most appropriate, the annual energy balance should also be taken into consideration.

Two studies that investigated the impact of cool roofs on the building energy use within London found that the application of the roofs resulted in an energy penalty in winter.[27,69] Studies have also shown that the added insulation provided by green roofs can reduce winter energy use for climates similar to

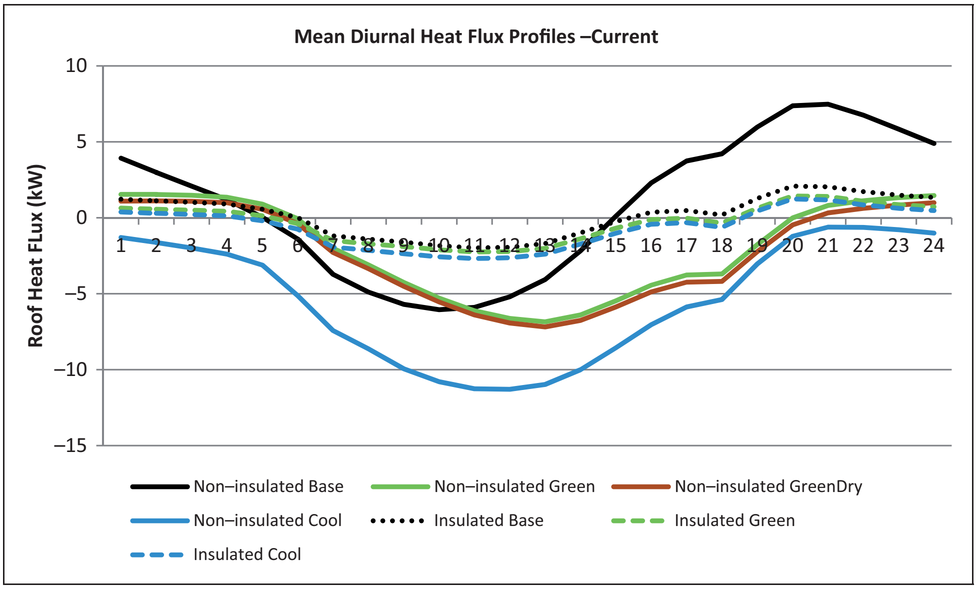

Figure 5. Mean diurnal heat flux of the both the non-insulated and insulated roofing scenarios for current climate, negative fluxes are out of the building.

London.[70] The choice of roof should therefore consider all these interrelated issues before a final decision is made.

Another interesting aspect of the heat flux profile in Figure 5 is how such a profile would contribute to the UHI effect. Green and cool roofs are used to mitigate the UHI effect, as they decrease the amount of heat absorbed into the fabric of the building and cool the surrounding microclimate. The basecase does the opposite, as solar radiation is absorbed throughout the morning and afternoon, the heat flux into the building increases and heat is stored in the thermal mass. At around 21:00 to 22:00, the direction of the heat flux reverses from a peak and heat begins to be emitted out of the building and contributes to UHI effect. This trend is typical of standard UHI profiles.[1]

Indirect effects

In terms of indirect cooling, green roofs are more effective than cool roofs. This is evidenced from the microclimatic modelling of the roofs, which showed that green roofs are slightly more effective at reducing daily rooftop air temperatures than cool roofs, for a variety of meteorological conditions. The results show that cool roofs are most effective when solar radiation is greatest, which usually precedes the daily temperature peaks. Hence, green roofs temperature perturbations are greatest in the evening and cool roofs in the morning.

Compared to direct effects, the indirect cooling of the roofing scenarios has little impact on reducing overheating. In current climates, the temperature and humidity perturbations have no significant impact on the internal operative temperatures whatever the roofing scenario.

In 2050, the indirect effects have a slightly greater impact on reducing overheating. UKCP09 projections for 2050 that are used in this study have days which are clearer and have higher temperatures of up to 3–5°C. The microclimatic modelling results in Table 5 show that green and cool roofs are more effective in clearer conditions. This is reflected in the overheating results, where the microclimatic cooling from the perturbations is more effective in the warmer, clearer conditions in 2050. As with the direct effects, the difference between irrigated and dry green roofs is also only noticeable in these drier conditions in the future climates scenario.

In terms of reducing overheating within this office model, the differences in fabric and surface properties have greater impact on heat transfer through roof than differences in reductions in rooftop air temperature. This study is limited to one single building model and consequently some assumptions have been made as to how indirect cooling of the roofs impacts the building. The study has assumed that the indirect cooling effect of the roofs at a height of 1.5 m above the roof surface will directly impact the internal environment by perturbing air temperatures and relative humidity. In reality and as has already been previously outlined in the literature review, the cooling effect at rooftop level will not have the same impact on the rest of the building. The impact of the roofs on the whole building will depend on the local topography, such as how high the roofs are situated and what the aspect ratio (Height/Width) of the street canyon is. The vertical cooling effect of the roofs was not modelled in ADMS. The perturbations used in the study were area averages at a rooftop level. Future work could investigate how the net effect of multiple green or cool roofs impact rooftop and street canyon temperatures and the consequent impact on the local buildings. This could then inform future planning and policy by providing evidence of the mitigation potential of wide-scale installation of green and cool roofs.

Effect of insulation

The level of insulation on the basecase roof was increased to meet current regulatory standards. The *U*-value for the non-insulated basecase roof was 2.76, non-insulated green roof was 1.36 and insulated basecase was 0.18. This had two main impacts on the levels of overheating. The first was that the added insulation slightly reduces overheating for the basecase. The second is that insulation significantly reduces the effectiveness of both green and cool roofs in both climate scenarios. Although the level of overheating is still reduced for all scenarios, the insulation significantly affects the heat flux in and out of the building compared to a non-insulated roof as shown in Figure 5. The insulation reduces the magnitude of the heat fluxes compared to non-insulated roofs and results in the green and cool roofs heat flux profiles being similar to the basecase roof. A cool roof has a constant negative heat flux as shown in Figure 5. This is in agreement with measurements carried out by Kolokotroni et al.,[27] where the surface of the cool roof was always at a lower temperature than the ceiling.

These results highlight issues that designers could potentially face when retrofitting buildings. If a roof has to be altered to meet current regulations, then the traditional approach would be to add insulation. But this traditional approach could be less effective at reducing overheating and energy use compared to using green or cool roofs. The non-insulated cool roof in study considerably outperforms the basecase insulated roof. The results also show how increased insulation levels negate a lot of the beneficial direct effects of the roofs. A potential solution to this could be more flexible regulations which are evidence based. Rather than having a fixed *U*-value that refurbished roofs must meet, the annual impact of the roofs on the energy use and comfort of the building could be assessed.

Comparison of old and new CIBSE overheating criteria

The new CIBSE overheating criteria has only recently been published and is more complex than the previous one outlined in the 2006 edition of CIBSE Guide A.[66]

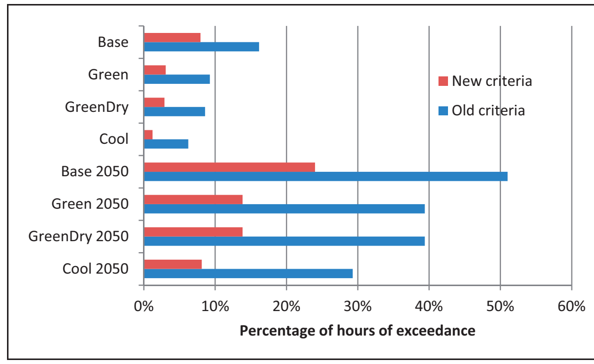

Figure 6. Comparison of old and new CIBSE overheating criteria for the TRY results.

The old criteria deemed overheating as the percentage of occupied hours that a building's operative temperature exceeded 28°C. The major difference between the two sets of overheating criteria is that the old criteria is stationary and does not take into consideration occupant's ability to gradually adapt to rises in external temperatures. By applying the two criteria to the results from this study, they can be compared to highlight some of the advantages of using an adaptive comfort criterion. Figure 6 shows the percentage of hours of exceedance for the new and old CIBSE overheating criteria for all the roofing scenarios modelled with the TRY. The results in the figure show the percentage of hours that two of the new overheating criteria are exceeded.

As the results from the roof modelling in Figure 6 show, the building exceeds the new criteria to much less of an extent than using the old criteria. This is especially true in the future climate scenario, where the basecase overheats for 50% of the occupied hours. The advantage of using the old criteria is that it is simple, quick to calculate and more easily interpretable. However, as these results show, they probably overestimate the extent of overheating. For future planning, this could potentially lead to overdesign and unnecessary costs in naturally ventilated buildings.

Conclusion

The modelling and analysis carried out in this study assessed the effectiveness of using green and cool roofs to mitigate overheating in an office in London for current and future climates. Green and cool roofs can represent low-cost, effective mitigation strategies when refurbishing buildings and have been shown in previous studies to both reduce energy use and overheating in London. The following conclusions can be drawn from the results of both the microclimatic and the building modelling and the application of the new CIBSE overheating criteria.

Table 8. Percentage of occupied hours that the models exceed the CIBSE overheating criteria when using a DSY compared to a TRY.

		Percentage of occupied hours exceeding criteria		
Scenario	Roof type	Criterion 1	Criterion 2	Criterion 3
DSY	Base	28	24	2
	Green	21	18	0
	Cool	12	11	0
TRY	Base	8	11	0
	Green	3	5	0
	Cool	1	2	0

The modelling demonstrated that in current and future climates, the office failed the new overheating criteria for all roofing scenarios. In the basecase scenario, the extent of overheating was greatest. In the future climate scenario, the basecase overheats for over a third of occupied hours demonstrating how the future extent of overheating within building will be exacerbated. For future refurbishments, it is likely that a number of strategies will be needed to mitigate the future risk of overheating. Although this study was limited to using a TRY to assess overheating, the results still highlight the potential of overheating within naturally ventilated buildings. As shown in Table 8, the use of a DSY would have increased the levels of overheating within the building, the TRY results reliably represent the relative impact each of the roofs has on overheating, however the absolute impacts are underestimated.

The type of refurbishments or alterations to buildings will also have to be carefully considered. By applying the regulatory standard insulation to the building, the effectiveness of the roofing strategies was decreased. This study shows further evidence that the most effective applications of green and cool roofs is on non-insulated roofs. If two alterations to the design of a roof are planned, then the combined impact of each change needs to be assessed.

The microclimatic modelling results showed that green and cool roofs can reduce air temperatures above a roof surface in London and that the magnitude of the cooling is dependent on the weather conditions. The cooling effect lasts longest during hot, still and sunny conditions, which correspond to when the UHI effect is most pronounced. Green roofs were shown to cool the rooftop microclimate for longer periods than cool roofs. The indirect effect of this microclimatic cooling at reducing overheating within the building was assessed by editing a TRY weather file with the area averaged temperature and humidity perturbations for a 250 m by 250 m area in the Victoria BID. The results from the building modelling show that this indirect cooling effect is very small and only slightly reduces the level of overheating. Further work needs to be carried out on how the net effect of green and cool roofs will impact buildings.

Cool roofs are the most effective strategy at reducing overheating within the office building in both current and future climates. Green roofs are slightly less effective than cool roofs. In future drier climate scenarios, non-irrigated green roofs lose some of their cooling capacity. The application of both green and cool roofs has to be analysed more holistically than in this study, if they are being considered as design options. This study specifically analysed the impact on summertime overheating. The impact of both roofing strategies on annual energy use needs to be carefully considered. A cool non-insulated roof was shown to be more effective than just insulating the current roof. A cool roof might be most effective at reducing overheating but could suffer from energy penalties in winter and other potential issues such as glare and material degradation. The insulation might not perform as well in summer but would increase comfort and save energy in the winter. As outlined previously, green roofs have other benefits other than their cooling capacity including providing extra insulation, but in a warming climate could require substantial irrigation.

The new CIBSE overheating criteria was used to assess the level of overheating within the model. The old criteria's effectiveness is due to its simplicity and interpretability. However, the results in this study highlight how the old criteria can overestimate the level of overheating, especially in warmer future climates.

The effectiveness of these strategies, along with their other costs and benefits should be considered in the context of other approaches that could be employed to reduce summertime overheating. A modelling study on London's domestic stock by Oikonomou et al.[71] found that the variation in internal temperatures, and thus potential exposure to heat stress, had a greater dependence on the thermal quality of the dwelling than the location within the UHI. The increase in overheating problems in London is being considered of such magnitude that it is likely that more than one strategy will have to be employed.[7] Green and cool roofs and other strategies to mitigate the UHI are likely to be an important role in managing summertime overheating in London and more work needs to be carried out to understand their other potential impacts on both buildings and the local microclimate.

Authors' contribution

All authors contributed equally in the preparation of this manuscript.

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References

1. Oke TR. The energetic basis of the urban heat island. *Q J R Meteorol Soc* 1982; 108(455): 1–24.
2. Watkins R, Palmer J, Kolokotroni M and Littlefair P. The London Heat Island: results from summertime monitoring. *Build Serv Eng Res Technol* 2002; 23(2): 97–106.
3. GLA. *London's urban heat island: a summary for decision makers*. London, UK: Greater London Authority, 2006.
4. Kovats RS, Johnson H and Griffith C. Mortality in southern England during the 2003 heat wave by place of death. *Health Stat Q* 2006; (29): 6–8.
5. UKCP09. UK climate projections 09, http://ukclimateprojections.defra.gov.uk (2010, accessed 10 May 2013).
6. DEFRA. *UK climate change risk assessment*. London, UK: DEFRA, 2012.
7. GLA. *Climate change adaptation strategy*. London, UK: Greater London Authority, 2011.
8. PHE. *The heatwave plan for England 2013*. London, UK: Public Health England, 2013.
9. Turton P. *Challenges for thermal management in a changing climate*. London, UK: The Modern Built Environment Knowledge Transfer Network, 2010.
10. CIBSE. TM36: Climate change and the indoor environment: impacts and adaptation. London, UK: Chartered Institution of Building Service Engineers, 2005.
11. Taha H, Akbari H, Rosenfeld A and Huang J. Residential cooling loads and the urban heat island—the effects of albedo. *Build Environ* 1988; 23: 271–283.
12. GLA. *The London plan*. London, UK: Greater London Authority, 2011.
13. LCCP. Commercial building stock and climate change adaptation: Costs, value and legal implications. London, UK: London Climate Change Partnership, 2009.
14. Takebayashi H and Moriyama M. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Build Environ* 2007; 42(8): 2971–2979.
15. Jacobson MZ and Ten Hoeve JE. Effects of urban surfaces and white roofs on global and regional climate. *J Climate* 2011; 25(3): 1028–1044.
16. Yaghoobian N and Kleissl J. Effect of reflective pavements on building energy use. *Urban Climate* 2012; 2: 25–42.
17. Akbari H, Menon S and Rosenfeld A. Global cooling: increasing world-wide urban albedos to offset CO_2. *Climatic Change* 2008; 94(3–4): 275–286.
18. Menon DM and Menon S. Regional climate consequences of large-scale cool roof and photovoltaic array deployment. *Environ Res Lett* 2011; 6(3): 34001.
19. Santamouris M. Cooling the cities – a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy* 2012, http://dx.doi.org/10.1016/j.solener.2012.07.003
20. Ray S and Glicksman L. Potential energy savings of various roof technologies. In: *DOE conference on the thermal performance of the exterior envelopes of whole buildings XI international conference*, Florida, USA, 5–9 December, 2010, paper no. 37.
21. Theodosiou TG. Summer period analysis of the performance of a planted roof as a passive cooling technique. *Energy Build* 2003; 35(9): 909–917.
22. Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A and Mihalakakou G. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy Build* 2001; 33(7): 719–729.
23. Jaffal I, Ouldboukhitine S and Belarbi R. A comprehensive study of the impact of green roofs on building energy performance. *Renew Energy* 2012; 43: 157–164.
24. Parizotto S and Lamberts R. Investigation of green roof thermal performance in temperate climate: a case study of an experimental building in Florianópolis city, Southern Brazil. *Energy Build* 2011; 43(7): 1712–1722.
25. Sfakianaki A, Pagalou E, Pavlou K, Santamouris M and Assimakopoulos MN. Theoretical and experimental analysis of the thermal behaviour of a green roof system installed in two residential buildings in Athens, Greece. *Int J Energy Res* 2009; 33(12): 1059–1069.
26. Zinzi M and Agnoli S. Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. *Energy Build* 2012; 55: 66–76.
27. Kolokotroni M, Gowreesunker BL and Giridharan R. Cool roof technology in London: an experimental and modelling study. *Energy Build* 2011; 67: 658–667.
28. Synnefa A, Santamouris M and Akbari H. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy Build* 2007; 39(11): 1167–1174.
29. Romeo C and Zinzi M. Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. *Energy Build* 2011; (2010): 58.
30. Jansz A. *Modelling the effects of green and cool roofs on the urban microclimate within the context of projected climate change*. MSc Dissertation, University College London, UK, 2011.
31. CIBSE. *TM52: The limits of thermal comfort: avoiding overheating in European buildings*. London, UK: Chartered Institution of Building Service Engineers, 2013.
32. Land Use Consultants & Green Roofs Consultancy. *A green infrastructure audit of the Victoria business improvement district*. London, UK: Land Use Consultants & Green Roofs Consultancy, 2010.
33. Mavrogianni A, Davies M, Batty M, Belcher SE, Bohnenstengel SI, Carruthers D, Chalabi Z, Croxford B, Demanuele C, Evans S, Giridharan R, Hacker JN, Hamilton I, Hogg C, Hunt J, Kolokotroni M, Martin C, Milner J, Rajapaksha I, Ridley I, Steadman JP, Stocker J, Wilkinson P and Ye Z. The comfort, energy and health implications of London's urban heat island. *Build Serv Eng Res Technol* 2011; 32(1): 35–52.
34. Hamilton I, Stocker J, Evans S, Davies M and Carruthers D. The impact of the London Olympic Parkland on the urban heat island. *J Build Perform Simul* 2014; 7(2): 119–132.
35. Carruthers DJ, Holroyd RJ, Hunt JCR, Weng WS, Robins AG, Apsley DD, Thompson DJ and Smith FB. UK-ADMS: A new approach to modelling dispersion in the earth's atmospheric boundary layer. *J Wind Eng Ind Aerodyn* 1994; 52(C): 139–153.
36. CERC. FLOWSTAR model, http://www.cerc.co.uk/environmental-software/FLOWSTAR-model.html (2013, accessed 10 May 2013).
37. Carruthers DJ and Weng WS. The effect of changes in surface resistance on temperature and humidity fields and fluxes of sensible and latent heat. *Boundary-Layer Meteorol* 1992; 60(1): 185–199.

38. Raupach MR, Weng WS, Carruther DJ and Huntd JCR. Temperature and humidity fields and fluxes over low hills. *Q J R Meteorol Soc* 1992; 118(504): 191–225.
39. CERC. ADMS 4 user guide, http://www.cerc.co.uk/environmental-software/model-documentation.html (2010, accessed 10 May 2013).
40. Hamilton I, Davies M, Steadman P, Stone A, Ridley I and Evans S. The significance of the anthropogenic heat emissions of London's buildings: a comparison against captured shortwave solar radiation. *Build Environ* 2008; 44(4): 807–817.
41. CERC. ADMS temperature and humidity user guide, http://www.cerc.co.uk/environmental-software/model-documentation.html (2010, accessed 10 May 2013).
42. Levermore GJ and Parkinson JB. Analyses and algorithms for new test reference years and design summer years for the UK. *Build Serv Eng Res Technol* 2006; 27(4): 311–325.
43. Thompson D. The Met input module (P05/01Q/10). The Met Office, http://www.cerc.co.uk/environmental-software/assets/data/doc_techspec/CERC_ADMS4_P05_01.pdf (2010, accessed 10 May 2013).
44. Carruthers DJ and Dyster SJ. *P07/05E/09: Boundary layer structure specification*. Cambridge, UK: Cambridge Environmental Research Consultants, 2010.
45. Met Office. Met Office Integrated Data Archive System (MIDAS) land and marine surface stations data (1853–current), http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas (2012, accessed 10 May 2013).
46. UKCP09. UK climate projections 09: user interface, http://ukclimateprojections-ui.defra.gov.uk/ui/start/start.php (2012, accessed 10 May 2013).
47. Belcher S, Hacker J and Powell D. Constructing design weather data for future climates. *Build Serv Eng Res Technol* 2005; 26(1): 49–61.
48. CIBSE. *TM48 –The use of climate change scenarios for building simulation: the CIBSE future weather years*. London, UK: Chartered Institution of Building Service Engineers, 2009.
49. Fuchs M and Hadas A. The heat flux density in a non-homogeneous bare loessial soil. *Boundary-Layer Meteorol* 1972; 3(2): 191–200.
50. Doll D, Ching JKS and Kaneshiro J. Parameterization of subsurface heating for soil and concrete using net radiation data. *Boundary-Layer Meteorol* 1985; 32(4): 351–372.
51. Anandakumar K. A study on the partition of net radiation into heat fluxes on a dry asphalt surface. *Atmos Environ* 1999; 33(24–25): 3911–3918.
52. Camuffo D and Bernardi A. An observational study of heat fluxes and their relationships with net radiation. *Boundary-Layer Meteorol* 1982; 23(3): 359–368.
53. Bohnenstengel SI, Evans S, Clark PA and Belcher SE. Simulations of the London urban heat island. *Q J RMeteorol Soc* 2011; 137(659): 1625–1640.
54. Porson A, Clark PA, Harman IN, Best MJ and Belcher SE. Implementation of a new urban energy budget scheme into MetUM. Part II: Validation against observations and model intercomparison. *Q J RMeteorol Soc* 2010; 136(651): 1530–1532.
55. Porson A, Clark PA, Harman IN, Best MJ and Belcher SE. Implementation of a new urban energy budget scheme in the MetUM. Part I: Description and idealized simulations. *Q J RMeteorol Soc* 2010; 136(651): 1514–1529.
56. Virk G, Jansz A, Mylona A, Mavrogianni A, Stocker J and Davies M. Microclimatic effects of green and cool roofs in London and their direct and indirect impacts on energy use for heating and cooling for a typical office building, 2014. Forthcoming.
57. Geoinformation Group. Cities revealed, http://www.geoinformationgroup.co.uk/ (2011, accessed 10 May 2013).
58. OS. Ordnance survey mastermap, http://www.ordnancesurvey.co.uk/products/osmastermap (2013, accessed 10 May 2013).
59. Oke TR. *Boundary layer climates*, 2nd ed. London: Routledge, 1987.
60. Hogenhout S. *Modelling the urban microclimate: a case study of the Barbican Estate in London*. MSc Dissertation, University College London, UK, 2010.
61. Sailor DJ. A green roof model for building energy simulation programs. *Energy Build* 2008; 40: 1466–1478.
62. Frankenstein S and Koenig GG. *FASST vegetation models*. Technical Report TR-04-25. Hanover, New Hampshire, USA: U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC/CRREL), 2004.
63. Demanuele C, Mavrogianni A, Davies M and Kolokotroni M. Using localised weather files to assess overheating in naturally ventilated offices within London's urban heat island. *Build Serv Eng Res Technol* 2011; 33(4): 351–369.
64. BRE. National calculation methodology (NCM), http://www.ncm.bre.co.uk/ (2009, accessed 10 May 2013).
65. DCLG. *Building regulations 2010: approved document L (Conservation of fuel and power)*. London, UK: DCLG, 2010.
66. CIBSE. CIBSE guide A: environmental design building. London, UK: Chartered Institution of Building Services Engineers, 2006.
67. British Standards Institution. *BS EN 15251:2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. London: British Standards Institution, 2007.
68. Kolokotroni M and Giridharan R. Urban heat island intensity in London: an investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Solar Energy* 2008; 82(11): 986–998.
69. Ascione F, Bianco N, de' Rossi F, Turni G and Vanoli GP. Green roofs in European climates Are effective solutions for the energy savings in air-conditioning? *Appl Ener* 2013; 104: 845–859.
70. Sailor DJ, Elley TB and Gibson M. Exploring the building energy impacts of green roof design decisions – a modeling study of buildings in four distinct climates. *J Build Phys* 2012; 35(4): 372–391.
71. Oikonomou E, Davies M, Mavrogianni A, Biddulph P, Wilkinson P and Kolokotroni M. Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. *Build Environ* 2012; 57: 223–238.