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Overheating and energy use in urban office buildings in a warming climate

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Abstract

Buildings are responsible for one-third of the UK's greenhouse gas (GHG) emissions. The move to reduce emissions has resulted in recent stringent building regulations primarily aimed at reducing heating and associated energy use, often by improving the building fabric's airtightness. However, internal gains dominated, highly–insulated and airtight non-domestic buildings will likely overheat in the projected warming climate, requiring energy-intensive cooling, thus diminishing the effectiveness of heating efficiency focused regulations. This research investigated the effects of the warming climate on overheating and energy use and resulting emissions in representative urban office spaces in London in the present-day and projected future climates using hourly dynamic thermal simulations. Findings suggest that airtight and highly–insulated office buildings in the temperate UK will overheat in the 2050s. Heating demand reduces by at least 36% in the 2050s but electricity consumption and summertime space conditioning will increase by at least 13% and 55% respectively when hybrid cooling is adopted to ameliorate overheating. Despite the increase, a mixed-mode ventilation strategy is one of the ways of achieving overall energy efficiency while meeting benchmark overheating and emissions targets. Current heating-focused legislation needs to be re-evaluated to account for the effects of the warming climate and overheating risks.

Keywords
climate change, energy consumption, greenhouse gas emissions, mixed-mode ventilation, natural ventilation, office buildings, overheating

1. Introduction

Anthropogenic global warming has led to unprecedented and unpredictable climatic changes. Global average surface temperatures increased by 1°C relative to pre-industrial levels in 2017 with a 0.2°C decadal rise.[1] The significant rise in temperature will profoundly impact energy demand and indoor thermal comfort in buildings. In the UK, the building stock and particularly non-domestic buildings account for 40% and 18% of the total greenhouse gas emissions, respectively.[2] Given the present-day temperate climate, achieving low or zero carbon energy generation and delivery while reducing energy demand and emissions from UK buildings calls for high levels of fabric insulation and airtightness. In contrast, UK Climate Projections predict milder winters and warmer summers throughout the UK. For instance, London is projected to experience a 2.7°C hotter and wet summer in the 2050s.[3,4] The effects of frequent higher temperature spells are energy-intensive for air-conditioned (AC) buildings and are discomforting for the occupants of naturally ventilated ones. By 2040, the Pan-European extreme summer heatwave of 2003 will be typical for London. By the 2050s, warm weather-related fatalities could witness a threefold increase with heightening summertime wellbeing anxieties.[5] Besides, a warming climate is likely to worsen indoor air temperature and quality, energy consumption and carbon emissions. Since the more intense and accelerating warming is now evident, buildings resilient to such extremes should be considered, in addition to the current insulation and heating efficiency centric regulations.

70% of the 2050 UK building stocks are likely to be from the 20th century with many non-residential structures lacking significant considerations of energy efficiency and decarbonization.

Conventional building regulations focus on greater insulation levels, which are aimed at energy efficiency, not necessarily summertime indoor overheating. Furthermore, fluid dynamic and hygrothermal characteristics of air and radiative temperature in London's urban and peri-urban built-up areas differ from their rural counterpart, culminating in an elevated urban heat island (UHI) effect. In addition, increased built densities in populated areas exacerbate summertime overheating and the effects of a heatwave. London temperatures have been found to be 4°C and 10°C hotter than the surrounding rural areas during a typical day and a hot spell respectively.[6,7] The affiliation between UHI and overheating's linear relationship is; therefore, increasingly being investigated by researchers because of neoteric recurrent UK-wide torridness. Similar to 2003 and 2006's heatwave, the combination of UHI and a warmer climate will further aggravate indoor overheating.[8] Consequently, health and productivity concerns of uncomfortable indoors necessitate the retrofit of many existing office buildings, as various climatic projections postulate higher cooling and lower heating energy demand trajectories for commercial buildings. Arguably, natural ventilation (NV) and mixed-mode ventilation (MMV) equipped buildings are seen as energy-efficient passive solutions with good indoor air quality (IAQ) and around 75% less carbon emission intensive than air-conditioned buildings.[9,10]

This paper investigates the viability of passive ventilation strategies as a recourse to indoor overheating in office buildings for present-day and projected future UK climates. The assessment criteria are obtained from UK Building Regulations Part L2A and Chartered Institution of Building Services Engineers (CIBSE) Guide A,[11] where overheating is defined as the number of hours operative temperature exceeds 25°C with 1% of the annual occupied hours, that is 25 h are allowed to exceed 28°C. Besides, good practice (GP) and typical practice (TP) benchmarks from Building Research Establishment[12] are considered for investigating the effects of ventilation strategies on energy use and carbon emissions. Four emission scenarios of the present-day test reference year (TRY) and design summer year (DSY) and projected 2050 TRY and DSY weather cases were explored for analyzing the resiliency of passive ventilation strategies in reducing overheating hours. Since the 2050s climate is projected to be hotter and passive ventilation may not perform satisfactorily, mixed-mode ventilation was also investigated for 2050 TRY and DSY. Urban London has been chosen as the study location as its climate is hotter than most of the UK, representing the worst-case scenario for indoor overheating in the UK.

The rest of the paper is structured as follows. The following section discusses performance metrics and climatic contexts, followed by the case study building in Section 3. Details of the simulation model are elaborated in Section 4, followed by the results and discussion in Sections 5 and 6. Finally, the conclusions are provided in Section 7.

2. Factors Affecting Building Performance

2.1 Indoor overheating and its assessment

Overheating is the period-dependent occupant thermal discomfort resulting from interactions between the building and the surrounding environment. It is the uncomfortable situation experienced due to threshold exceeding temperatures over a relatively extended period, typically days or weeks, as opposed to the repetitive, sometimes diurnal occurrences of short-duration temperatures above the comfort threshold. Contemporary airtight buildings' design shortcomings and inadequate background ventilation, coupled with elevated ambient temperatures due to a warming climate and urbanization-induced UHI effects are cited to be the likely reasons for indoor overheating. Moreover, contemporary lean low thermal mass construction lacks heat retention attributes, which aggravates indoor warming. Site-specific microclimatic factors such as the lack of vegetation and water bodies and thermal characteristics of surrounding built forms also manifest in varying heated effects where external temperatures' magnitude surrogates internal overheating.[13,14] Furthermore, the desire for outdoor views and clean aesthetics proliferated the construction of highly glazed commercial buildings, which exacerbates the greenhouse effect and resulting indoor overheating through radiative and operational heat accumulation. Consequently, the lack of mechanical ventilation during warm summer spells will reason overheated passive buildings. In contrast, mixed-mode (MM) ventilation supplements the cooling of air when natural ventilation is ineffective in extreme summer regimes, with the possibility of no or little overheating.

British Standards outline overheating with the following[15]:

A **Percentage outside range**: threshold discomfort temperature exceedance in occupied hours;
B **Degree hours criteria**: magnitude of the exceedance of total occupied hours the operative temperature (OT) surpasses the discomfort threshold; and
C **PPD-weighted criteria**: total occupied hours, the percentage of persons dissatisfied (PPD) according to a thermal comfort model's limit.

For Criterion A, the exceedance of 28°C expresses the frequency, not the severity. Criterion B covers both, assuming a linear relationship between exceeded temperature and discomfort. Fanger's adaptive thermal comfort model integrated Criterion C can assess free-running buildings where thermally neutral operative temperature (T_{op}) is 'neither too cool nor too warm' and external and internal environments are linearly related. Typically, Criterion A is used for assessing indoor thermal comfort where the thermal neutrality of predicted comfort (T_{c}) is:

$$T_{\mathrm{c}} = 0.33T_{\mathrm{rm}} + 18.8. \tag{1}$$

The running mean of the outside dry-bulb temperature (T_{rm}) is found using Equation (2):

$$T_{\mathrm{rm}} = aT_{\mathrm{rm-1}} + (1\text{–}a)T_{\mathrm{mean-1}}. \tag{2}$$

Here, a is constant (0.8). $T_{\mathrm{rm-1}}$ and $T_{\mathrm{mean-1}}$ are the running mean temperature and the average temperature of the preceding day, respectively. Instead of PPD calculation, British Standards impart a potential daily discomfort (PPD) model to satisfy Criterion C overheating metric using adaptive thermal comfort concepts. Thus,

$$PDD = \frac{1}{24} \sum_{\substack{\text{all hours} \\ \Delta T > 0}} F(\Delta T), \tag{3}$$

where ΔT is the difference between the T_{op} and T_{c}. The predicted fraction of people uncomfortable (F) is on voting either 'warm' or 'not'. Thus,

$$F = \frac{1}{1 + e^{(2.61 - 0.473\Delta T)}}. \quad (4)$$

2.2 Weather data

Typically, overheating is the extreme end of the temperature profile and one in eight summers is termed as a warm return period. The climate change adjusted 2006 CIBSE TRY and DSY files-based simulation weighs the success of benchmark annual energy consumption and avoidance of overheating of free-running buildings, respectively. DSY averaged from the increasing value of the dry bulb temperature metric of April–September as near extreme warm summer years. TRY is the representative year averaged from the historical baseline of the 1983–2004 period. These are morphing method centric, involving stretching and shifting the present-day observed time series for a monthly average statistical time sequence of the United Kingdom Climate Impacts Programme 2002 (UKCIP02) climate change scenario. This also includes 2080s low and medium-low emission scenarios for wide-scale resiliency analysis. However, the UK climatic projections also undergo periodic change and new algorithms centered 2016 release is based on the United Kingdom Climate Impacts Programme 2009 (UKCIP09) climatic model. This research is conducted before the latest release and with the 2006 dataset. In fact, the study shows that these two releases have shown no significant differences in assessing buildings' resiliency to climate change. For instance, overheating in present and future climatic scenarios employing both the CIBSE releases for all 14 UK locations sways little with similar findings in other published literature.[16–18] Even the absence of future high temporal resolution data with degree-day and dynamic simulation methods predict heating demand within a few percentiles of one another while cooling demand was slightly varied due to the examined region's low yearly cooling requirement.[19] Furthermore, the room temperature profile for a naturally ventilated office building is much worse than a predicted 2050s medium-high emission scenario. Despite this, morphed future weather data are one of the ways to help ascertain building overheating, and a few percentile differences in simulation results attributed to weather file release is rather dwarfed in this research by the exploration of the applicability of passive measures in the adaptive future-resilient building.

2.3 Energy and emissions trends

The built environment's energy and carbon count are climate-sensitive and undeniably, the expected warmer future scenarios will profoundly impact this sum. Between 1984 and 2004, the world's primary energy usage climbed by 49% and carbon dioxide (CO_2) emissions by 43%, with an annual average escalation of 2% and 1.8%, respectively. However, from 1973 to 2004, carbon emissions aggravated only 5%, a lower rate than the hiked energy consumption.[20] Besides, research point to decreased net total energy consumption in colder and an increase in warmer regions of the world. The Intergovernmental Panel on Climate Change (IPCC) HadCM3 (Hadley centre coupled model version 3) scenario-based study also points to most Southeastern US cities' increased cooling and heating load by 2080s, while opposite for the north. Then again, a curtain wall equipped commercial building witnessed decreasing heating energy trajectory from 1981 to 2010. The UK's increasing and decreasing cooling and heating energy trends are also similar. London's UHI and a warming climate arrogated 25% cooling and a 22% lessened heating load in a conventional AC building than rurality.[14,21,22] However, Shanghai's global climatic model based future weather study identifies high-performance building envelope's minimal impact on present and future energy ingestion.

Furthermore, 80% of the UK building stock is likely to remain standing in the 2050s. Commercial buildings account for 12% of the whole building stock, of which 30% are offices. Recent improvements also resulted in 40% air-conditioned equipped commercial building stock against 10% in 1990. Consequently, both heating and cooling will be affected since electricity and gas demand will increase by 30% and decrease by 43%, respectively, for the 2014–2030 period. Thus, air-conditioning will be responsible for 50% and 20% of the total building and national energy demand, respectively.[23,24] Energy demand from lighting and appliances will be 25% of the total. Besides, low or mid-rise buildings and lower floors are more energy and carbon emissions efficient than high-rise buildings and higher floors.[20,25]

However, a double skin façade (DSF) serves both daylight inclusion and façade-induced natural or mixed-mode ventilation for retrofit and new-build. Besides, daylight-coupled ventilation improves productivity and efficiency by 18% and 11%, respectively. Views outside improve mental function and memory by 10%–25%.[26]

That aside, the UK's low carbon built environment regulations earnestly targeted to curtail one-third of the yearly atmospheric secretion through this sector, as estimated emissions are above the 2050 aimed trajectory of the 2008 CCA and the 2016 Paris Climate Agreement goals.[24,27] Henceforth, the TP and GP energy and carbon emission benchmarks of energy consumption guide (ECG) 19 are recommended for office buildings (Table 1).[28]

3. Case Study Building and the Site

The case study building bearing a 0.81-acre site was placed through the Integrated Environmental Solutions Virtual Environment (IES VE) software's SunCast shade and shadow analysis targeting all seasons' daylight availability (Figures 1A,E,F). The study was conducted 1st and 15th days of each month initially. Then, monthly views were attained by merging these 2 (two) into 50% transparencies. Similarly, January–February, February–March, March–April and so forth merges were carried out with 6 (six) attained images. Again, 3 (three) merges of January–April, May–August and September–December were produced. The final merging was from these 9 (nine) obtained figures (Figure 1E). Additional merging from 12 (twelve) monthly outputs was for comparison (Figure 1F). The outputs are analogous to each other, as the yellow-colored part represents the best sunlit area.

Given the above, the westside core lessens solar radiation gain for the open-plan office where external noise is inhibited by both the stacks, the core and the atrium. Besides, roof pergolas are meant to minimize structural solar radiation gain. Furthermore, the red and blue areas are DSF or warm-stack or warm zone and the cool-stack or cold zone, respectively. Here, the thermally differing cool and warm region aids in buoyancy-driven ventilation. In addition, the northern inlets bear windbreakers to pacify turbulent incoming cool air (Figures 1D and 2A,B). Moreover, buoyancy flow expels convection air via the warm-stack's outlet. Additionally, 3.75 m floor-to-floor height also aids in buoyancy-driven natural ventilation. Tables 2 and 3 outlines the building's ventilation strategies and material

TABLE 1. Energy and carbon emissions benchmarks

	Good practice				Typical practice			
	Natural ventilation[a]		Air-conditioning[b]		Natural ventilation		Air-conditioning	
	Energy[c]	Emissions[d]	Energy[c]	Emissions[d]	Energy[c]	Emissions[d]	Energy[c]	Emissions[d]
Fuel	79		97		151		178	
Electricity	54		128		85		226	
Total	133	43.1	225	85	236	72.9	404	151.3

[a] Open-plan office. [b] Comparable to mixed-mode building. [c] Energy use: kWh/m^2.y. [d] Carbon emissions: kgCO$_2$/m^2.y.

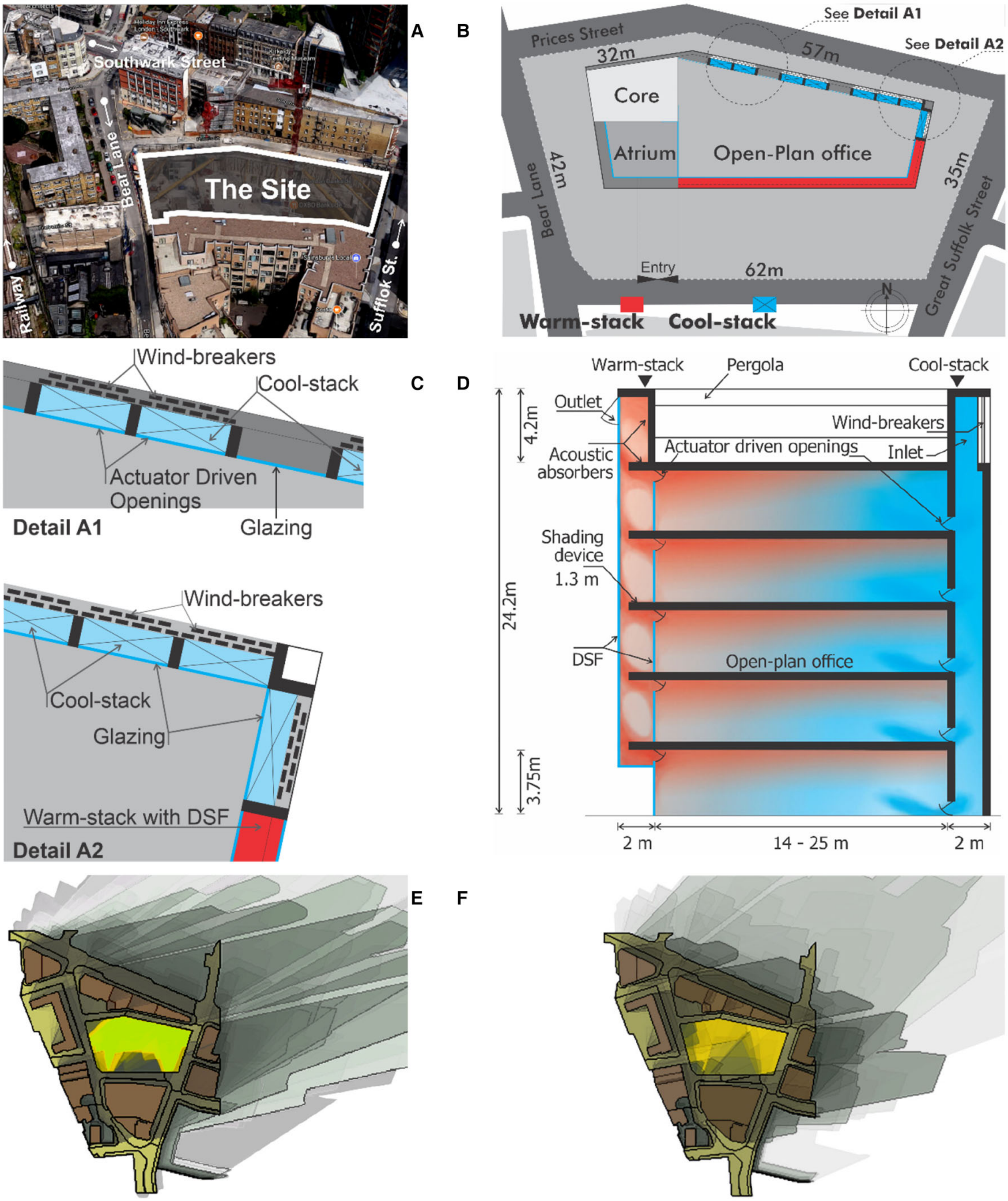

FIGURE 1. (A) Site view (maps.google.com), (B) schematic plan, (C) detail A1 and detail A2 of figure 1B, (D) transverse section, (E) image of 50 morphs and (F) image of 12 morphs

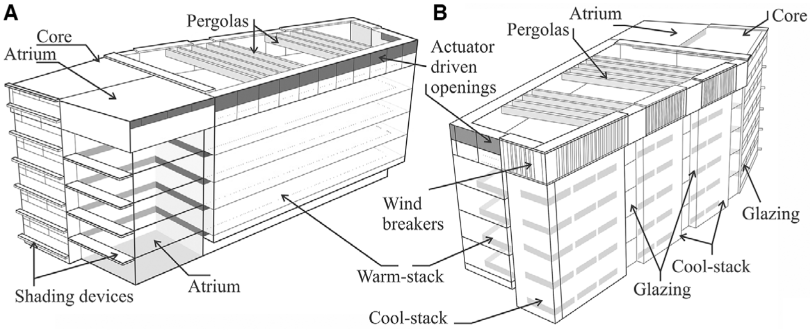

FIGURE 2. 3D view of the case study building. (A) Southwest and (B) Northeast view

TABLE 2. Opening attributes and their actuation strategies

Category	Location	Exposure	Co-efficient of discharge	Functions	Attributes/details	
Openable window or door	External	Exposed	0.4	Function A	Occupied hours	$ramp(ta,16,0,21,1) \mid gt(CO_2,1400,1200)$
	Internal	Not exposed				
	Cool-stack	Semi exposed			Night cooling	$gt(ta,18,4)$
	Warm-stack	Semi exposed		Function B	Occupied hours	$ramp(ta,30,0,35,1) \mid gt(CO_2,3000,2400)$
					Night cooling	$gt(ta,18,4)$
Closed window	External	Exposed	0.0	NA	Off continuously	

Note: *ta* and CO_2 are 'air temperature' and 'carbon dioxide' of the zone, respectively. Step function *gt*() denotes the fuzzy version of the greater than function and its third argument is the proportional bandwidth. The crack length is assumed to be 30% (usually after 5 years of operation) and the crack flow coefficient is 0.15 with a 30%–70% openable area attribute.

properties, respectively. Also, lean 14 m (Southeast) and 22 m (Northwestern) floor depth aid daylit interiors. Besides, a natural gas generator and boiler (90% efficient) deals building's services requirement. Taking the above into consideration, the subsections here detail the contextualization of the adoption of various low-carbon strategies as critical design components.

3.1 Double skin façade

Reviewed literature and initial ventilation and daylight simulation iterations engendered this research case. Century wide DSFs' realization led to its extensive adoption mostly in office buildings. Besides, the benefits of natural light and visuals further augment its urbane aesthetics with enhanced noise and thermal barriers. Reduced heat stress next to the double skin than orthodox glass boxed edifice and natural or mixed-mode ventilation's addition also justifies buffered cavity equipped DSF with low winter heat loss attributes. Additionally, efficiency and low operational cost incurred halved heating and cooling expenditures, compensating for its upfront cost.

In fact, designers' intent diverges partial or fully glazed DSF's configuration, and often, it consists of (a) exterior skin, (b) inner skin, (c) varying cavity depth (with natural or mechanical ventilation provision) and (d) shading devices. Here, both outer and inner skins can be partially or fully glazed. However, unfitting acknowledgment of building physics may detrimentally supersede its benefits. For instance, differing solar insolation owing to geolocation should entail varying DSF-integrated shading strategies and eventual success. Moreover, sunlight through DSF usually introduces glare and unexpected solar radiant heat at certain times of the day. Cavity shading, along with spectrally selective glazing, can negate such negatives. Cavity overheating may also be curtailed with spectrally selective Low-E glazing. Furthermore, a curtain covering half the transparent area can reduce 10% solar insolation gain.[29] Here, cavity shading close to the inner pane reduces 40% heat gain in a natural ventilation case. Moreover, experimental and CFD simulations of Venetian blinds in DSF show enhanced natural ventilation flow within the cavity with a significant interior heat gain reduction.[30,31] Furthermore, the DSF of a refurbished office is found to balance the whole life energy and carbon figures within 25 years of service life on the count of operational energy and carbon savings. Here, the duel panel outperforms single skin's life cycle energy and carbon performances at 98% and 83%, respectively.[32] DSF's success also bears on the cavity aeration, double-glazed exterior skin and night-purging scheme, which also enhances building security as traditional nighttime cross-ventilation requires large openings (2% of floor area).[33,34] Furthermore, heated-up cavity space can raise summertime air temperature to 10°C favoring the stack effect for natural ventilation and a fan-assisted strategy can avoid the top floors' short-circuiting effect. Shading devices, followed by the cavity width and then the tapering DSF cavity with an inclined outer layer are also sensitive to mixed modes' performance. Besides, a one-and-a-half-floor DSF's extension from the roof eliminates reverse heat flow.[35,36] Thus, this discussion justifies DSF's integration in urban settings, along with its effectiveness as a natural ventilation facilitator.

3.2 Daylight

Lighting's 13% share of the building energy consumption instigates daylight's efficient utilization in buildings.[37] Notably, diffuse natural light or daylight bearing low spectral solar heat gain profile halves artificial lighting load. Besides, avoiding summer and incorporating low hemispheric winter sun's radiation reduces cooling and heating loads, respectively. However, London's higher latitude imparts difficulty in harnessing

TABLE 3. Physical and thermal properties of the envelope

Type	Physical properties	U-value (W/m^2-K)
Ground contact concrete floor	London clay (0.75 m), cast concrete (0.15 m), mineral fiber slab (0.12 m), screed (0.05 m) and synthetic carpet (0.01 m)	0.2190
Internal ceiling or floor	Synthetic carpet (0.01 m), medium weight cast concrete (0.1 m) and ceiling tiles (0.01 m)	1.6216
Internal partitions	Gypsum plasterboard (0.013 m), air cavity (0.072 m) and gypsum plasterboard (0.013 m)	1.6598
External walls	External rendering (0.01 m), mineral fiber slab (0.13 m), medium density concrete block (0.1 m) and gypsum plasterboard (0.013 m)	0.2391
Roof	Aluminium (0.01 m), mineral fiber slab (0.15 m) and ceiling tiles (0.01 m)	0.2172
External glazed doors, windows and double skin façade	Pilkington 6 mm double glazed window with 12 mm air cavity gap (including 10% frames)	1.9773
Internal glazed doors and windows	6 mm Clear float glass with 10% metal frames	3.6643

both, since overly extended shading hinders views and favorable winter shortwave gain. Autodesk Ecotect Analysis software's yearly shading percentage calculation of the south façade devised the 1.3 m shading (Figure 1d). Here, the peak summer season (June–August), the entire summer (April–September) and the low winter sun see 70%, 60% and 12% shaded occupied office hours, respectively. Moreover, glazing side light-colored finish materials reflect in deeper daylight penetration. Besides, Venetian blinds or advanced glazings like inert gas-filled, low-E or spectrally selective and photochromic glazing, can further improve direct summer solar gain, glare and thermal performance.

Generally, 5% is the recommended average daylight factor (DF) for general office space with a minimum of 2.5%, measured at 0.85 m desk level from the floor. Moreover, 1/25 glazed area of a floor space accommodates 2% DF.[38] Besides, 25 m floor depth suffice for a successful daylit environment if it is lit from two sides. Since the examined building has a 225 m^2 fully glazed south façade (30% of the open-plan floor area) and a partially glazed north façade, both the average and minimum values are covered here. Consequently, DSF-based maximization of daylight and minimization of artificial lighting load of the studied building was achieved while accommodating natural ventilation strategy as depicted in Figures 1B,C,D and 2A,B.

3.3 Noise attenuation

Sound transmission loss (TL) of various building assemblies pivots noise attenuation attributes for attaining better naturally ventilated or mixed-mode buildings in urban settings. Characteristically, common building materials exhibit superior airborne sound TL characteristics than standard glazing unless construction or design fails. Therefore, the view assembly's sound attenuation undergoes special scrutiny. Typically, permissible levels for open plan office areas, reception, atrium, corridors, lobbies, restrooms and tea rooms are between 45–50 dBA except 55 for lift lobbies. Notably, composite envelope assembly can achieve TL of 55–60 dB.[39] Contrary to the single-glazed facade, a double-skin façade's enhanced sound insulation results in a quieter and more productive indoor setting. Besides, a natural ventilation strategy based double skin façade can sustain attenuation up to 27 to 35 dB, which equals the amount of a fully closed window. Similarly, 35 dB to 40 dB abatement is possible for multistory variants than other types. Moreover, acoustic insulation against specific types of noise can be achieved by modifying the type and composition of a glazing unit. Thus, street and airborne noise reduction up to 40 dBA is possible, with double skin facade having various design interventions.[40,41]

On the other hand, the examined site is within 60 dB noise level as per the Department for Environment, Food and Rural Affairs (DEFRA) Strategic Noise Map for London.[42] Moreover, London City Airport's flight path and associated 2011's noise contour map of 57 dB fall past 6.5 km from the site.[43,44] Hence, predominant UK construction materials and the typical composition of double skin facade are adequate for reducing 20 to 40 dB noise, while allowing natural ventilation possibilities in city contexts.

4. Dynamic Simulation Model

Generally, October–April and May–September are the winter and summer seasons, respectively, modulating building heat gain and ventilation profile. Monday–Friday is weekly and 9:00–17:00 h act as daily profiles. Opening, cleaning, and overtime extend 1 h at each end and the holidays are adjudged closed. The MacroFlo opening profiles (IES VE) are external or internal openable windows or doors, openable cool-stack and warm-stack and external closed windows. Here, the background or night cooling or out-of-office hour ventilation profiles (step function based) shut and open at 16°C and 20°C, respectively. Before 8:00 am, these opening profiles ensure neither a too-cold nor too-hot temperature profile. At midnight, they stay 10% open and gradually increase the opening to 40% at 8 am. This persists till 9 am and from 5 pm onwards, gradually minimizes to 10% by midnight again. Besides, dynamic thermal simulation ramp Function A based occupied hour ventilation profiles open and close at 21 and 16°C, respectively. Similarly, at 1200 and 1400 parts per million (ppm) CO_2 levels, they shut and open, respectively. Here, Function B based top floor warm-stack outlets open and shut at 35 and 30°C, respectively, and keep a higher temperature gradient for year-round buoyancy-driven ventilation between the two stacks. Additionally, uninhabitable warm-stack zone outlets shut and open at 2400 and 3000 ppm CO_2 levels, respectively, to maintain the necessary warmth (Table 2; Figure 2A,B). Then again, DSF-induced high-temperature stratification is nulled by the hybrid mode's local cooling without the energy-intensive background ventilation or cool-stack's fresh air intake.

Furthermore, infiltration rates for the atrium, restrooms and office areas are modeled as 1, 6 and 1 air change per hour, respectively. In addition, the building management system (BMS) actuates operable windows based on the MacroFlo opening profiles to ensure a thermally comfortable environment and indoor air quality.

4.1 Internal heat gain profiles

DSF, atrium and north glazing imparts a daylit environment with low artificial lighting requirement and counted carry half the requisite energy expenditure. That aside, the undertaken atrium occupancy is six users and one receptionist plus 10 counts for the core and toilets at any given time. Besides, 10 m^2/person density and energy-efficient lighting resulted in 4 W/m^2 of heat gain per 757 m^2 floor area excluding 137 m^2 of ancillary rare usage spaces, that is; lounges, coffee corners and utilities. Sensible heat gains from sedentary office work, computers and gadgets are also modeled as 80 W, 75 W and 5 W per occupant, respectively. Here, a diversity factor of 60% for personal computers is modeled considering turned-off hours and energy-saving mode.[45] Furthermore, warm-stack and cool-stack's lighting heat gain is counted as 4 and 0 W/m^2, respectively, referring to the rare usage of the latter.

5. Results

The overheating hours, energy consumption and carbon emissions benchmarks are assessed in natural and hybrid modes in six TRY and DSY simulation scenarios. The benchmark energy data are compared in Section 5.1. Floor level overheating is examined in the Section 5.2 using mean and standard deviation estimates, while Section 5.3 compares energy and carbon emissions. Finally, the Section 5.4 discusses the sensitivity of each month's energy consumption.

5.1 Energy consumption scenarios

Predominantly, envelope airtightness-centric enhanced insulation standards dominate temperate UK climates' heating-focused building regulations. However, simulation results exhibit 2050 climates leaning toward electricity-intensive cooling with less fuel-centric heating than present inclinations in achieving thermal satisfaction. Here, summertime expends of mixed-mode regimes bear 15%–21% of total energy compared to natural ventilation mode's 6%–8%—an extra 9%–13%, with similar findings in other research (Figure 3).[46,47] To compare,

a. Overall Energy: The 2050 TRY hybrid is 30% and 20% more energy-efficient than the present and 2050 TRY natural ventilation scenarios, respectively. Similarly, the DSY hybrid sees 26% and 15% less energy intensity than the present and 2050 DSY natural ventilation cases. Thus, mixed-modes are at least 15% more efficient than natural ventilation modes while meeting overheating benchmarks (Figures 3 and 7).
b. Heating plant and fuel loads: 2050 natural ventilation scenarios are at least 16% less heating plant load intensive than their present counterparts. Similarly, hybrid DSY is 46.6% and 35.6% less fuel-sensitive than the present and 2050 DSY natural ventilation cases, respectively. Therefore, the future climate is less fuel sensitive than present heating-centric trends.
c. Space-conditioning and electricity: Hybrid expends 22.42 and 49.12 megawatt-hour (MWh) more space conditioning energy for the TRY and DSY cases, respectively, that is, 5.5% and 11.84% of the total energy, respectively. Here, it inherits a 55% to 121% higher cooling load than the 2050 natural ventilation cases (Figures 3, 4 and 9). Its BMS exhausts 25% and 13% more electricity than the present and 2050 DSY natural ventilation scenarios in attaining energy and overheating benchmarks reflected by its higher and lower summer and wintertime energy necessity, respectively. Thus, the hybrid DSY is yearly 1.46% more energy-demanding than the respective TRY case in meeting the benchmark overheating target. Contrarily, the 2050 natural ventilation winter mode consumes more energy than the respective hybrid mode due to more fresh air intake in maintaining indoor air quality and thermal acceptability (Figure 3; Table 4).

Nevertheless, natural and mixed-mode strategies are less energy exhaustive than the GP or TP AC building. Hybrid exhibits nearly 60% and more than 75% less energy severity against GP and TP air-conditioned buildings' expenditure, respectively. Similarly, present TRY and DSY natural ventilation scenarios are similar to 5% and 45% to 47% less energy-dominating than GP and TP building targets, respectively (Figure 4). Furthermore, since 2005, energy-efficient technology inclination halved 17% of the UK end-use power usage on both actual and temperature-corrected basis. Despite this, commercial offices account for 8% or 1540 ktoe (oil equivalent) of the total 14% of the UK service sector's energy usage in 2015's estimate. Therefore, hybrids' integration cleaves 20%–30% or at least 308 ktoe of fuel while satisfying benchmark targets. This is noteworthy, since 2011 to 2018, fluctuations and volatility of steady international fuel sourcing affected its prices to hover between 280–600 pounds sterling (£) per thousand liters. Furthermore, the recent 40% of total fuel import leniency also factored up the urgency of an energy-efficient built environment.[37,48]

5.2 Comparison of overheating risks

Hybrid cases exhibit only 6 and 26 overheated hours and here, DSY's 1 h exceedance of 25 h benchmark is

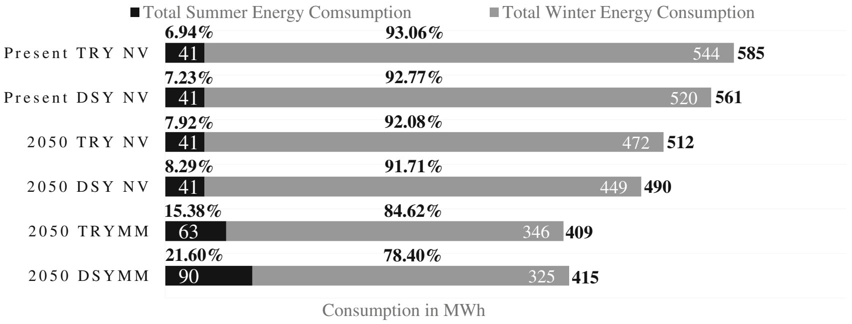

FIGURE 3. Energy usage comparison for examined weather scenarios and ventilation strategies

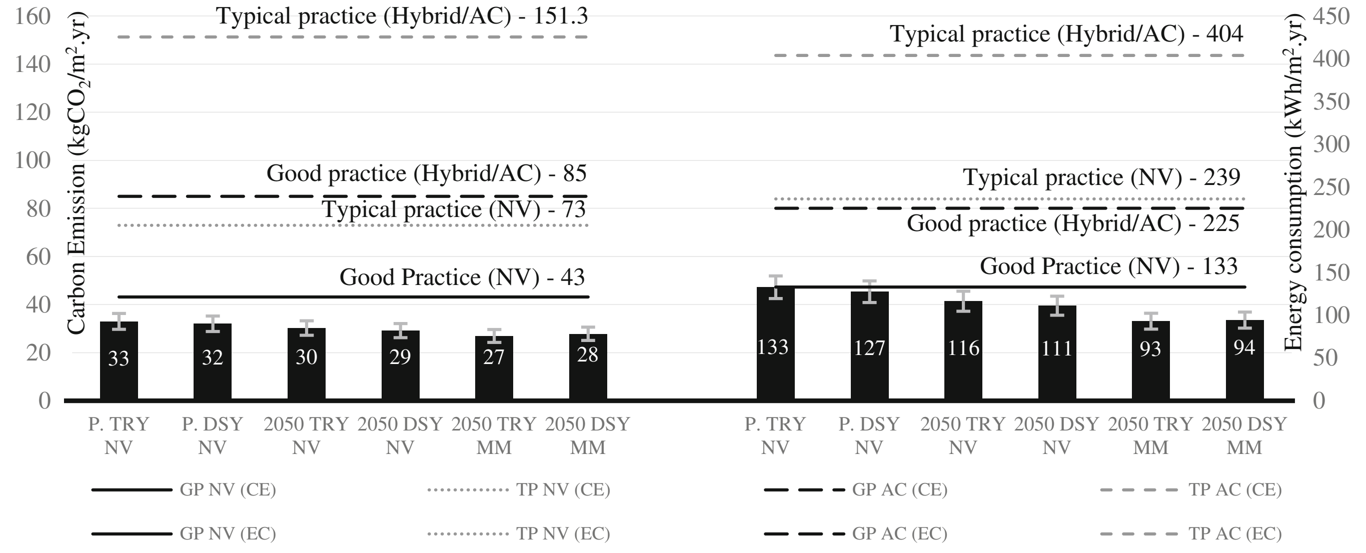

FIGURE 4. A comparison of energy use and carbon emissions against the good practice (GP) and typical practice (TP) benchmarks. Error bars are at 10%

TABLE 4. Annual energy use and carbon emissions in six climatic scenarios

Climate		Present-day		2050s			
Weather scenarios Ventilation strategy		TRY[a] NV	DSY NV	TRY NV	DSY NV	TRY MM	DSY[b] MM
Fuel, electricity and space-conditioning energy use	Total electricity (MWh)	142	142	142	142	164	191
	Total fuel (MWh)	443	420	370	348	245	224
	Total energy (MWh)	585	561	512	490	409	415
	Total space-conditioning energy (MWh)	443	420	370	348	268	273
	Wintertime energy (MWh)	544	520	471	449	346	325
	Summertime energy (MWh)	41	41	41	41	63	90
	Electricity intensity (kWh/m^2)	32.3	32.3	32.3	32.3	37.3	43.4
	Fuel intensity (kWh/m^2)	100.7	95.5	84.1	79.1	55.7	51
	Energy intensity (kWh/m^2)	133	128	116	111	93	94
Carbon emissions	Total carbon emissions (kgCO$_2$)	145 003	140 721	133 008	128 254	118 560	122 336
	Carbon emissions intensity (kgCO$_2$/m^2)	33	32	30	29	27	28

[a] Energy use and carbon emission intensive amongst all scenarios (winter heating dominates). [b] Electricity use intensive amongst all scenarios (summer cooling dominates).

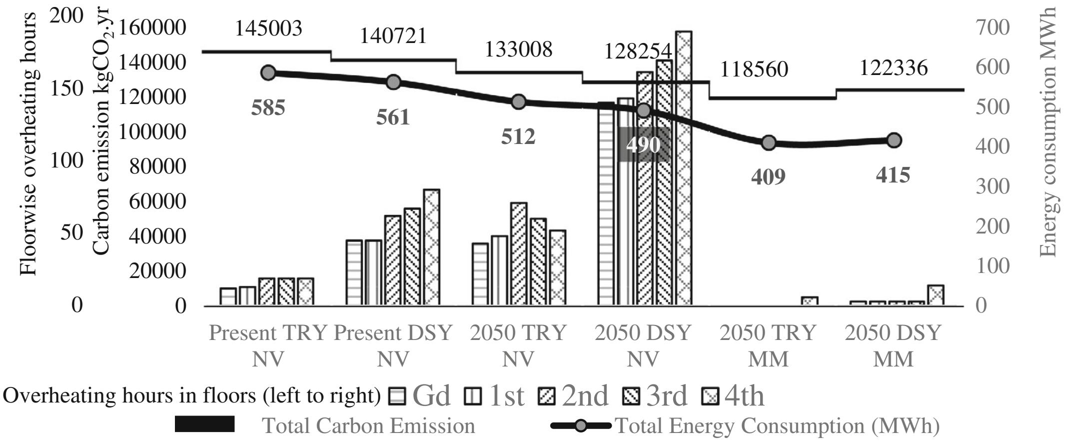

FIGURE 5. Correlation and comparison of overheating hours and energy consumption

TABLE 5. Comparison of energy use and carbon emissions

	Scenarios (TRY and DSY)	GP target	TP target	
Better performance or less energy usage intensity	Present NV	0 to 5%	45 to 47%	Better performance direction
	2050 NV	13 to 17%	52 to 54%	
	2050 MM	59%	77%	
Better performance or less carbon emission intensity	Present NV	23 to 26%	65 to 66%	
	2050 NV	30 to 33%	59 to 60%	
	2050 MM	68%	82%	

TABLE 6. Comparison of energy, carbon emissions and overheating hours at different weather scenarios (bold and shaded results are the higher values and exception cases)

Assessment criteria		DSY scenario Present NV	DSY scenario 2050 NV	DSY scenario 2050 MM	TRY scenario Present NV	TRY scenario 2050 NV	TRY scenario 2050 MM
Total energy consumption (MWh/y)		561	490	415	**585**	512	409
% less than the present scenario		NA	12.6%	26%	NA	12.4%	**30%**
Energy consumption rate (kWh/m^2.y)		128	111	94	**133**	116	93
NV	% less than the GP energy consumption (133)*	3.7%	16.5%	NA	EQ	12.8%	NA
	% less than the TP energy consumption (236)*	45.7%	53%	NA	43.6%	50.8%	NA
MM/AC	% less than the GP energy consumption (225)*	NA	NA	58.2%	NA	NA	**58.7%**
	% less than the TP energy consumption (404)*	NA	NA	77%	NA	NA	**77%**
Total carbon emission (KgCO$_2$/y)		140 721	128 254	122 336	**145 003**	133 008	118 560
% less than the present scenario		NA	8.8%	13%	NA	8.3%	**18.2%**
Carbon emission rate (KgCO$_2$/m^2.y)		32	29	28	**33**	30	27
NV	% less than the GP carbon emission (43)*	25.6%	32.5%	NA	23.2%	30.2%	NA
	% less than the TP carbon emission (73)*	56.2%	60.3%	NA	55%	59%	NA
MM/AC	% less than the GP carbon emission (85)*	NA	NA	67%	NA	NA	**68.2%**
	% less than the TP carbon emission (151.3)*	NA	NA	81.5%	NA	NA	**82.1%**
Overheating occupied hours in a year		299	**802**	26	82	274	6
% Overheating occupied hours in a year		11.96%	**32.08%**	1.04%	3.28%	10.96%	0.24%

* Reference value.

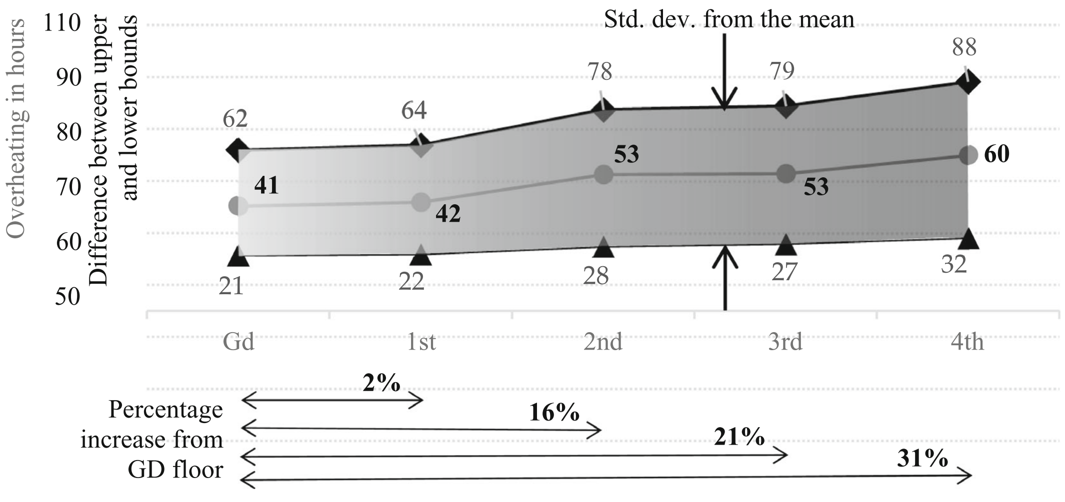

FIGURE 6. Floor level trends of mean overheating hours in standard deviation bounds (aggregated data for weather scenarios)

acceptable due to computational limitations in mimicking real-life space settings. Here, the present TRY observes an annual 3.28% overheating hours, against the 1% target with the same and 45% less energy consumption against the GP and TP values, respectively. Likewise, the present DSY scenario resort to 11.96% overheating hours in 5% and 47% less energy expenditure than GP and TP goals, respectively. Differently, hybrid scenarios attained at least 30% less

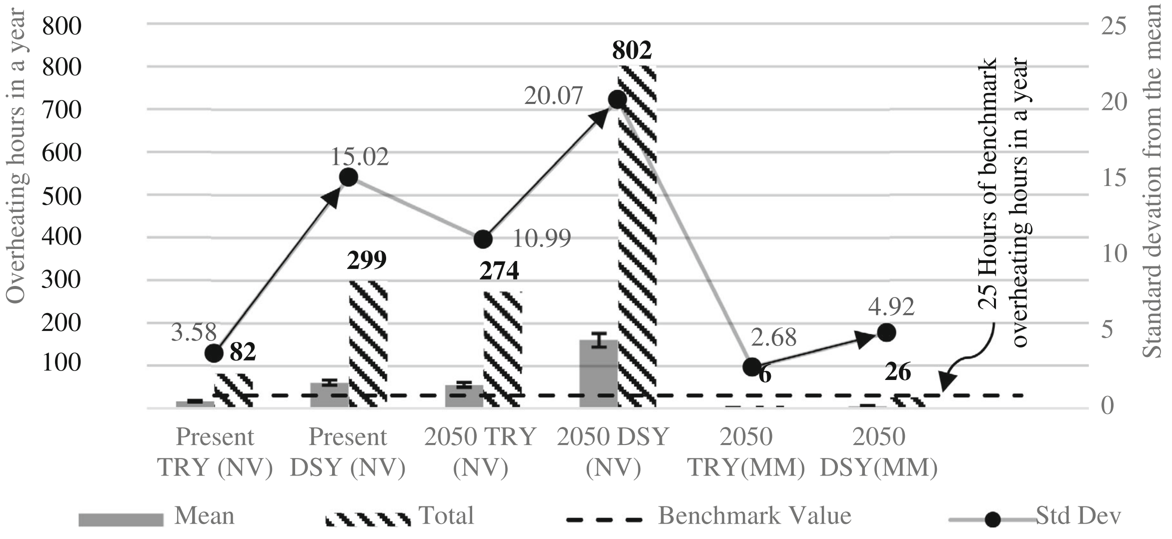

FIGURE 7. Comparison of overheating hours and ventilation strategies (with mean and standard deviation from the mean)

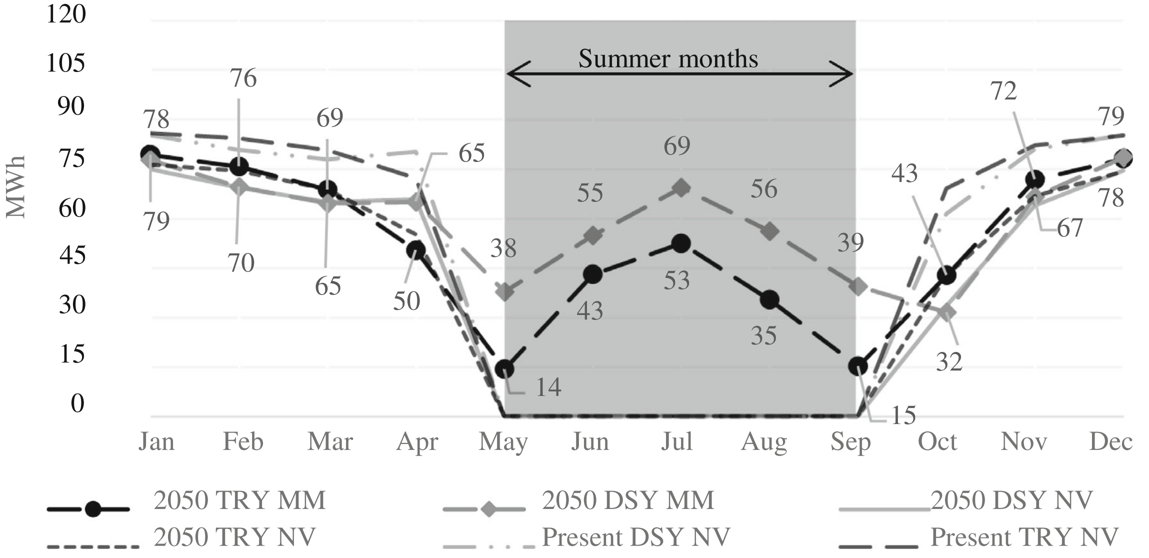

FIGURE 8. Monthly energy consumption for space conditioning

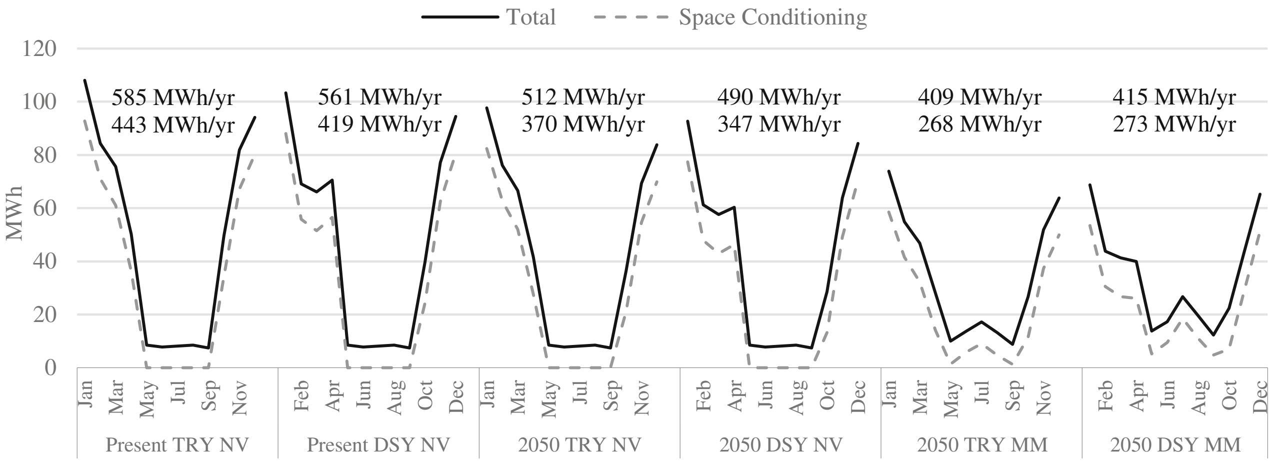

FIGURE 9. Annual total and space conditioning energy usage

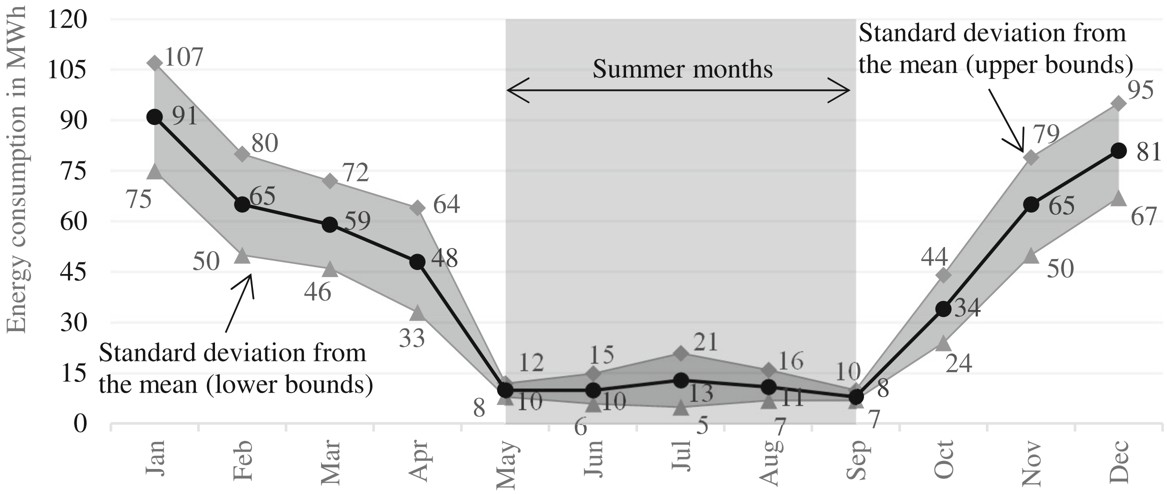

FIGURE 10. Aggregated mean energy usage data plot with standard deviation

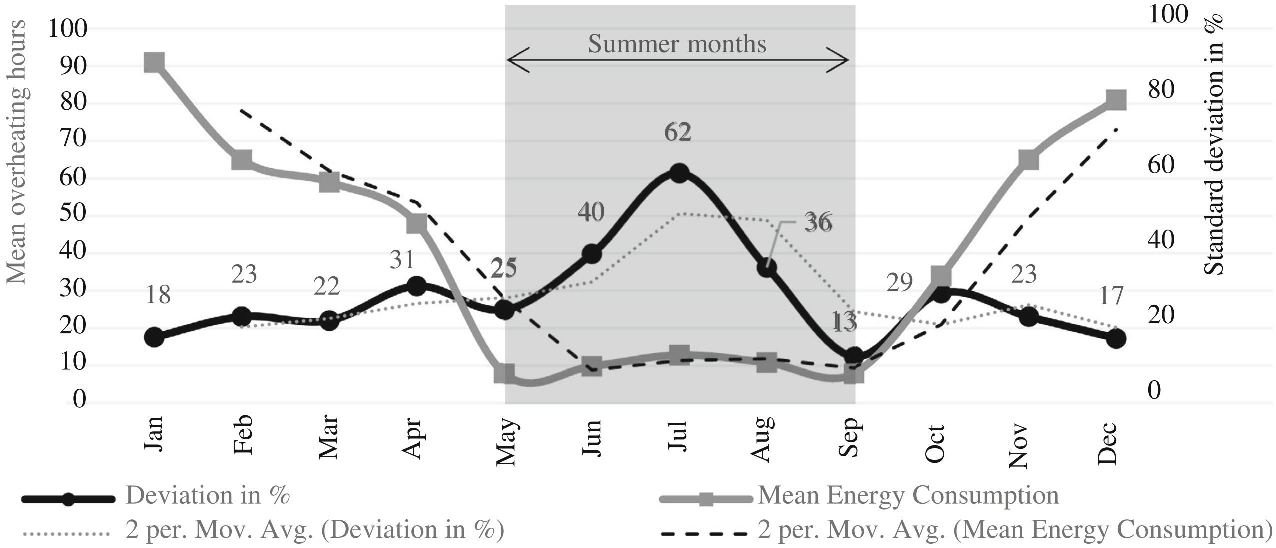

FIGURE 11. Aggregated mean energy use data with deviation in percentage (includes 2 percent moving average trendlines)

energy expenditure than the GP and TP values, while overheating exceeds only 0.04% extra. Natural ventilation modes of present and future DSY scenarios will witness at least 10.96 to 32.08% yearly overheating hours, which is contrastingly immense to hybrid TRY's low 1.04% overheating hours (Figures 4 and 7). Therefore, unlike natural ventilation modes, current fabric airtightness distinguished only the hybrid approach's thermal, energy and carbon emission targets attainment, with other researchers confirming the same. Besides, the standard deviation of the aggregated mean overheating hours distinguished upper floors' susceptibility suggesting early-stage upper-floor design interventions in addressing overheating (Figures 6 and 5).[49,50]

5.3 Energy consumption and associated carbon emissions

In the warming future climate, comfort cooling will throttle thermal comfort expenditure than space heating alone. For instance, July's space conditioning entails nearly 70% of its total energy count. These additional summer expenses are compensated in dwarfed winter estimates. In addition, hybrids' May, September and October months' space conditioning tallies below 40% of the total energy expenses, representing the annual's least energy usage state. Thus, mixed-mode excelled over both natural ventilation and air-conditioned modes in inhibiting carbon emissions (Figures 8 and 9).

Furthermore, the carbon emissions exhibit linear relation to overall energy consumption, except for mixed modes' low emission summertime electricity expenditure, resulting in 18.2% and 13.06% less carbon secretion against heating-dominated present natural ventilation scenarios, respectively (Figure 4). It is because emissions from combined cycle gas turbine based electricity generation are lower than other fuel sources. They emit 0.184, 0.214 and 0.254 $KgCO_2$/kWh of generation for natural, liquefied petroleum and refinery gas, respectively, compared to 0.267 $KgCO_2$/kWh for fuel oil. Nearly 50% of the UK power generation is fuel and gas-based and the rest are mostly from low-emission nuclear and renewables.[37,51]

All scenarios met GP and TP energy consumption limits except in the present case with 10% error bars, which equates to GP natural ventilation mode's target of 133 kWh/m^2.y (Figure 4). Here, the 2050 natural and hybrid modes' operations are at least 8.27% and 13.06% more emission-smart than present natural ventilation cases. Against a GP 43.1 $kgCO_2/m^2$.y carbon emissions target, the natural ventilation modes' emission efficiencies are 33, 32, 30 and 29 $kgCO_2/m^2$.y for present TRY, present DSY, 2050 TRY and 2050 DSY instances, respectively. Besides, against a GP 85 $kgCO_2/m^2$.y target hybrid TRY and DSY are 27 and 28 $kgCO_2/m^2$.y efficient, respectively. Additionally, natural ventilation modes are 7%–12% and 6%–7% energy usage and carbon efficient in the 2050s than present scenarios, respectively. All in all, GP and TP hybrid cases tamed overheating and are 23%–42% and 16%–35% less energy and carbon emission intensive than natural ventilation modes' respective targets (Table 5; Figures 4 and 7).

5.4 Aggregated energy use

All-weather aggregated monthly mean energy data illustrates winters' peaked responsiveness for November–April (Figure10). However, July month's sensitivity with the deviation in percentage and 2% moving average plot results in a 62% peak sum (Figure 11). This implies that July's overheating risk assessment may suffice instead of a yearly simulation run.

6. Discussions

In light of the above simulation results, it is rather essential in the adoption of passive and low-carbon intensive design recourse from the conceptual stage of any building design. Any legislative exertion shall be to acquire office building stocks that bear the aptitude of withstanding both the vehemence of winter and summer circumstances tallying climatic adversities. Otherwise, it may compromise occupants' comfort in the warmer future climates due to overheating and would trail behind in impeding carbon emissions from building operations. The adoption of a DSF-based hybrid strategy confirmed optimal thermal comfort for occupants while ensuring energy benchmark and associated carbon emission aspirations. Besides, automation advances of the BMS have eased building spaces to be run in both on-demand natural ventilation and air-conditioning mode and with varying degrees. On the whole, hybrid ventilation strategies have to be combined with the present need for a more airtight building to curb the heating intensity of the winter months and to offset the adverse effect of the warming climatic trends. Table 6 represents DSY vs TRY modes' energy consumption, carbon emissions and overheating value summaries.

In summary,

a. Energy intensity: Natural ventilation modes are more energy-intensive than hybrids due to the background ventilation and bulkier fresh air intake in maintaining air quality while attaining thermally comfortable indoors. On the whole, DSY scenarios are more energy-efficient than TRY except for the 2050 TRY's 1.46% compromise—indicating summer cooling or space conditionings' dominancy in the future (Table 6; Figures 3, 4 and 8).
b. Benchmark consumptions: All scenarios perform within benchmark GP and TP energy consumption targets except Present TRY, which is the same as the GP target. Hybrid cases are highest with 59% and 77% more energy-efficient than GP and TP targets, respectively (Figure 4).
c. Electricity and Fuel Use: Despite hoisted electricity consumption, the building is less fuel or otherwise energy-intensive in the future weather contexts than in present cases (Figure 3).
d. Space-conditioning count: Comfort cooling also arrogated prominence in the 2050 DSY and TRY hybrid scenarios with yearly 49.12 and 22.42 MWh more cooling energy intensity, respectively, in satisfying benchmark overheating values (Figure 3).
e. Carbon emissions intensity: Like energy expenses, future weather natural and mixed-mode cases are more carbon emission smart than present instances. For example, 2050 TRY hybrid mode is the least energy and carbon emission expenditure case among all (Figures 4 and 5).
f. Benchmark carbon emissions: Natural and hybrid scenarios are at least 23% and 67% more carbon-efficient than GP targets, respectively. Similarly, they are at least 65% and 82% less carbon-intensive than TP targets, respectively (Figure 4).
g. Overheating risk assessment: July month peaks overheating versus mean energy consumption's sensitivity suggests only its assessment instead of the whole-year simulation run. Besides, upper floors are at greater risk of overheating than lower floors urging early-stage design interventions (Figures 6, 10, and 11).
h. Overheating hours: Unlike natural ventilation, hybrid DSY and TRY satisfied occupants with a thermally acceptable environment and showed yearly benchmark exceedance of only 1 h for the DSY case (Figures 5 and 7).

7. Conclusion

Statutory routes are leaned on adopting stringent airtightness and hygrothermal attributes in pursuit of harnessing energy and carbon efficient built environments. However, studies indicate that insulation-centric energy efficiency and decarbonization agendas are prone to overheating in climate-projected warming trends unless effective ventilative cooling or passive strategies are adopted. Failing to address overheating in the workspace also risks the health, well-being and productivity of the office personnel. In light of that, this research assessed a representative case study building in London in benchmark overheating hours, energy consumption and associated carbon emissions in the present and climate-projected future weather scenarios. The natural and hybrid ventilation strategies bearing present-day airtightness and fabric attributes are assessed against good and typical practices of energy consumption and carbon emissions while overheating is the key evaluated variable.

The findings of this research exhibit that natural ventilation coupled airtight fabric-based low-carbon outlook is susceptible to overheating despite energy consumption and carbon emissions being within legislative trajectories. We know that typically naturally ventilated buildings are at risk of overheating on a warm still summer day with little air movement. Besides, a top-notch air-conditioning system's thermal satisfaction attainment is more energy severe than passive cooling. However, the incorporation of a highly sealed envelope with the passive mixed-mode ventilation strategy of this study achieved overheating hours, energy and carbon emission benchmarks.

Further research in passive design strategies like earth-coupled ventilation, solar tower or chimney, windcatcher and phase change material-based façade as thermal modulation and retention techniques have the potential to ameliorate overheating risks for the current and future climatic trends. These approaches can be adopted alongside a hybrid ventilation scheme for attenuating the overheating risk of new or retrofitted building stocks. In reality, an inefficient ad-hoc cooling system will be a likely scenario in future climates if not retrofitted by then for thermal comfort intentions. Nevertheless, the severity of built environments' carbon emission scenario is also understudied owing to the lack of UHI data. Integration of indoor warming potential due to UHI and climate projections is also one of the many possibilities of overheating risk study since both are highly site-specific. Besides, optimization of natural and mixed-mode ventilation control algorithms can be a part of future similar studies for thermal comfort and energy efficiency measures.

Disclosure

The authors have no conflicts of interest to declare.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Nomenclature

ΔT	the difference between the operative temperature (T_{op}) and thermal neutrality of the predicted comfort (T_{c})
AC	air-conditioned
BMS	building management system
CIBSE	Chartered Institution of Building Services Engineers
DSF	double skin façade
DSY	design summer year
F	predicted fraction of people uncomfortable
GP	good practice (for energy and carbon emissions of buildings)
MM	mixed-mode
MMV	mixed-mode ventilation
NV	natural ventilation
PPD	percentage of persons dissatisfied (%)
T_{c}	thermal neutrality of the predicted comfort
TL	the transmission loss of sound waves
$T_{\mathrm{mean-1}}$	the average temperature of the preceding day (°C)
T_{op}	operative temperature (°C)
TP	typical practice (for energy and carbon emissions of buildings)
T_{rm}	running mean of the outside dry-bulb temperature (°C)
$T_{\mathrm{rm-1}}$	running mean temperature (°C)
TRY	test reference year
UHI	urban heat island

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