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Comparative assessment of night ventilation performance in a nearly zero-energy office building during heat waves in Brussels

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ABSTRACT

With increasing urbanization, overheating intensifies, resulting in a greater risk of indoor overheating in commercial buildings, which already have high internal gains. The impact of urban climate on the cooling energy needs of buildings has been extensively researched. However, the building performance during extreme heat events needs further investigation to reduce the energy demand from the grid during critical events and to ensure an acceptable indoor thermal environment. Here, a comparative assessment approach for natural and mechanical night ventilation performance to reduce indoor overheating and energy needs of a nearly zero-energy office building in Brussels, Belgium, was evaluated for the heat wave and non-heat wave periods in urban and rural microclimates, using calibrated thermal-energy simulations. The analysis indicated that active cooling with natural night ventilation was more effective during heat waves than other cooling strategies. In addition, natural night ventilation was also effective in maintaining safer levels of heat index values in the reference office compared to other strategies. Natural night ventilation reduced overheating by 0.39 °C in the urban microclimate and 0.50 °C in the rural microclimate relative to the Baseline. Considering the cooling energy use, natural night ventilation had no significant impact. In contrast, mechanical night ventilation increased energy use by 0.54 kWh/m^2 in urban microclimate and 0.40 kWh/m^2 in rural microclimate due to prolonged ventilation fan operation in the reference office building. The presented findings in the paper lead to the formulation of design guidelines, recommendations for future practices and identifying needs for further research.

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
DX	Direct Expansion
EN	European Norm
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IOD	Indoor Overheating Degree
ISO	International Organization for Standardization

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KPI	Key Performance Indicator
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
SET	Standard Effective Temperature
SCORPION	Super COmputeR ProcessIng wOrkstatioN
UHI	Urban Heat Island
VRF	Variable Refrigerant Flow

1. Introduction

1.1. Study background

Growing global urbanization has increased population concentration, natural surface loss, and living space expansion to above and below the ground. All of these factors affect the balance of solar radiation, heat retention, and water penetration, altering the climate characteristic of cities [1]. Due to the Urban Heat Islands (UHI), the ambient temperature in cities is often higher than in surrounding rural areas. This phenomenon has been well documented in over 400 cities worldwide [2]. Human activities significantly alter the environment in large urban areas, resulting in unique meteorological and climatological characteristics, deterioration of indoor thermal comfort, and the corresponding increase in cooling energy demand during summer, creating extra stress on the existing grids [3].

Urban overheating is caused by various factors, including the thermal characteristics of the materials used in cities, the heat humans have released, the radiative geometry of canyons, the urban greenhouse effect, the reduction of evaporative surfaces, etc. [4]. Temperature differences between urban and rural areas are often maximum during nighttime. This is because cities retain much heat stored in buildings, roads, and other structures at night, whereas rural areas cool off more quickly. As a result, the most considerable urban-rural temperature difference, or maximum magnitude of the urban heat island, occurs in the evening or at nighttime. From the analysis of data collected using 101 Asian and Australian cities in Ref. [5], the magnitude of UHI can range from 0.5 °C to 11 °C, with an average value close to 4.1 °C. A similar analysis using data from 110 European cities in Ref. [6] revealed that the magnitude of UHI varies between 1 °C and 10 °C, with an average maximum value close to 6 °C. Urban overheating adversely impacts cities' environmental quality [7].

The findings from Ref. [8] indicated that the night air temperatures in urban areas were frequently 3 °C–4 °C greater than those in nearby non-urban areas. This results in cooling loads that are, on average, 13% higher in buildings in urban areas than in rural areas. Due to the UHI effect, urban populations are more vulnerable to heat exposure than rural populations [9]. Cooling demand has increased throughout many nations, mainly commercial buildings, in recent decades. The need for building cooling rises as summer weather becomes more extreme, internal and solar heat gains and comfort expectations rise [10]. Given the increasing cooling demand in moderate climates, night ventilation may provide many potential benefits, like energy savings and indoor thermal regulation. The exposed thermal mass of a structure can be cooled via natural or mechanical night ventilation to act as a heat sink the following day whenever the nighttime exterior air temperature is low enough [11]. Natural night ventilation is provided in Belgian office buildings [12], like Renson in Waregem [13].

1.2. Literature review

From the existing literature, the relevant studies that deal with night ventilation performance are reviewed in Table 1, including the study results and key findings. The studies from Ref. [14] found that the diurnal variation in indoor and outdoor temperature gradually increased with an all-day closed state, mechanical night ventilation, and natural night ventilation. A combination of night ventilation and thermal mass strategies proved to be the most effective method for maintaining an adequate indoor thermal environment from studies [15]. The studies from Refs. [16–18] indicated that various parameters like outdoor environment, thermal mass, etc., affect the performance of night ventilation and cause discrepancies in indoor thermal environment. The results from Ref. [19] found that night ventilation was an effective strategy in providing summer thermal comfort in a low-energy heavy office building, and [20,21,29] indicated that night ventilation was particularly adequate when there is a significant change in the ambient temperature between day and night.

In addition, parametric simulation results from Ref. [22] showed that the night ventilation equipped with daytime air conditioning assured the ideal thermal comfort and energy-saving benefit. In this study, this configuration is adopted for performance assessment. The findings from Ref. [23] found that natural night ventilation would only moderately help a typical air-conditioned office building, and since fans need additional power to operate during the night, mechanical night ventilation would demand more energy use. This study further provided solutions to increase the effectiveness of night ventilation in buildings like exposed thermal mass, west orientation, reduced glazing ratio, reduced internal gains, increased airtightness, etc. The above findings were supported by Ref. [24], which showed that the impact of night ventilation on the building performance depends on the structure and design, climate, location, applied air flow rate, thermal mass, and assumed operational conditions. However, night ventilation strategies come with their drawbacks. Natural night ventilation is generally unstable, and its efficiency and effectiveness depend heavily on factors like the local temperature, building orientation, room depth, window size, and automation [25].

These factors affect the ability of night ventilation systems to provide optimal performance in real-world scenarios. Furthermore,

Table 1
Summary of existing literature on the night ventilation performance in buildings.

Location	Method	Microclimate	Building features	Study results	Key findings	Reference
Shenyang, China	Simulations using DeST	Not specified	A 2-story ultra-low energy office building with a high heat transfer coefficient and high-performance envelope.	The variation in peak indoor and outdoor temperatures was 4.47 °C, 6.6 °C, and 8.54 °C with all-day closed state, mechanical night ventilation, and natural night ventilation.	The night ventilation impact on the building's indoor temperature was significant. Night ventilation can decrease indoor temperature and also increase indoor and outdoor temperature variations.	Li et al. [14]
Nowy Kisielin, Poland	Observations using measurements	Rural	Experimental rooms with light, heavy, and very heavy construction located on the south facade.	As per the weighted exceedance analysis of temperature, night ventilation provided the least benefit with a reduction of 37.5%, increasing thermal mass provided a marginally higher reduction of 51.6%, and combining both methods produced a significantly higher reduction of 77.3%.	In the high thermal mass room, using night ventilation did not significantly reduce the number of hours of exceedance. The indoor temperature variations are significantly increased using night ventilation in a lightweight construction that will cause poor thermal comfort.	Kuczyński et al. [15]
Eugene, USA	Observations using measurements	Not specified	L-shaped buildings with a south building for academic and administrative purposes and a north building for student housing	The variation in thermal mass's hourly heat loss remained largely constant through the night from 0.095 to 0.596 °C. Outdoor conditions during each campaign help to explain this discrepancy partially.	Overall, night ventilation in the reference building performed well when functioning correctly, but many ways exist to improve it and return its energy efficiency to its as-built level.	Mhuireach et al. [16]
Chongqing, China	Simulations using EnergyPlus, jEPlus, and SimLab	Not specified	Multistory office building	Between 1991 and 2050, the effects of global warming increased by 13.2% and 18.7%, as did the annual night ventilation hour and the amount of sensible heat dissipated by night ventilation.	The ventilation hours, cooling time, and residual heat amount for future climate scenarios increased slightly. Due to increased scorching days, the night ventilation hours are reduced in the summer.	Shi et al. [17]
Aalborg, Denmark	Experimental using test chambers and measurements	Not specified	An office room model with dimensions of 4.2 m (L) × 3.6 m (W) × 2.5 m (H).	Due to the high gradient velocity and temperature, the convective heat transfer coefficients of the nine sections at the ceiling were very different.	Activating the building's thermal mass significantly affects night ventilation efficiency.	Guo et al. [18]
Kortrijk, Belgium	Simulations using TRNSYS-COMIS	Not specified	Low-energy heavy building, well insulated with exposed concrete ceilings.	Weighted excess hours of 6 h for night ventilation with an earth-to-air heat exchanger and 61 h for only night ventilation.	Natural night ventilation delivered good summer thermal comfort. It is more efficient with earth-to-air heat exchangers.	Breesch et al. [19]
Aarhus, Denmark	Simulations using EnergyPlus, jEPlus, and SimLab	Not specified	Multistory office building	The most sensitive parameters for night ventilation performance are window-to-wall ratio, convective heat transfer coefficient, internal thermal mass, and mechanical night ventilation rate.	Different night cooling solutions have very different thermal comfort performance and cooling energy efficiency capabilities. Night ventilation paired with daytime air conditioning is recommended for optimal thermal comfort and energy-saving benefit.	Guo et al. [22]
Southeast England, UK	Simulations using 3 TC	Not specified	Cellular office room with heavyweight, medium weight, and lightweight construction.	Night ventilation decreases energy consumption by 5% and peak plant capacity by 6%. The energy savings increased for heavyweight buildings with low glazing ratios and high infiltration rates.	Natural night ventilation was found to benefit an air-conditioned building marginally. Mechanical night ventilation increased energy use due to fans. Night ventilation could increase energy savings if building parameters like exposed thermal mass and west orientation are optimized with low-energy design principles.	Kolokotroni and Aronis [23]
London, UK	Simulations with IESVE	Urban Rural	Lightweight and heavyweight office buildings.	Annual cooling load ranges from 6.5 to 39 kWh/m^2 in 2000 and 16.5 to 59 kWh/m^2 based on medium to high internal gains. The sensible cooling load increased from 46% in a lightweight building without night cooling in the city center to 90% in a heavyweight construction with night cooling in reference sites in 2050.	Night ventilated offices that use natural means have less cooling demand and are better for environmental impact. In the future, heavyweight construction will significantly increase overheating hours even with night ventilation.	Kolokotroni et al. [33]

(*continued on next page*)

Table 1 (*continued*)

Location	Method	Microclimate	Building features	Study results	Key findings	Reference
Brussels, Belgium	Simulations using TRNSYS-COMIS	Rural	Heavy building with exposed ceiling, heavy façade, raised floor, and light internal walls.	Baseline with extra thermal mass and baseline with top cooling and ventilation gave a higher probability of comfort in average weather. Baseline with top cooling and ventilation gave a high comfort probability in warm weather.	Natural night ventilation can only handle specific weather scenarios and does not guarantee high thermal comfort in warm weather. Night ventilation must be combined with top cooling and thermal mass to ensure good thermal comfort while reducing performance uncertainty in a warming climate.	Breesch and Janssens [34]
London, UK	Simulations using 3 TC	Urban Rural	Cellular office room with heavyweight, medium weight, and lightweight construction.	The cooling energy demand ratio with no night cooling in rural London was 0.86, and with night cooling was 0.83 and 0.84 in 1999 and 2000. With optimized thermal mass, the ratio was 0.85 and 0.82; with night cooling, the ratio fell to 0.76 and 0.73 in 1999 and 2000.	Rural offices used only 84% of cooling energy during a typical hot week compared to urban reference offices. Rural-optimized offices would require 42% cooling energy compared to urban-optimized offices. Urban-optimized offices reduced cooling demand by 10% compared to urban reference offices.	Kolokotroni et al. [35]
Hamm, Germany	Simulations using ESP-r	Not specified	Building with adequate insulation and moderate window dimension for low cooling energy demand.	Free night ventilation removes half of the heat. The heat gains and losses of around 10% are caused due to heat capacity of office furniture and walls.	Passive cooling through natural night ventilation improved thermal comfort without increasing electricity use. Hybrid ventilation schemes must be carefully applied to avoid disturbing natural ventilation with additional mechanically driven airflows.	Pfafferott et al. [36]
Freiburg, Germany	Simulations using ESP-r	Not specified	Low-energy building design with optimized daylighting and solar heat gains.	The average value of indoor temperature was reduced by 2 to 3 K with solar protection and 3 to 4 K with night ventilation. The average value of indoor temperature was decreased by 5.7 K by combining both.	The user behavior impacts variations in energy and temperature at the same level as the effects of various operation strategies and design decisions.	Pfafferott et al. [37]
Larnaca, Cyprus	Simulations using IES-VE and EnergyPlus	Not specified	2-story secondary school	For the current scenario, the east-west facing classrooms failed TM52 criterion 1 by 1% but passed TM52 criteria 2 and 3, whereas the classroom with the largest windows facing south and north passed all three criteria. All classrooms failed all TM52 criteria for overheating predictions for future scenarios.	The findings indicate that night ventilation effectively reduces the risk of overheating, particularly in the current scenario. However, The reference school cannot cope with overheating predictions using only the current passive cooling measures for future scenarios from the 2050s and 2090s.	Heracleous and Michael [38]

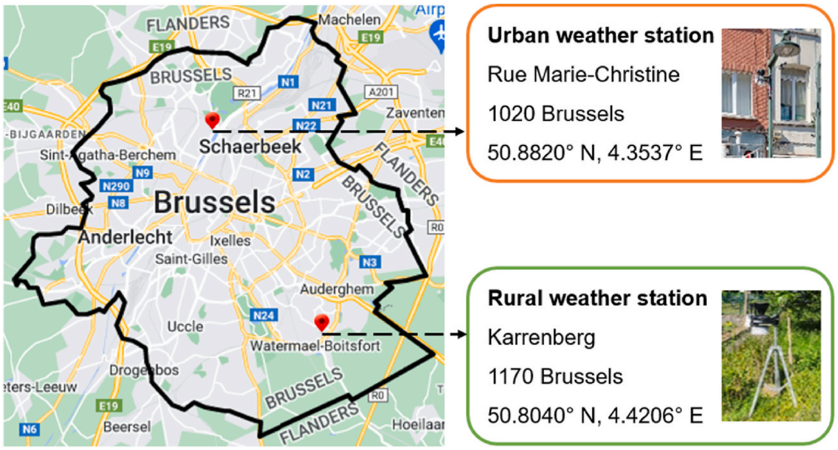

Fig. 1. Weather stations used to characterize Brussels's urban and rural microclimates.

air pollution, acoustic environment, and privacy concerns are associated with using natural ventilation techniques [26], whereas mechanical ventilation comes with increased energy demand due to the operation of fans and other auxiliaries [23]. The rise in ambient temperature due to the combination of global warming and urban heating and the reduction in wind speed in urban canyons also affects the cooling potential of night ventilation [26]. In the existing literature, night ventilation is recommended as a reliable solution to decrease cooling energy use [14,27,28] and to maintain an acceptable thermal environment [11,21] in buildings. However, studies like [15,30–32] have contradicted these findings.

The analysis of recent literature indicated the following missing aspects. Several studies (e.g., Refs. [23,33,35]) did not analyze thermal comfort, which is an essential aspect in the context of building performance, especially when there is growing evidence of the effects of local climate on indoor comfort [39]. Where thermal comfort was considered (e.g., Refs. [36,37]), the performance indices did not measure the extent or degree of discomfort in the building and predicted comfort comfortable vs. uncomfortable as a binary factor [40]. Studies like [38] assessed the performance of night ventilation and overheating in educational buildings using hours of exceedance and predicted comfort as pass vs. fail according to TM52 criteria. Understanding the night ventilation performance in urban and rural microclimates is essential to ensure minimum cooling energy use and maximum occupant comfort.

1.3. Relevance and novelty

The relevance of this study is based on many aspects. The study used an approach integrating building performance in urban and rural microclimates to explore the night ventilation performance for nearly zero-energy office buildings during heat and non-heat wave days. Measuring urban and rural weather data is crucial for building performance analysis since it enables the design of cooling strategies customized to the area's particular climate, topography, and other characteristics. This will ensure that the cooling system is better optimized for the local climate, increasing its effectiveness and efficiency. Furthermore, the nearly zero-energy building requirements have been in place in Brussels since 2010. These requirements are where high energy performance is advised based on the passive house standard. Many buildings are constructed and renovated to meet these requirements with nearly zero or very low energy

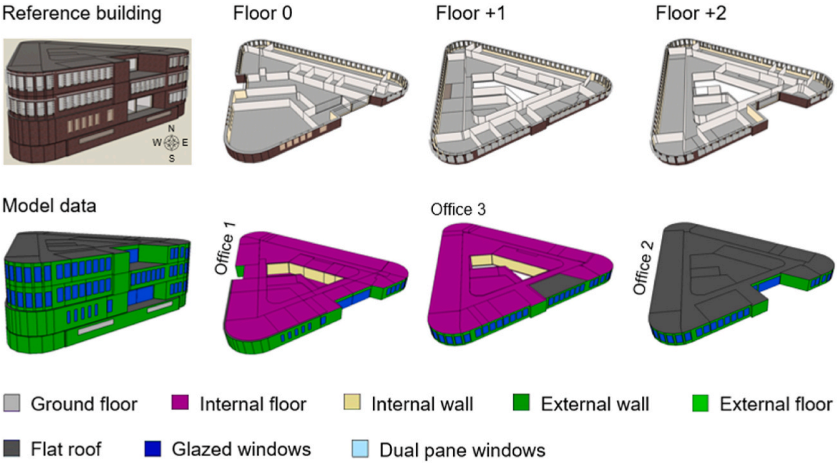

Fig. 2. Reference nearly zero-energy office building in Brussels, Belgium, and thermal zones for different floors [49].

consumption [41].

Based on these observations, the paper aims to address the following research questions:

a. How does night ventilation perform during heat wave and non-heat wave periods?
b. How does night ventilation perform in urban and rural microclimates?

The main novelty of the study is that it investigates the suitability of different key performance indicators for the thermal environment and energy use during extreme short-term events like heat waves. This is performed by a comparative approach with three different cooling strategies involving natural and mechanical night ventilation using real measured urban and rural microclimatic data and dynamic building simulations. To the best of the authors' knowledge, this study represents the first attempt to assess the cooling potential of night ventilation for extreme heat events in urban and rural areas in a mixed humid climate. This scientific literature reports combining active and passive cooling methods like VRF systems and night ventilation in an entire building while providing real design guidelines tailored for mixed humid climates. The proposed cooling configurations were validated using a calibrated, nearly zero-energy office building while factoring in the effects of local microclimate for time-integrated and multizonal thermal discomfort analysis.

2. Methodology

The workflow and methodology used in this study are as follows:

- Weather data at urban and rural sites in the Brussels area have been collected from Jul. 11, 2022, to Aug. 21, 2022, and used as input to the building performance simulations.
- A calibrated office building model is used to analyze the thermal performance of different configurations using standard effective temperature (SET) [°C] [42], heat index [°C] [42], and peak cooling demand [W/m^2] during heat waves.
- Indoor overheating is characterized using IOD [43,44], and exceedance hours [h] for different configurations are calculated using the PMV model in different zones during the occupied hours.
- The cooling energy use [kWh/m^2] in the reference office building for the VRF system and the system fans for different configurations in urban and rural study locations in Brussels was calculated.

2.1. Study scope

The study location is in Brussels, which is in a mixed humid climate (4A), as per ASHRAE 169 [45]. The building design in these heating-dominated regions primarily focused on maintaining heat indoors during winter. This was achieved using highly insulated and airtight designs, which hinder heat dissipation during hot summers and increase building overheating [46]. To avoid overheating problems during hot summers in urban and rural microclimates, relying only on passive cooling methods will be challenging. Hence, a mixed-mode approach of active and passive strategies was implemented to assess the overheating and energy use in a nearly zero-energy office building.

2.2. Study approach

This section discusses the global study approach, which can be applied to future studies regardless of location, climate zone, building type, etc. The study deals with building performance during the monitored period.

2.2.1. Weather stations

There is no established network of professional weather stations in the city of Brussels, with the closest station of the Royal Meteorology Institute (RMI) located in Uccle, approximately 6.6 km from the city of Brussels. Other nearby stations are located at Brussels Airport in Zaventem at 14.4 km. Hence, two identical weather stations have been deployed: one within Brussels (mounted on a lamp post) at 4 km from the city center and a second one at a rural site at 10 km from the city center, shown in Fig. 1. The weather

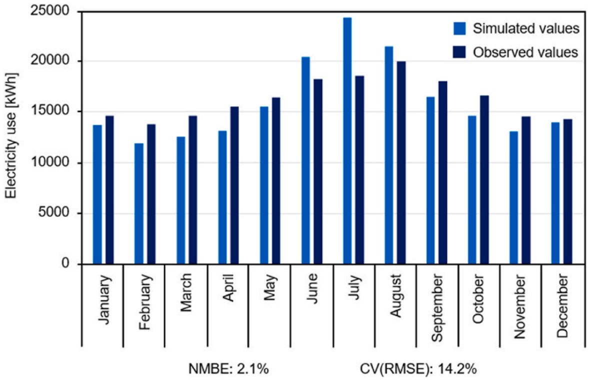

Fig. 3. Observed and simulated monthly electricity use in the reference nearly zero-energy office building for 2019 [44].

Table 2
Envelope characteristics of the reference nearly zero-energy office building used in the study.

Envelope	Layers	Materials used	Thickness [m]	U-value [W/m^{2}K]
Ground floor	Outer	Urea-formaldehyde foam	0.1327	0.250
	Third	Cast concrete	0.1000	
	Second	Floor screed	0.0700	
	Inner	Timber flooring	0.0300	
Internal floor	Single	Dense concrete slab	0.1000	2.929
External floor	Outer	External rendering	0.0250	0.250
	Second	MW stone wool rolls	0.1482	
	Inner	Timber flooring	0.0050	
External roof	Outer	Asphalt	0.0100	0.250
	Third	MW glass wool rolls	0.4000	
	Second	Air gap	0.2000	
	Inner	Plasterboard	0.0130	
External wall	Outer	Brickwork	0.1000	0.350
	Third	XPS extruded polystyrene	0.0785	
	Second	Concrete block	0.1000	
	Inner	Gypsum plastering	0.0130	
Internal partition	Outer	Gypsum plasterboard	0.0250	1.639
	Second	Air gap	0.1000	
	Inner	Gypsum plasterboard	0.0250	
Doors	External	Painted Oak	0.0350	2.823
	Internal	Painted Oak	0.0350	2.823
Windows	External	Triple-glazed, clear, low emissivity, argon filled	0.003/0.013	0.500
	Internal	Double pane, clear, air-filled	0.006/0.006	3.094

stations consist of a sensor suite with temperature and humidity sensors in a passive radiation shield, a rain collector, a solar radiation sensor, a UV radiation sensor, and an anemometer in a single package (Davis Vantage Pro2 Plus). The details of the sensors used and the installation procedure is briefly described in Ref. [47]. The urban weather station was mounted on a lamp post 6 m above the ground level (within the urban canopy layer) to avert vandalism in Brussels on the street with buildings on either side and regular traffic to characterize the urban microclimate. The rural weather station was installed outside the city of Brussels near a residential area 1.5 m above the ground level on an open space isolated from sizable obstructions like fences, trees, or buildings to characterize the rural microclimate.

2.2.2. *Key performance indicators*

Key Performance Indicators (KPIs) offer a quantified measure of how the target variable performs within the study's intended parameters. The following is a list of various KPIs used in this study.

2.2.2.1. Heat wave vs. non-heat wave days. In this paper, heat wave days were detected using the methodology from Ref. [48] using thresholds like Spic (99.5%) beyond which a heat wave was detected, Sdeb (97.5%) determines when a heat wave begins and ends, and Sint (95) allows merging two consecutive heat waves without a noticeable decrease in temperature [49]. These thresholds are calculated using a distribution of air temperature values over several years. A custom Python script [50] based on [51] identified the heat wave in Brussels from Aug. 10, 2022, to Aug. 16, 2022. The threshold values were calculated using the weather data retrieved from the RMI Opendata Platform extracted from the weather station in Uccle, about 11 km from Brussels City. The combined impact of heat waves on heat exposure and peak cooling demand [52] is evaluated in this study.

SET considers indoor air temperature [°C], relative humidity [%], mean radiant temperature [°C], air velocity [m/s], as well as metabolic rate [W/m^2] and clothing factor [clo] [53]. SET is an index recommended by ASHRAE 55 [54]. ASHRAE Handbook [55] defines SET as "the equivalent air temperature of an isothermal environment at 50% RH in which a subject, wearing standardized clothing for the corresponding activity, has the same and thermoregulatory strain (skin wettedness) and heat stress (skin temperature) as in a genuine environment." This paper uses SET to assess the night ventilation impact with 26 °C as the upper limit and 20 °C as the lower limit [56]. The SET values were calculated using the CBE Clima tool [57]. Hours of exceedance [hours] [58] for SET values are the number of occupied hours above 26 °C [56] and are represented as a percentage of total occupied hours.

The heat index, also known as apparent temperature, measures how it feels when relative humidity is considered along with the air temperature [59]. The heat index considers air temperature and relative humidity as operational parameters and is used to assess heat exposure in studies like [42]. The heat index is calculated as in equation (1).

$$HI = -42.379 + 2.04901523 \times T_a + 10.14333127 \times RH - 0.22475541 \times T_a \times RH - 6.83783 \times 10^{-3} \times {T_a}^2 - 5.481717 \times 10^{-2} \times RH^2 + 1.22874 \times 10^{-3} \times {T_a}^2 \times RH + 8.5282 \times 10^{-4} \times T_a \times RH^2 - 1.99 \times 10^{-6} \times {T_a}^2 \times RH^2 \tag{1}$$

where, T_a is air temperature [°C], and RH is relative humidity [%]. Adjustments are made to equation (1) based on air temperature [°C]

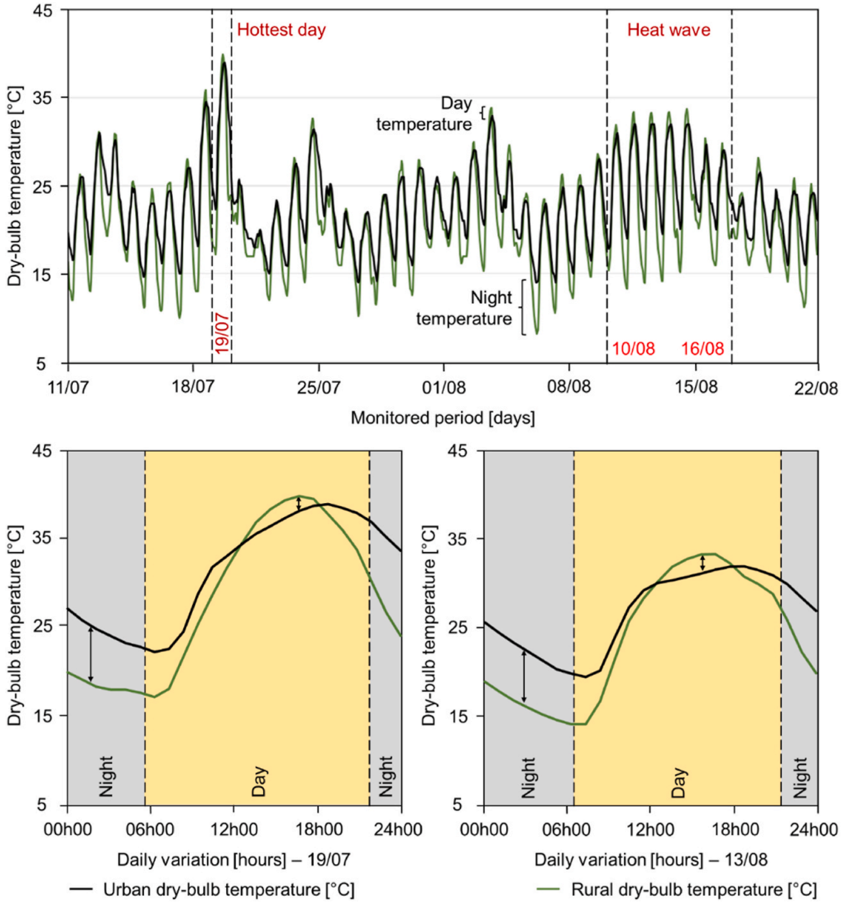

Fig. 4. Urban and rural outdoor air temperatures during the monitored period from Jul. 11, 2022, to Aug. 21, 2022.

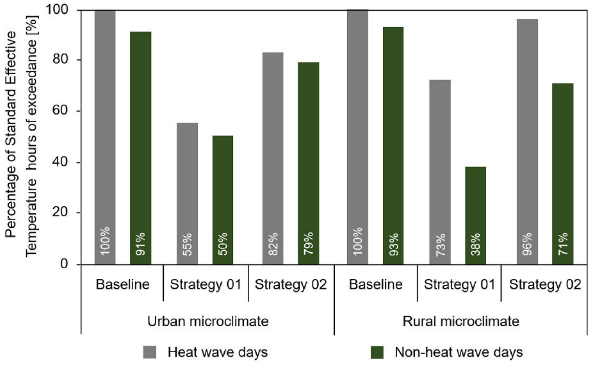

Fig. 5. Percentage of SET hours of exceedance [%] in the reference building during the monitored period in Brussels during the monitored period with configurations of (i) Baseline: Active cooling without night ventilation, (ii) Strategy 01: Active cooling with natural night ventilation, (iii) Strategy 02: Active cooling with mechanical night ventilation.

and relative humidity [%] levels and converted to metrics. The heat index hours [hours] are the number of hours within each category and are represented as a percentage of total occupied hours [60]. The results from Ref. [61] indicated that the maximum heat index [°C] was an appropriate weather index to assess the heat-related public health risk in the hot weather of New York City, which has a similar mixed humid climate in Brussels as per ASHRAE 169 [45].

The amount of energy required by the cooling systems and fans to remove sufficient heat to maintain an acceptable room temperature every hour during the hottest summer is known as the peak cooling demand [W/m^2].

2.2.2.2. Urban vs. rural microclimates. Indoor Overheating Degree (IOD) [43] was selected to estimate the degree of overheating in the

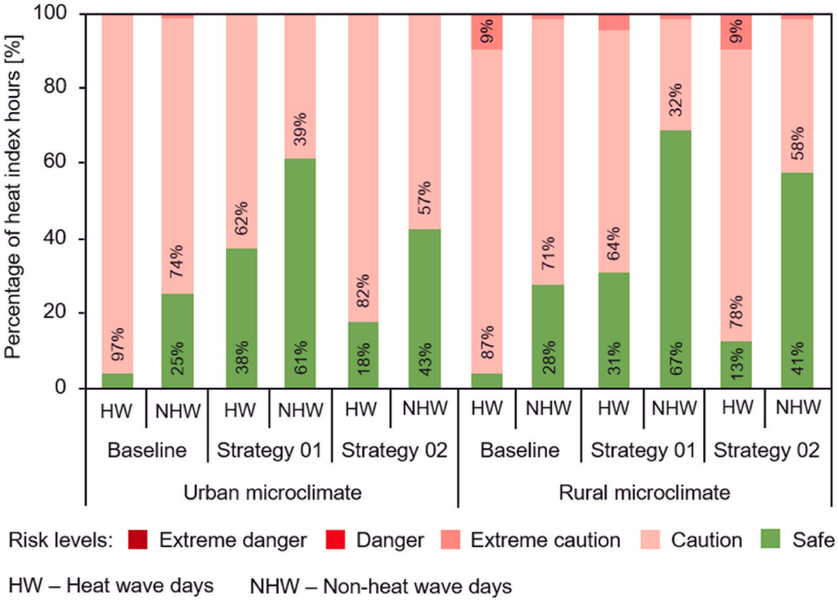

Fig. 6. Percentage of heat index hours [%] in the reference building during the monitored period in Brussels with configurations of (i) Baseline: Active cooling without night ventilation, (ii) Strategy 01: Active cooling with natural night ventilation, (iii) Strategy 02: Active cooling with mechanical night ventilation.

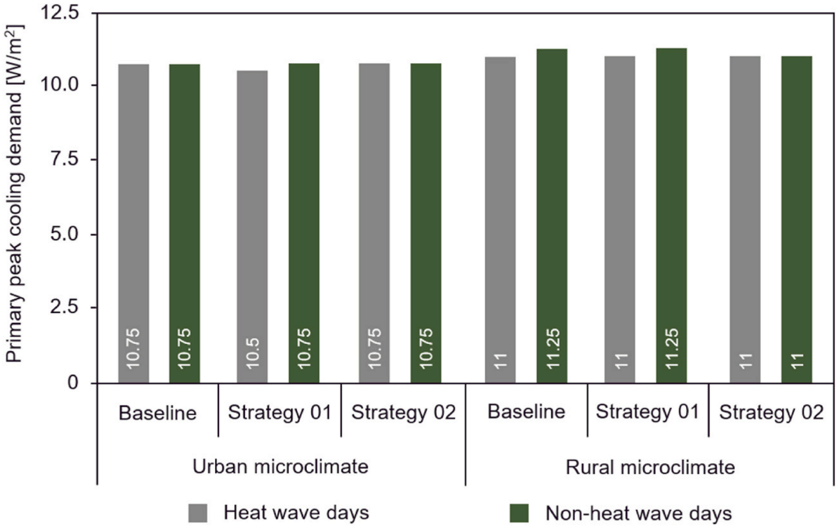

Fig. 7. Primary peak cooling demand [W/m^2] in the reference building during the monitored period in Brussels with configurations of (i) Baseline: Active cooling without night ventilation, (ii) Strategy 01: Active cooling with natural night ventilation, (iii) Strategy 02: Active cooling with mechanical night ventilation.

reference office building. IOD is a multizonal time-integrated index. The formula used to determine IOD is given in equation (2).

$$IOD = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{in,z,i} - T_{comf,upper,z,i}\right)^{+} \times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}} \tag{2}$$

where Z is the total conditioned zones in the building, i is the occupied hour counter, $N_{occ}(z)$ is the occupied hours in zone z, $T_{in,z,i}$ is the indoor operative temperature at time step i in zone z in $[^{\circ}C]$, $T_{comf,upper,z,i}$ is the maximum threshold in zone z at hour i. The PMV/PPD models in ISO 17772-1 [56], which have similar thresholds to EN 16798-1 [62], is used to calculate $T_{comf,upper,z,i}$. The ISO 17772-1 category II PMV/PPD comfort model, recommended for new buildings and renovations mechanically cooled with 26 °C as the upper limit and 20 °C as the lower limit, is used here [56].

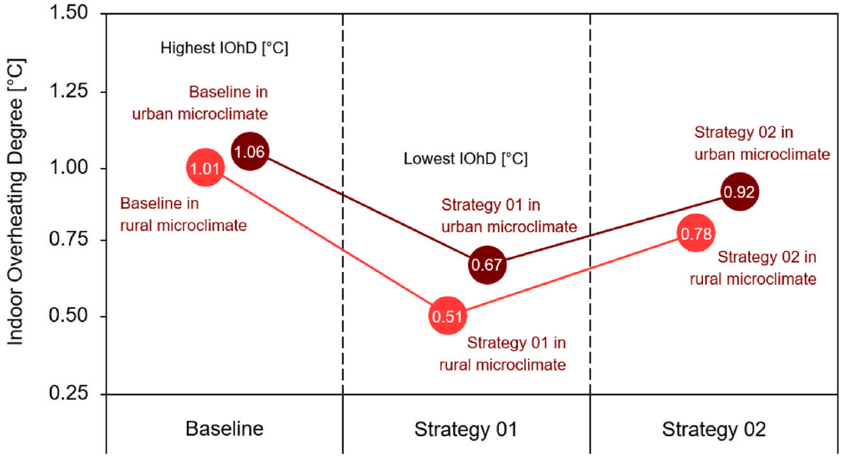

Fig. 8. Indoor Overheating Degree [°C] in the reference building in urban and rural microclimates in Brussels with configurations of (i) Baseline: Active cooling without night ventilation, (ii) Strategy 01: Active cooling with natural night ventilation, (iii) Strategy 02: Active cooling with mechanical night ventilation.

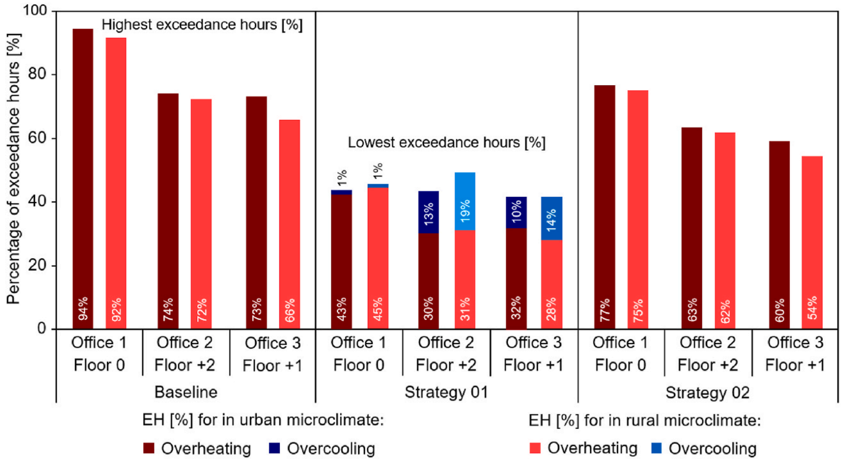

Fig. 9. Percentage of exceedance hours [%] in the worst affected zones in the reference building in urban and rural microclimates in Brussels with configurations of (i) Baseline: Active cooling without night ventilation, (ii) Strategy 01: Active cooling with natural night ventilation, (iii) Strategy 02: Active cooling with mechanical night ventilation.

The number of occupied hours within a specific period during which the indoor environmental parameters exceed the recommended thresholds is known as an exceedance hour [54]. The formula for calculating the exceedance hours for the PMV model (EH_{PMV}) is shown in equation (3). The exceedance hours [h] are calculated based on PMV limits since the reference building is cooled using active cooling systems during the occupied hours [54].

$$EH_{PMV} = \sum\nolimits_{i=1}^{N_{occ}(z)} H_{disc} \tag{3}$$

$$H_{disc} = 1, |PMV| > 0.5$$

$$H_{disc} = 0, |PMV| \leq 0.5$$

where H_{disc} is the discomfort hours [h].

The energy used by the cooling system and fans to remove heat and maintain an acceptable temperature in the building during the monitored period is termed the cooling energy use [kWh/m^2]. According to Belgian regulations, the site energy used for cooling was changed into primary energy using a factor of 2.5 as the conversion coefficient for electricity [63,64].

2.3. Reference building

The reference building is situated close to Brussels, Belgium (Latitude: 50.67° N, Longitude: 4.56° E, Elevation: 112 m), and has three floors, along with offices, conference rooms, and other amenities like a multipurpose hall, and a parking garage in the basement and is shown in Fig. 2. The structure has fixed horizontal solar protections. It is a nearly zero-energy office building. More information on the building is available on [65].

The federal government created the legal zero-energy concept in Belgium as a requirement for passive home criteria [66]. However, these criteria' application and computation methods differ at the regional level [67,68]. The total energy demand for space heating and cooling is less than or equal to 15 kWh/m^2. This reference building model was calibrated with ASHRAE Guideline 14 [69] using metered monthly electricity use data for 2019. The calibration results for the building model [49] are shown in Fig. 3. The calibration results gave a Normalized Mean Bias Error (NMBE) of 2.1% and a Coefficient of Variation of the Root-Mean-Square Error (CV(RMSE)) of 14.2%, within the recommended values of ±5% and 15%, respectively [69]. The building envelope details are listed in Table 2.

The general building properties are taken from Ref. [44]. The parametric simulation results from Ref. [22] indicated that installing active daytime cooling alongside night ventilation is the best strategy to get the best thermal comfort and energy-saving benefit. Furthermore, the findings from Ref. [70] demonstrated that night ventilation could not independently provide the entire office building's cooling needs and that additional active cooling was necessary. In line with these studies, three different HVAC configurations are studied for urban and rural microclimates, including mixed-mode operation of active and passive cooling strategies are used here. An electric, reversible VRF unit with DX cooling coils was used to implement active cooling in this study over other systems because these systems provide the precise amount of cooling that a space needs in a given situation while operating at a lower capacity and using less energy [71].

The occupancy schedule for the reference office building was from 07h00 to 18h00, 5 days a week during the daytime and with no occupancy during weekends. Different factors, like internal equipment gain values, lighting gain, etc., were assumed from the actual building values. The schedules for night ventilation from 22h00 to 06h00 were obtained from Ref. [24]. The studies from Ref. [25] used night ventilation from 17h00 to 08h00. However, this schedule was not appropriate for the current study as the average sunset and sunrise were estimated to be 22h00 and 06h00 during the monitored period in Brussels, Belgium. The different configurations used to cool the building differed according to the night ventilation strategies. In addition to active cooling using a reversible VRF unit with DX cooling coils and hygienic ventilation with a design rate of 1.4 l/s/m^2 [72] for an office building category II as per EN 16798-1 [62] during the occupancy hours, (i) Baseline had no night ventilation, (ii) Strategy 01 used natural night ventilation from 22h00 to 06h00 [24], through window openings at 3 ACH [33] for favorable wind conditions, and (iii) Strategy 02 used mechanical night ventilation from 22h00 to 06h00 [24], at a rate of 1.1 l/s/m^2 [73].

The model assumption used for the HVAC strategies is listed in Table A1 in Appendix A. The primary sources of heat gain during the day are occupancy gains, solar gains, internal equipment gains, mechanical ventilation gains, and lighting gains. The primary sources of heat loss during the day are active cooling and during the night due to natural ventilation for strategy 01 and mechanical ventilation for strategy 02. Heat transfer due to infiltration happens 24/7 [74], adding to heat gains during the day and heat loss at night. This has a considerable impact on the building energy loads [75]. The EnergyPlus simulation engine estimated the thermal capacities and design flow rates based on the exterior conditions and building configurations. The VRF system was sized using design day calculations by ISO 15927-2 [76]. The maximum and minimum dry-bulb temperature and coincident wet-bulb temperature [77,78] were set at 39 °C, 22 °C, and 19.3 °C for urban microclimate and 40 °C, 17 °C, and 23.4 °C for rural microclimate.

3. Results

The percentage of SET hours of exceedance, heat index hours, peak cooling demand, indoor overheating degree, exceedance hours, and primary cooling energy use results in the reference building for urban and rural microclimates are presented here. The characterization results indicate that operative temperature levels in the reference office building were the lowest for Strategy 01 using active cooling with natural night ventilation and highest for Baseline using active cooling without night ventilation. The outdoor air temperature variations [79] from the weather stations during the monitored period from Jul. 11, 2022, to Aug. 21, 2022, are illustrated in Fig. 4.

3.1. How does night ventilation perform during heat wave and non-heat wave periods?

The percentage of SET hours of exceedance [%] above 26 °C during the occupied hours for different HVAC strategies in the reference office building is illustrated in Fig. 5. The results showed that the Baseline percentage of SET hours of exceedance above 26 °C for 100% of the occupied hours for urban and rural microclimates in Brussels during heat wave days. During non-heat wave days, the percentage of SET hours of exceedance above 26 °C was 91% and 93% for urban and rural microclimates. Strategy 01 showed that during heat wave days, the percentage of SET hours of exceedance was 55% and 73% during heat waves and 50% and 38% during non-heat wave days in urban and rural microclimates. For Strategy 02, the percentage of SET hours of exceedance was 82% and 96% during heat wave days and 50% and 38% during non-heat wave days in urban and rural microclimates.

The percentage heat index hours in different categories during the occupied hours for different HVAC strategies during the monitored days in the reference office building are illustrated in Fig. 6. The results showed that in Baseline, the reference office building in caution during 97% and 87% of the occupied hours during heat waves and 74% and 71% of the occupied hours during non-heat wave days for urban and rural microclimates, respectively. Furthermore, the building was under extreme caution for 9% and 1% of the occupied hours in rural microclimates. In Strategy 01, the reference office building was under caution for 62% and 65% of the occupied hours during heat wave days, and 39% and 32% of the occupied hours were under caution during non-heat wave days for urban and rural microclimates, respectively. Furthermore, the building was under extreme caution for 5% and 1% of the occupied hours in rural microclimates. For Strategy 02, the reference office building was under caution for 82% and 78% of the occupied hours during heat wave days and 57% and 58% of the occupied hours during non-heat wave days for urban and rural microclimates, respectively. Furthermore, the building was under extreme caution for 9% and 1% of the occupied hours in rural microclimates.

The primary peak cooling demand [W/m^2] analysis results are illustrated in Fig. 7. During heat wave days, the primary peak cooling demand was highest at 11 W/m^2 and 11.25 W/m^2 for Baseline and Strategy 01 using active cooling with natural night ventilation in rural microclimate, and lowest at 10.5 W/m^2 and 10.75 W/m^2 for Strategy 01 During heat wave and non-heat wave periods.

3.2. How does night ventilation perform in urban and rural microclimates?

The operative temperature limits exceeded the PMV/PPD limits for category II office buildings with active cooling. This extent of overheating in the reference building was calculated using IOD. The IOD values for different HVAC strategies in urban and rural microclimates in Brussels are shown in Fig. 8. From the results, Baseline with active cooling showed the highest level of overheating with an IOD of 1.06 °C and 1.01 °C, Strategy 01 using active cooling with natural night ventilation showed the lowest level of overheating with an IOD of 0.67 °C and 0.51 °C, and Strategy 02 using active cooling with mechanical night ventilation showed overheating with an IOD of 0.92 °C and 0.78 °C for urban and rural microclimates. The difference in overheating for urban and rural microclimates was 0.05 °C for Baseline, 0.16 °C for Strategy 01, and 0.14 °C for Strategy 02.

The percentage of exceedance hours was higher in the urban microclimate compared to the rural microclimate, as shown in Fig. 9. The results for the most overheated office room in the reference building are that Baseline with active cooling showed the highest percentage of overheating exceedance hours with 94% and 92%, Strategy 01 using active cooling with natural night ventilation showed the lowest rate of overheating exceedance hours at 43% and 45%, Strategy 02 using active cooling with mechanical night ventilation showed 77% and 75% for urban and rural microclimates and in the urban and rural microclimates, respectively. Furthermore, Strategy 01, using active cooling with natural night ventilation, showed overcooling exceedance hours of 1% each in the urban and rural microclimates.

The cooling energy use analysis is illustrated in Fig. 10 and indicated that Strategy 01, using active cooling with natural night ventilation, recorded the lowest energy use and highest for Strategy 02, using active cooling with mechanical night ventilation. This was because, in Strategy 02, ventilation fans were prolonged during the night, which added to the total cooling energy use. The energy use for Strategy 01 was 5% and 6% lower compared to Baseline, while the energy use for Strategy 02 in urban and rural microclimates was 21% and 20% higher compared to Baseline in urban and rural microclimates. The energy use variations among the urban and rural microclimates were 4%, 5%, and 5% for Baseline, Strategy 01, and Strategy 02.

4. Discussion

The fact that the peak cooling load is higher in the rural area than within the city is consistent with the higher peak daytime air temperatures in the rural area than in the city. This is normal because: a. rural areas do not have much thermal inertia compared to urban areas, b. urban areas have larger shadowing and masking due to buildings, and c. office buildings have the peak cooling load during daytime in line with the occupancy. Though pretty well known, these considerations are reiterated through the study results. The increasing rate of ambient temperature is evident from studies like [80,81]. This will only contribute to an increase in heat exposure in buildings. Adaptive measures like acclimatization [82] indicate that human physiology mechanisms can adjust over ten days such that heat stress will have a reduced impact [83,84]. Additionally, design elements like adding overhangs and using optimum insulation can improve the potential of night ventilation in warm, humid climates, as per the findings from Ref. [12]. This should be considered for future studies.

4.1. Main findings

The peak cooling demand stays approximately the same for the heat wave and non-heat wave periods from the analysis, as shown in Fig. 7. These results add to the consideration that absolute peak load values are not the best metric to assess building performance in response to extreme heat events. This is since the days outside the definition of heat waves could still have a high peak temperature resulting in higher peak cooling demands during non-heat wave days, as was the case here. During the monitored period, Jul. 19, 2022, recorded the highest peak temperature of 37 °C and 39 °C in urban and rural microclimates in Brussels, as shown in Fig. 4, but did not fit current definitions of a heat wave day. The indoor overheating analysis using IOD in the reference building showed a gradual decrease in overheating for strategies with no night, mechanical, and natural night ventilation. This aligns with the findings from Ref. [14], where indoor and outdoor temperature variations gradually increased with an all-day closed state, mechanical night, and natural night ventilation. This supports the finding that natural night ventilation was the better solution against indoor overheating in the reference building among the strategies assessed.

Furthermore, the hygrothermal discomfort assessment using the heat index metric gave similar results in line with the indoor overheating analysis. Strategy 01 with natural night ventilation performed better than other configurations in maintaining safer levels of hygrothermal exposure. The reference office building was under caution for the significant number of occupied hours for both heat wave and non-heat wave periods for Baseline and Strategy 02. It was found that the implementation of night ventilation did not significantly reduce the temperature and overheating levels in the reference building, and these findings are in line with results from Ref. [15] that showed that using night ventilation did not significantly reduce the hours of exceedance that the maximum temperature was surpassed in the high thermal mass room. It is important to note that the results from this study are consistent with existing study findings [23] carried out in Southeast England in the UK and [34] in Brussels, Belgium, in a similar mixed humid climate. The findings from Ref. [85] indicated that night ventilation during extreme heat events would be counterproductive for buildings with high thermal mass. However, the current study results here suggest that natural night ventilation during the heat wave event did decrease the heat

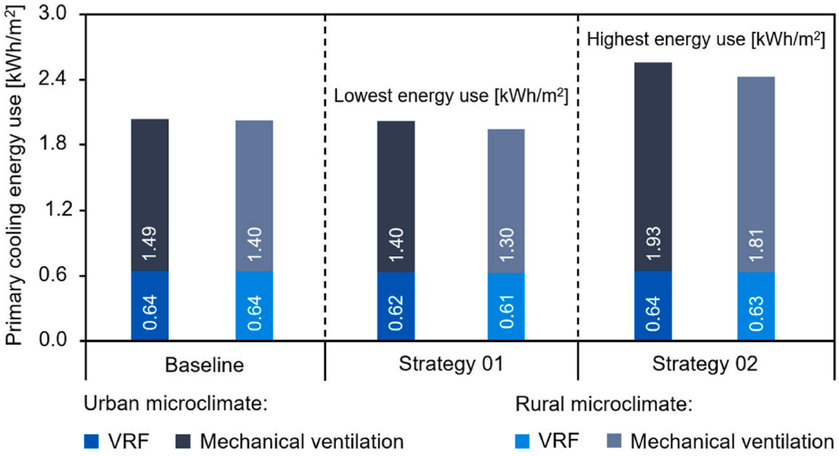

Fig. 10. Hourly primary cooling energy use [kWh/m^2] in the reference building in urban and rural microclimates in Brussels with configurations of (i) Baseline: Active cooling without night ventilation, (ii) Strategy 01: Active cooling with natural night ventilation, (iii) Strategy 02: Active cooling with mechanical night ventilation.

exposure risk in the reference building, and this is evident from SET hours of exceedance and heat index hours analysis results.

4.2. *Design guidelines for practitioners*

The impact of night ventilation as a mitigative measure against overheating depends on the microclimate where it is used. The study results imply that the cooling potential of night ventilation against overheating in buildings was more effective in rural microclimates than in urban microclimates. Natural night ventilation has a moderate impact on mitigating overheating effectively during summer without increasing energy use. To further improve the effectiveness of night ventilation, openings must be closed if the outdoor air temperature at night (i) falls below a predetermined threshold to prevent overcooling in the morning and (ii) gets warmer than the indoor air temperature to prevent overheating during the day. Additionally, natural night ventilation is more energy-efficient than mechanical night ventilation.

Natural night ventilation is more effective during heat wave days than mechanical night ventilation. However, the privacy concerns of leaving the windows open during the night should be factored in while considering the cost benefits of this strategy. It is important that the designers should go beyond the design criteria defined by current standards and best practices, e.g., EN 16798-1 [62] recommends a maximum temperature of 26 °C for Category II office buildings with active cooling. However, to mitigate heat wave impacts like overheating, the design temperature should be lower than the temperature thresholds recommended by the existing standards. Future design frameworks should consider humidity as a significant factor that can affect the comfort in the reference building [86], and measures like dehumidification should be adopted to keep the humidity levels according to EN 16798-1 [62]. Also, humidity-controlled night ventilation strategies should be introduced to keep hygrothermal exposure safe.

4.3. *Strengths and limitations*

The study’s comparative approach combining three separate cooling strategies, including natural and mechanical night ventilation, using real observed data from urban and rural microclimates for extreme heat events is its key novelty. The strengths of this study are based on the fact that actual weather data obtained from the weather stations in urban and rural areas of Brussels, Belgium, that can provide a localized forecast based on actual readings were used in the study. This weather data helped to simulate more realistic building performance outputs. In addition, the study analyzed the building performance in urban and rural microclimates. Since urban microclimates significantly influence buildings considering thermal comfort and energy use [87], it is important to compare different microclimates to design cooling strategies consistent with the topography and climate of the specific area. The calibrated nearly zero-energy office building set according to ASHRAE Guideline 14 [69] using monthly energy use value was used for the study. This improved the consistency of the model outputs with the building performance in real-world scenarios.

The limitations of this study are that the weather data was collected between Jul. 11, 2022, to Aug. 21, 2022. Although this period covered the hottest period in Brussels, this is a limited period of 7 weeks. Future work should consider this limitation and perform multiyear measurements with more weather stations installed in multiple study locations. Even though the paper provides insights into the efficacy of diverse cooling strategies during heat waves, operating as a potential case study focusing on a nearly zero-energy office building in Brussels. However, the results must be compared with similar studies from other mixed humid climates to apply universally to other structures or regions.

4.4. *Implications for future work*

The current study shows that urban heat islands will lead to increased nighttime temperatures, reducing the efficiency of night ventilation. As urbanization and global climate change result in higher nocturnal warming, the efficacy of night ventilation will likely be diminished [88]. The exacerbated heat index levels shown in the study in urban areas contribute to heat-related health risks [89], especially in vulnerable populations like the elderly, low-income individuals, children, pregnant women, etc. [90,91]. Furthermore, the effects of heat waves, which are very hot and frequently humid periods, will also be exacerbated by urban heat islands [92]. Furthermore, urban heat islands exacerbate the need for active cooling in buildings. This is supported by case studies from several countries that found that for every 1.1 °C rise in temperature, the electricity consumption for air conditioning rose by 1% to 9%.

This increase in electricity usage is evident in the majority of buildings that use air conditioning [3]. The increased electricity demand results in increased electricity costs creating an economic strain. In addition to increasing total energy demand, heat islands will increase peak energy demand. On hot summer weekday afternoons, electricity demand will peak when air conditioning is on in offices and residences [92,93]. This increased demand during high-heat events will create grid overload causing critical infrastructure failures like power outages [94–96]. The disparities in the effectiveness of night ventilation measures in terms of thermal comfort and energy use in the reference office building were obtained in this case study, and there is a need for additional studies to determine the extent of their usefulness in different building types like offices, schools, residences, etc.

5. Conclusions

This paper assessed the cooling potential of night ventilation as a mitigative measure against overheating in urban and rural microclimates in Brussels, Belgium. The study findings will aid policymakers in shaping resilient solutions to the detrimental effects of urban heat islands on building performance, including thermal comfort and energy use. These policies will improve thermal comfort considerably while also assisting the construction industry in building climate-resilient buildings in urban and rural microclimates. During the monitored period, this study evaluated overheating in a calibrated reference building model representative of nearly zero-energy office buildings with and without night ventilation in urban and rural microclimates in Brussels. The building's thermal performance was analyzed for multiple configurations with and without night ventilation through natural and mechanical ventilation in combination with active cooling during the day.

The study found that night ventilation did not significantly improve the building's performance. However, overheating in nearly zero-energy office buildings in Brussels to 0.67 °C in urban microclimate and 0.51 °C in rural microclimate by combining natural night ventilation with active cooling systems. This configuration also reduced exceedance hours due to overheating to 43% and 45% in urban and rural microclimates for the worst affected building zone. Among the three configurations tested, natural night ventilation with daytime active cooling also had the lowest cooling energy use at 2.02 kWh/m^2 and 1.91 kWh/m^2 for urban and rural microclimates. Natural night ventilation with daytime active cooling also performed better for heat exposure during heat wave vs. non-heat wave days. This configuration reduced SET hours of exceedance to 55% and 50% during heat wave and non-heat wave days in urban microclimates and 73% and 38% during heat wave and non-heat wave days in rural microclimates. Similar patterns were observed for heat index values, with the percentage of occupied time under caution falling to 62% and 39% during heat wave and non-heat wave days in urban microclimates and 64% and 32% during heat wave and non-heat wave days in rural microclimates.

In recent decades, heat exposure has increased throughout many regions, particularly commercial buildings. This phenomenon will rise as summer weather becomes harsher [44], internal equipment and solar heat gains increase, and comfort expectations rise. As in the paper, the passive cooling of buildings via natural night ventilation and active daytime cooling is one option to deal with the increasing heat exposure in commercial buildings. The effectiveness of these measures should be improved by analyzing the potential of combining other passive cooling technologies, like cool roofs, solar shading, etc., to reduce the overheating risks in nearly zero-energy office buildings. Furthermore, the increased integration of renewable energy sources and renovation of traditional building systems will accelerate as well as contribute to the EU 2030 goal of reducing emissions by 55% [44]. To summarize, under the comparative assessment of three configurations with and without night ventilation, the study recommends natural night ventilation with daytime active cooling for better indoor overheating performance and cooling energy use in Brussels. In future studies, the effectiveness of absolute peak load values as an indicator in response to extreme heat events should also be assessed in detail.

CRediT author statement

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Author statement

The authors declare that financial support was provided by the Walloon Public Service and MK Engineering, Belgium. The funders had no role in the study design, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results. We wish to confirm that no known conflicts of interest are associated with this publication. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship. We further confirm that all have approved the order of authors listed in the manuscript.

Data availability

Data will be made available on request.

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Appendix A

The reference building's external [65] and internal views are shown in Fig. A1. The HVAC characteristics and assumptions used in the reference office building are listed in Table A1. The Coefficient of Performance (COP) for the VRF unit for cooling was taken from the existing energy efficiency standards as 3.3 [97].

Fig. A1. The reference nearly zero-energy office building external [65] and internal view.

Table A1
The building simulation model inputs for HVAC strategies: (i) Baseline: active cooling without night ventilation, (ii) Strategy 01: active cooling with natural night ventilation, and (iii) Strategy 02: active cooling with mechanical night ventilation.

Parameters	Baseline	Strategy 01	Strategy 02
Active Cooling			
Target zones	Zone 1		
Cooling thresholds	Setpoint: 26 °C [62], Setback: 50 °C		
Production	Reversible VRF unit		
Nominal COP	3.3 [97]		
Distribution	DX cooling coils		
Fuel type	Electricity		
Sizing factor	Autosize		
Air velocity	0.10 m/s [62]		
Schedule	On: Weekdays, 07h00 to 18h00, and Off: Weekends & Oct. to Apr.		
Hygienic ventilation			
Target zones	Zone 1 and Zone 2		
AHU type	Variable Air Volume (VAV) unit		
AHU fan	Variable volume fans		
Nominal COP	0.7		
Ventilation rates	1.4 l/s/m^2 [62]		
Fuel type	Electricity		
Schedule	On: Weekdays, 07h00 to 18h00, and Off: Weekends.		
Night Ventilation			
Target zones	–	Zone 1 and Zone 2	
Type	–	Natural ventilation	Mechanical ventilation
AHU type	–	–	VAV unit
AHU fans	–	–	Variable volume fans
Ventilation rates	–	3 ACH	1.1 l/s/m^2 [73]
Outdoor temperature control	–	Maximum: 26 °C [62] Minimum: 20 °C [62]	–
Nominal COP	–	–	0.7
Fuel type	Electricity		
Schedule [19,30]	–	On: Weekdays, Monday to Thursday, 22h00 to 06h00 Weekends, Sunday through Monday, 22h00 to 06h00 Off: All other days	

Zone 1: Offices, meeting rooms, forum, cafeterias, and multipurpose hall, Zone 2: Halls, circulations, stairways, and lavatories

References

[1] S. Yamashita, Some studies of heat Island in Japan, Geogr. Rev. Jpn. B 61 (1) (1988) 1–13, https://doi.org/10.4157/grj1984b.61.1.

[2] M. Santamouris, Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change, Energy Build. 207 (Jan. 2020), 109482, https://doi.org/10.1016/j.enbuild.2019.109482.

[3] M. Tewari, F. Salamanca, A. Martilli, L. Treinish, A. Mahalov, Impacts of projected urban expansion and global warming on cooling energy demand over a semiarid region, Atmos. Sci. Lett. 18 (11) (Nov. 2017) 419–426, https://doi.org/10.1002/asl.784.

[4] T.R. Oke, G.T. Johnson, D.G. Steyn, I.D. Watson, Simulation of surface urban heat islands under 'ideal' conditions at night part 2: diagnosis of causation, Boundary-Layer Meteorol. 56 (4) (Sep. 1991) 339–358, https://doi.org/10.1007/BF00119211.

[5] M. Santamouris, Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions, Sci. Total Environ. 512 (513) (Apr. 2015) 582–598, https://doi.org/10.1016/j.scitotenv.2015.01.060.

[6] M. Santamouris, Innovating to zero the building sector in Europe: minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change, Sol. Energy 128 (Apr. 2016) 61–94, https://doi.org/10.1016/j.solener.2016.01.021.

[7] M. Santamouris, et al., Heat mitigation technologies can improve sustainability in cities. An holistic experimental and numerical impact assessment of urban overheating and related heat mitigation strategies on energy consumption, indoor comfort, vulnerability and heat-related mortality and morbidity in cities, Energy Build. 217 (Jun. 2020), 110002, https://doi.org/10.1016/j.enbuild.2020.110002.

[8] R. Paolini, et al., The hygrothermal performance of residential buildings at urban and rural sites: sensible and latent energy loads and indoor environmental conditions, Energy Build. 152 (Oct. 2017) 792–803, https://doi.org/10.1016/j.enbuild.2016.11.018.

[9] C. Heaviside, H. Macintyre, S. Vardoulakis, The urban heat Island: implications for health in a changing environment, Current Environmental Health Reports 4 (3) (Sep. 2017) 296–305, https://doi.org/10.1007/s40572-017-0150-3.

[10] N. Artmann, R.L. Jensen, H. Manz, P. Heiselberg, Experimental investigation of heat transfer during night-time ventilation, Energy Build. 42 (3) (Mar. 2010) 366–374, https://doi.org/10.1016/j.enbuild.2009.10.003.

[11] N. Artmann, H. Manz, P. Heiselberg, Parameter study on performance of building cooling by night-time ventilation, Renew. Energy 33 (12) (Dec. 2008) 2589–2598, https://doi.org/10.1016/j.renene.2008.02.025.

[12] H. Breesch, A. Janssens, Reliable design of natural night ventilation using building simulation, in: Thermal Performance of the Exterior Envelopes of Whole Buildings X, Clearwater Beach, FL, USA, 2007.

[13] H. Breesch, K. Descheemaeker, A. Janssens, L. Willems, Evaluation of natural ventilation systems in a landscaped office, in: *21st International Conference Passive and Low Energy Architecture (PLEA)*, 2004. Eindhoven, The Netherlands.

[14] X.-X. Li, K.-L. Huang, G.-H. Feng, W.-Y. Li, J.-X. Wei, Night ventilation scheme optimization for an Ultra-low energy consumption building in Shenyang, China, Energy Rep. 8 (Nov. 2022) 8426–8436, https://doi.org/10.1016/j.egyr.2022.06.059.

[15] T. Kuczyński, A. Staszczuk, M. Gortych, R. Stryjski, Effect of thermal mass, night ventilation and window shading on summer thermal comfort of buildings in a temperate climate, Build. Environ. 204 (Oct. 2021), 108126, https://doi.org/10.1016/j.buildenv.2021.108126.

[16] G.Á. Mhuireach, et al., Lessons learned from implementing night ventilation of mass in a next-generation smart building, Energy Build. 207 (Jan. 2020), 109547, https://doi.org/10.1016/j.enbuild.2019.109547.

[17] D. Shi, Y. Gao, P. Zeng, B. Li, P. Shen, C. Zhuang, Climate adaptive optimization of green roofs and natural night ventilation for lifespan energy performance improvement in office buildings, Build. Environ. 223 (Sep. 2022), 109505, https://doi.org/10.1016/j.buildenv.2022.109505.

[18] R. Guo, et al., Experimental investigation of convective heat transfer for night ventilation in case of mixing ventilation, Build. Environ. 193 (Apr. 2021), 107670, https://doi.org/10.1016/j.buildenv.2021.107670.

[19] H. Breesch, A. Bossaer, A. Janssens, Passive cooling in a low-energy office building, Sol. Energy 79 (6) (Dec. 2005) 682–696, https://doi.org/10.1016/j.solener.2004.12.002.

[20] Y. Wang, F.Y. Zhao, J. Kuckelkorn, X.H. Li, H.Q. Wang, Indoor air environment and night cooling energy efficiency of a Southern German passive public school building operated by the heat recovery air conditioning unit, Energy Build. 81 (Oct. 2014) 9–17, https://doi.org/10.1016/j.enbuild.2014.06.008.

[21] N. Heijmans, P. Wouters, Pilot study report: probe, Limelette, Belgium, in: P. Heiselberg (Ed.), Principles of Hybrid Ventilation, Aalborg University, Aalborg, Denmark, 2002. Available: https://iea-ebc.org/Data/publications/EBC_Annex_35_Principles_of_H_V.pdf.

[22] R. Guo, Y. Hu, M. Liu, P. Heiselberg, Influence of design parameters on the night ventilation performance in office buildings based on sensitivity analysis, Sustain. Cities Soc. 50 (Oct. 2019), 101661, https://doi.org/10.1016/j.scs.2019.101661.

[23] M. Kolokotroni, A. Aronis, Cooling-energy reduction in air-conditioned offices by using night ventilation, Appl. Energy 63 (4) (Aug. 1999) 241–253, https://doi.org/10.1016/S0306-2619(99)00031-8.

[24] V. Geros, M. Santamouris, A. Tsangrasoulis, G. Guarracino, Experimental evaluation of night ventilation phenomena, Energy Build. 29 (2) (Jan. 1999) 141–154, https://doi.org/10.1016/S0378-7788(98)00056-5.

[25] R. Guo, P. Heiselberg, Y. Hu, C. Zhang, S. Vasilevskis, Optimization of night ventilation performance in office buildings in a cold climate, Energy Build. 225 (Oct. 2020), 110319, https://doi.org/10.1016/j.enbuild.2020.110319.

[26] M. Santamouris, Night Ventilation Strategies, *Air Infiltration and Ventilation Centre*, INIVE EEIG, Brussels, Belgium, 2004 [Online]. Available: https://www.aivc.org/sites/default/files/members_area/medias/pdf/VIP/VIP04.Night%20ventilation.pdf. (Accessed 18 November 2022).

[27] M. Santamouris, A. Sfakianaki, K. Pavlou, On the efficiency of night ventilation techniques applied to residential buildings, Energy Build. 42 (8) (Aug. 2010) 1309–1313, https://doi.org/10.1016/j.enbuild.2010.02.024.

[28] R. Guo, Y. Hu, P. Heiselberg, H. Johra, C. Zhang, P. Peng, Simulation and optimization of night cooling with diffuse ceiling ventilation and mixing ventilation in a cold climate, Renew. Energy 179 (Dec. 2021) 488–501, https://doi.org/10.1016/j.renene.2021.07.077.

[29] M. Kolokotroni, B.C. Webb, S.D. Hayes, Summer cooling with night ventilation for office buildings in moderate climates, Energy Build. 27 (3) (Jun. 1998) 231–237, https://doi.org/10.1016/S0378-7788(97)00048-0.

[30] V. Geros, M. Santamouris, S. Karatasou, A. Tsangrassoulis, N. Papanikolaou, On the cooling potential of night ventilation techniques in the urban environment, Energy Build. 37 (3) (Mar. 2005) 243–257, https://doi.org/10.1016/j.enbuild.2004.06.024.

[31] L. Yang, Y. Li, Cooling load reduction by using thermal mass and night ventilation, Energy Build. 40 (11) (Jan. 2008) 2052–2058, https://doi.org/10.1016/j.enbuild.2008.05.014.

[32] R. Guo, et al., Optimization of cool roof and night ventilation in office buildings: a case study in Xiamen, China, Renew. Energy 147 (Mar. 2020) 2279–2294, https://doi.org/10.1016/j.renene.2019.10.032.

[33] M. Kolokotroni, X. Ren, M. Davies, A. Mavrogianni, London's urban heat island: impact on current and future energy consumption in office buildings, Energy Build. 47 (Apr. 2012) 302–311, https://doi.org/10.1016/j.enbuild.2011.12.019.

[34] H. Breesch, A. Janssens, Performance evaluation of passive cooling in office buildings based on uncertainty and sensitivity analysis, Sol. Energy 84 (8) (Aug. 2010) 1453–1467, https://doi.org/10.1016/j.solener.2010.05.008.

[35] M. Kolokotroni, I. Giannitsaris, R. Watkins, The effect of the London urban heat island on building summer cooling demand and night ventilation strategies, Sol. Energy 80 (4) (Apr. 2006) 383–392, https://doi.org/10.1016/j.solener.2005.03.010.

[36] J. Pfafferott, S. Herkel, M. Wambsganß, Design, monitoring and evaluation of a low energy office building with passive cooling by night ventilation, Energy Build. 36 (5) (May 2004) 455–465, https://doi.org/10.1016/j.enbuild.2004.01.041.

[37] J. Pfafferott, S. Herkel, M. Jäschke, Design of passive cooling by night ventilation: evaluation of a parametric model and building simulation with measurements, Energy Build. 35 (11) (Dec. 2003) 1129–1143, https://doi.org/10.1016/j.enbuild.2003.09.005.

[38] C. Heracleous, A. Michael, Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions, Energy 165 (Dec. 2018) 1228–1239, https://doi.org/10.1016/j.energy.2018.10.051.

[39] T.R. Oke, The heat island of the urban boundary layer: characteristics, causes and effects, in: J.E. Cermak, A.G. Davenport, E.J. Plate, D.X. Viegas (Eds.), Wind Climate in Cities, Springer Netherlands, Dordrecht, 1995, pp. 81–107, https://doi.org/10.1007/978-94-017-3686-2_5.

[40] S. Salimi, E. Estrella Guillén, H. Samuelson, Exceedance Degree-Hours: a new method for assessing long-term thermal conditions, Indoor Air 31 (6) (Nov. 2021) 2296–2311, https://doi.org/10.1111/ina.12855.

[41] S. Attia, T. Canonge, M. Popineau, M. Cuchet, Developing a benchmark model for renovated, nearly zero-energy, terraced dwellings, Appl. Energy 306 (Jan. 2022), 118128, https://doi.org/10.1016/j.apenergy.2021.118128.

[42] M. Sheng, M. Reiner, K. Sun, T. Hong, Assessing thermal resilience of an assisted living facility during heat waves and cold snaps with power outages, Build. Environ. 230 (Feb. 2023), 110001, https://doi.org/10.1016/j.buildenv.2023.110001.

[43] M. Hamdy, S. Carlucci, P.J. Hoes, J.L.M. Hensen, The impact of climate change on the overheating risk in dwellings - a Dutch case study, Build. Environ. 122 (Sep. 2017) 307–323, https://doi.org/10.1016/j.buildenv.2017.06.031.

[44] D. Amaripadath, et al., Climate change sensitive sizing and design for nearly zero-energy office building systems in Brussels, Energy Build. 286 (2023), 112971, https://doi.org/10.1016/j.enbuild.2023.112971.

[45] ANSI/ASHRAE, ASHRAE Standard 169: Climatic Data for Building Design Standards, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA, 2013.

[46] R. Rahif, D. Amaripadath, S. Attia, Review on time-integrated overheating evaluation methods for residential buildings in temperate climates of Europe, Energy Build. 252 (Dec. 2021), 111463, https://doi.org/10.1016/j.enbuild.2021.111463.

[47] Davis Instruments, User Manual – Integrated Sensor Suite, Davis Instruments, Hayward, CA, USA, 2022 [Online]. Available: https://cdn.shopify.com/s/files/1/0515/5992/3873/files/07395.333_VP2_ISS_Manual_RevM_web.pdf?v=1661460996. (Accessed 18 January 2023).

[48] G. Ouzeau, et al., Heat waves analysis over France in present and future climate: application of a new method on the EURO-CORDEX ensemble, Climate Services 4 (Dec. 2016) 1–12, https://doi.org/10.1016/j.cliser.2016.09.002.

[49] A. Machard, et al., A methodology for assembling future weather files including heatwaves for building thermal simulations from the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) climate data, Energies 13 (13) (2020), https://doi.org/10.3390/en13133424.

[50] M.Y. Joshi, D. Amaripadath, A. Machard, S. Attia, Heatwaves Identification Classification and Visualisation with python: v.1.0.0, Zenodo, 2022, https://doi.org/10.5281/zenodo.7326894.

[51] A. Machard, AMachard/Assembling-Future-Weather-Files-Including-heatwaves: v1.0.0, Zenodo, 2022, https://doi.org/10.5281/zenodo.7300024.

[52] H. Saeed Khan, R. Paolini, P. Caccetta, M. Santamouris, On the combined impact of local, regional, and global climatic changes on the urban energy performance and indoor thermal comfort—the energy potential of adaptation measures, Energy Build. 267 (Jul. 2022), 112152, https://doi.org/10.1016/j.enbuild.2022.112152.

[53] A.P. Gagge, Y. Nishi, R. Gonzalez, Standard effective temperature - a single temperature index of temperature sensation and thermal discomfort, in: CIB Commission W45 Symposium, 1972. London, UK.

[54] ANSI/ASHRAE, ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA, 2020.

[55] ANSI/ASHRAE, ASHRAE Handbook - Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA, 2009.

[56] ISO, ISO 17772-1. Energy Performance of Buildings – Indoor Environmental Quality. Part 1: Indoor Environmental Input Parameters for the Design and Assessment of Energy Performance in Buildings, International Standards Organization, Geneva, Switzerland, 2017.

[57] F. Tartarini, S. Schiavon, T. Cheung, T. Hoyt, CBE Thermal Comfort Tool: online tool for thermal comfort calculations and visualizations, SoftwareX 12 (Jul. 2020), 100563, https://doi.org/10.1016/j.softx.2020.100563.

[58] CIBSE, CIBSE TM52, The Limits of Thermal Comfort: Avoiding Overheating in European Buildings, Chartered Institution of Building Services Engineers, London, UK, 2013.

[59] R.G. Steadman, The assessment of sultriness. part I: a temperature-humidity index based on human physiology and Clothing Science, J. Appl. Meteorol. 18 (7) (1979) 861–873.

[60] X. Luo, T. Hong, K. Sun, Simulating thermal resilience of buildings and their influence by urban microclimate using EnergyPlus, in: IBPSA Building Simulation Conference, Bruges, Belgium, 2021, https://doi.org/10.26868/25222708.2021.30174.

[61] K.B. Metzger, K. Ito, T.D. Matte, Summer heat and mortality in New York City: how hot is too hot? Environ. Health Perspect. 118 (1) (2010) 80–86, https://doi.org/10.1289/ehp.0900906.

[62] CEN, EN 16798-1: Energy Performance of Buildings - Ventilation for Buildings - Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, European Committee for Standardization, Brussels, Belgium, 2019.

[63] M. Carlier, Nearly Zero-Energy Building Definitions in Selected Countries, Master Thesis, Ghent University, Ghent, Belgium, Jul. 2016 [Online]. Available: www.libstore.ugent.be/fulltxt/RUG01/002/301/108/RUG01-002301108_2016_0001_AC.pdf.

[64] IBGE, "Performance Energétique des Bâtiments, Guide des exigences et des procédures de la 960 réglementation Travaux PEB en Région de Bruxelles Capitale, 2017. Brussels, Belgium.

[65] D. Amaripadath, M. Velickovic, S. Attia, Performance evaluation of a nearly zero-energy office building in temperate oceanic climate based on field measurements, Energies 15 (18) (2022), https://doi.org/10.3390/en15186755.

[66] Performance Énergétique des Bâtiments, "La performance énergétique des bâtiments - La PEB, une réglementation à 3 volets," Environnement Brussels, Belgium [Online]. Avaiable: www.environn ement.brussels/thematiques/batiment-et-energie/obligations/la-performance-energetique-des-batiments-peb. (Accessed 25 February 2022).

[67] M. Hamdy, K. Sirén, S. Attia, Impact of financial assumptions on the cost optimality towards nearly zero energy buildings – a case study, Energy Build. 153 (2017) 421–438, https://doi.org/10.1016/j.enbuild.2017.08.018.

[68] S. Attia, N. Shadmanfar, F. Ricci, Developing two benchmark models for nearly zero energy schools, Appl. Energy 263 (2020), 114614, https://doi.org/10.1016/j.apenergy.2020.114614.

[69] ANSI/ASHRAE, ASHRAE Guideline 14: Measurement of Energy, Demand, and Water Savings, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA, 2014.

[70] H. Bakhtiari, J. Akander, M. Cehlin, A. Hayati, On the performance of night ventilation in a historic office building in Nordic climate, Energies 13 (16) (Aug. 2020) 4159, https://doi.org/10.3390/en13164159.

[71] P. Rumsey, J. Le Garrec, A. Levasseur, How building decarbonization can transform HVAC, ASHRAE J. 63 (9) (Sep. 2021) 14–27.

[72] N. Dodd, S. Donatello, M. Cordella, Level(s) Indicator 4.1: Indoor Air Quality, JRC Technical reports, European Commission, Brussels, Belgium, 2020 [Online]. Available: https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2020-10/20201013%20New%20Level(s)%20documentation_Indicator%204.1_Publication%20v1.0.pdf. (Accessed 2 December 2022).

[73] A. O'Donnavan, et al., "Ventilative Cooling Design Guide," Venticool, Aalborg University, Aalborg, Denmark, 2022 [Online]. Available: https://venticool.eu/wp-content/uploads/2016/11/VC-Design-Guide-EBC-Annex-62-March-2018.pdf. (Accessed 4 December 2022).

[74] U. Mathur, R. Damle, Impact of air infiltration rate on the thermal transmittance value of building envelope, J. Build. Eng. 40 (Aug. 2021), 102302, https://doi.org/10.1016/j.jobe.2021.102302.

[75] C. Younes, C.A. Shdid, G. Bitsuamlak, Air infiltration through building envelopes: a Review, J. Build. Phys. 35 (3) (2011) 267–302, https://doi.org/10.1177/1744259111423085.

[76] ISO, ISO 15927-2: Hygrothermal Performance of Buildings - Calculation and Presentation of Climatic Data - Part 2: Hourly Data for Design Cooling Load, International Standards Organization, Geneva, Switzerland, 2009.

[77] J. Żuławińska, Wet Bulb Calculator, Omni Calculator, 2022 [online]. Available: www.omnicalculator.com/physics/wet-bulb. (Accessed 17 March 2022).

[78] D.J. Vecellio, S.T. Wolf, R.M. Cottle, W.L. Kenney, Evaluating the 35°C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project), J. Appl. Physiol. 132 (2) (Feb. 2022) 340–345, https://doi.org/10.1152/japplphysiol.00738.2021.

[79] R. Ramponi, I. Gaetani, A. Angelotti, Influence of the urban environment on the effectiveness of natural night-ventilation of an office building, Energy Build. 78 (Aug. 2014) 25–34, https://doi.org/10.1016/j.enbuild.2014.04.001.

[80] G.P. Peters, et al., The challenge to keep global warming below 2 °C, Nat. Clim. Change 3 (1) (Jan. 2013) 4–6, https://doi.org/10.1038/nclimate1783.

[81] J. Hansen, M. Sato, R. Ruedy, A. Lacis, V. Oinas, Global warming in the twenty-first century: an alternative scenario, Proc. Natl. Acad. Sci. USA 97 (18) (Aug. 2000) 9875–9880, https://doi.org/10.1073/pnas.170278997.

[82] M.A. Folkerts, et al., Long term adaptation to heat stress: shifts in the minimum mortality temperature in The Netherlands, Front. Physiol. 11 (2020), https://doi.org/10.3389/fphys.2020.00225.

[83] J.D. Périard, S. Racinais, M.N. Sawka, Adaptations and mechanisms of human heat acclimation: applications for competitive athletes and sports, Scand. J. Med. Sci. Sports 25 (Jun. 2015) 20–38, https://doi.org/10.1111/sms.12408.

[84] J.D. Périard, G.J.S. Travers, S. Racinais, M.N. Sawka, Cardiovascular adaptations supporting human exercise-heat acclimation, Auton. Neurosci. 196 (Apr. 2016) 52–62, https://doi.org/10.1016/j.autneu.2016.02.002.

[85] G. Hatvani-Kovacs, M. Belusko, J. Pockett, J. Boland, Heat stress-resistant building design in the Australian context, Energy Build. 158 (Jan. 2018) 290–299, https://doi.org/10.1016/j.enbuild.2017.10.025.

[86] D. Amaripadath, R. Rahif, M. Velickovic, S. Attia, A systematic review on role of humidity as an indoor thermal comfort parameter in humid climates, J. Build. Eng. 68 (2023), 106039, https://doi.org/10.1016/j.jobe.2023.106039.

[87] T. Hong, Y. Xu, K. Sun, W. Zhang, X. Luo, B. Hooper, Urban microclimate and its impact on building performance: a case study of San Francisco, Urban Clim. 38 (Jul. 2021), 100871, https://doi.org/10.1016/j.uclim.2021.100871.

[88] A. Baniassadi, D.J. Sailor, E.S. Krayenhoff, A.M. Broadbent, M. Georgescu, Passive survivability of buildings under changing urban climates across eight US cities, Environ. Res. Lett. 14 (7) (Jul. 2019), 074028, https://doi.org/10.1088/1748-9326/ab28ba.

[89] EPA, Heat Island Impacts [Online]. Available:, United States Environmental Protection Agency, Washington DC, USA, 2022 https://www.epa.gov/heatislands/heat-island-impacts#_ftn1. (Accessed 4 January 2023).

[90] A. Sakka, M. Santamouris, I. Livada, F. Nicol, M. Wilson, On the thermal performance of low income housing during heat waves, Energy Build. 49 (Jun. 2012) 69–77, https://doi.org/10.1016/j.enbuild.2012.01.023.

[91] C.R. O'Lenick, O.V. Wilhelmi, R. Michael, M.H. Hayden, A. Baniassadi, C. Wiedinmyer, A.J. Monaghan, P.J. Crank, D.J. Sailor, Urban heat and air pollution: a framework for integrating population vulnerability and indoor exposure in health risk analyses, Sci. Total Environ. 660 (Apr. 2019) 715–723, https://doi.org/10.1016/j.scitotenv.2019.01.002.

[92] K. Maxwell, et al., Built Environment, urban systems, and cities, in: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, II, US Global Change Research Program, Washington DC, 2018, pp. 438–478, https://doi.org/10.7930/NCA4.2018.CH11.

[93] C. Zamuda, et al., Energy supply, delivery, and demand, in: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, II, U.S. Global Change Research Program, Washington DC, 2018, pp. 174–201, https://doi.org/10.7930/NCA4.2018.CH4.

[94] M. Rajput, et al., Heat exposure during a power outage: a simulation study of residences across the Metro Phoenix area, Energy Build. 259 (Mar. 2022), 111605, https://doi.org/10.1016/j.enbuild.2021.111605.

[95] B. Stone Jr., et al., Climate change and infrastructure risk: indoor heat exposure during a concurrent heat wave and blackout event in Phoenix, Arizona, Urban Clim. 36 (Mar. 2021), 100787, https://doi.org/10.1016/j.uclim.2021.100787.

[96] B. Stone Jr., et al., Compound climate and infrastructure events: how electrical grid failure alters heat wave risk, Environ. Sci. Technol. 55 (10) (May 2021) 6957–6964, https://doi.org/10.1021/acs.est.1c00024.

[97] Legal Information Institute, 10 CFR § 431.97 - energy efficiency standards and their compliance dates, Cornell Law School, NY, USA. [Online]. Available, https://www.law.cornell.edu/cfr/text/10/431.97#fn1_tbl2. (Accessed 12 December 2022).