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Heat exposure mitigation in renovated nearly zero-energy dwellings during concurrent heat waves and power outages

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ABSTRACT

As heat waves increase in intensity and duration, the risk of heat exposure in dwellings in countries with mixed humid climates is expected to rise. The impact of heat waves on building performance has been extensively researched. However, building performance during concurrent heat waves and power outages needs further investigation to reduce the dependency on active cooling during critical infrastructure failures. This paper presents a simulation-based study of heat exposure risks for a nearly zero dwelling during a concurrent heat wave and power outage in Brussels, Belgium using weather data from field measurements. Combinations of promising passive design strategies like natural ventilation, cool roof, and solar shading were evaluated along key performance indicators like indoor overheating degree, standard effective temperature, exceedance hours, and heat index. The building performance results showed that existing building-level passive cooling renovation strategies like natural ventilation alone would not be sufficient to mitigate heat exposure with an indoor overheating degree of 0.59 °C. Therefore, they will require additional passive measures like solar shading using window louvres to mitigate heat exposure risks and lower indoor overheating to 0.19 °C. The findings provide unique insights that inform building renovation practices, setting the stage for future research on the topic.

Abbreviations

ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBE	Center for the Built Environment
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DHW	Domestic Hot Water
EH	Exceedance Hours
EN	European Standard
EU	European Union

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HI	Heat Index
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IOD	Indoor Overheating Degree
ISO	International Organization for Standardization
KPI	Key Performance Indicator
MBE	Mean Bias Error
LEED	Leadership in Energy and Environmental Design
PHPP	Passive House Planning Package
RMI	Royal Meteorological Institute
SET	Standard Effective Temperature

1. Introduction

1.1. Background

Heat exposure in buildings has grown significantly in importance over the past few decades. The current rate of climate change makes it likely that the problem will worsen [1]. Another effect of this situation is compound events like heat waves and power outages. Such events may affect occupant well-being in dwellings, motivating the need to measure extreme heat events and characterize their impact [2]. When evaluating and developing passive climate change mitigation strategies, the frequency and intensity of heat waves are crucial indicators. There is minimal research in Europe currently that characterizes building thermal performance under a concurrent heat wave and power outage. Additionally, the increasing heat wave frequency and intensity during summer months will harm society [3,4], diminishing residents' quality of life and safety [5]. Dwellings will become less comfortable to live in due to the projected rise in temperature and frequent heat waves [6]. The health and comfort of the residents, especially older people, can be put at risk by the overheated and poorly ventilated sleeping and living areas. When exposed to high levels of solar radiation and internal heat gains, newly constructed structures are at a higher risk of heat exposure and overheating [7,8]. After the severe heat waves that hit Europe in 2006 from [9] and New York in 2003 from [10], building simulation communities began looking into how the current home stock might fare in case of such an extreme heat event [11,12]. Recently, it has become more apparent that extreme heat events will impact the generation and transmission of power supply as per [13] due to increased cooling demand leading to transformer overheating.

Furthermore, our society depends on electricity, and an unexpected power failure can impact multiple levels of society, including households and industry. The population can be exposed to dangerously high levels of heat both outside and inside buildings when power outages coincide with heat waves [14], as had recently happened when the electrical networks were overloaded by high peak demand, making active cooling systems inoperable. The Belgian National Crisis Center performed a large-scale risk assessment for 2018 to 2023 in [15] to study the possible impact and frequency of various natural and anthropogenic disasters in 2018. The possible impact and probability of heat waves and power outages were assessed as part of this report. According to the current forecasts from [16], climate change will exacerbate the intensity and frequency of these risks. However, the assessment did not include a risk analysis for Belgium's concurrent heat waves and power outages. Buildings relying solely on mechanical ventilation and air conditioning may become inhospitable during heat events and power outages due to rising temperatures beyond what humans can tolerate [17]. Therefore, buildings should be designed and retrofitted passively since they can significantly increase thermal resilience against heat waves [18]. To maintain a comfortable indoor thermal climate during a power outage, a building must rely on passive strategies to retain cool air, lower internal heat gains, and remove excess heat outdoors.

1.2. Literature review

A systematic literature review on resilient cooling strategies focused on their performance during extreme heat events was conducted in [19]. The review concluded that a combination of cooling strategies with various capacities is necessary to achieve resilient cooling of buildings during an extreme event. This is because a single cooling strategy typically does not have all the necessary resilience capacities, like limiting heat gains, reducing sensible/latent heat, and improving personal comfort [19]. The study also noted the significance of developing a numerical-based approach to test these strategies. Some key literature on building thermal performance during extreme heat events is explained here. Stone et al. [13] found that building-interior heat exposures will increase with urban heat island (UHI) intensity and building structure type. Furthermore, Stone et al. [20] indicated that 1-story single-family houses were found to be slightly cooler at night or equivalent to multistory houses since they had less internal volume to cool off. Furthermore, due to shared walls that lowered solar gain during the day, apartment buildings exhibited lower maximum and lowest temperatures than multistory houses. Furthermore, the effect of shading was minimal when the landscape design included less dense trees that blocked a small fraction of solar radiation on the facades in Rajput et al. [12]. Using building simulations, Sheng et al. [21] evaluated thermal resilience in an assisted living facility. The study found that energy-saving measures like passive strategies increased thermal resilience while reducing the backup power capacity by 19%.

Additionally, Baniassadi et al. [22] explored the impact of new energy codes on building passive survivability and found that energy codes are becoming less resilient to heat exposure in buildings in some colder climates. In the same way, the findings from Zeng et al. [23] identified the factors that influence the potential of pre-cooling to mitigate overheating in residential buildings. This study extracted an improved rule-based pre-cooling schedule from an optimized schedule tested in Fresno, California. Similarly, Sailor et al. [24] predicted indoor temperature in four residential buildings using measured data from temperature sensors equipped to monitor the rise in indoor temperature during power outages. The study simulated a power outage in Phoenix by turning off the air conditioning. However, the power outage in Houston was caused by Hurricane Harvey and was not planned. The impact of heat exposure at nighttime prevents physiological recovery from high daytime temperatures, which is required for adequate thermoregulation [25]. Eleven different passive measures were evaluated for prototype buildings by Sun et al. [26], and the study found that installing window films and adding roof insulation were the most effective measures against heat exposure. Studies from Amada et al. [27] found that a family of four living in a net zero-energy home with a photovoltaic production of 4.62 kW and a storage battery capacity of 5.6 kWh can remain at home with 24-h air-conditioning in the living room and ventilation by daytime during a 72-h summer power outage in sunny weather in Japan while maintaining acceptable thermal comfort and preventing the risks of heat stroke.

1.3. Knowledge gaps

The analysis of recent literature indicated the following missing aspects. Despite the risk of serious health consequences, minimal research has been done up to this point on heat exposures brought on by concurrent heat waves and power outages in Europe. This study assessed how a concurrent heat wave and power outage elevate heat exposure in the reference dwelling for different combinations of passive cooling strategies. Furthermore, most studies from existing literature characterize heat exposure using key performance indicators (KPIs) that are point-in-time and express thermal comfort as a binary factor – comfortable vs. uncomfortable [28], which do not give the extent of overheating in the building. On the contrary, the time-integrated overheating index used in this study provides the extent of overheating in the reference dwelling, considering the operative temperature in each building zone. The present study aims to contribute to thermal building resilience research by simulating the performance of different passive cooling strategies during intense heat periods.

1.4. Research objectives

The present study aims to fill this gap by assessing passive cooling strategies like natural ventilation that will retain cool air and/or expel excess heat, a cool roof that will limit excess heat gains, and window louvres that will limit excess heat gains in a renovated reference dwelling. The study's main objective is to assess heat exposure in renovated dwellings during a concurrent heat wave and power outage and how it can be mitigated using passive strategies.

1.5. Relevance and novelty

Nearly zero-energy buildings are defined as "A building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby," according to Energy Performance of Buildings Directive from the European Union [29]. The nearly zero-energy building requirements have been in place in the Brussels-Capital Region since 2010, and it is one of the European cities with a significant number of passive house buildings [30]. The Brussels-Capital Region has placed stringent guidelines, which aim for "nearly zero" or "very low" energy consumption, based on the "passive house standard," which prioritizes high energy efficiency. Since announcing this policy, many terraced row dwellings have been renovated to meet the nearly zero-energy building codes. The relevance of the study is based on the following aspects. Findings from [31] indicate that present building-level renovation measures alone will not reduce overheating in the reference renovated nearly zero-energy dwelling and require active cooling. However, active cooling will become inoperable during a concurrent heat wave and power outage, increasing the risk of overheating and heat exposure in the reference dwelling. Therefore, it is necessary to identify possible passive retrofit strategies to mitigate these scenarios. Additionally there is a significant increase in observed hourly outdoor air temperature during the heat wave period in 2022 compared to the same period in 2021, as shown in Fig. 1. The mortality rate from the Belgian Mortality Monitoring (Be-MOMO) model

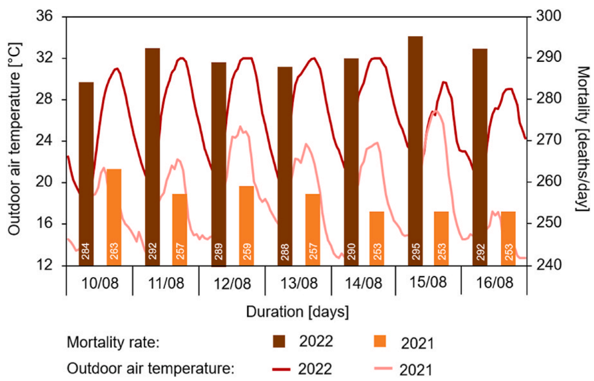

Fig. 1. The hourly outdoor air temperature and observed mortality rate in Belgium, excluding the COVID-19 pandemic from the Belgian Mortality Monitoring (Be-MOMO) during the heat wave period in 2022 compared to the same period in 2021.

from [32] during the heat wave from August 10 to August 16 in 2022 was 13% higher compared to the same period in 2021 and is also shown in Fig. 1. The daily observed numbers are the average of the previous day, three previous days, and three subsequent days. The increase in mortality rate can be attributed to the impact of a heat wave, as the analysis excluded mortality due to the COVID-19 pandemic.

In addition to contributing to the development of numerical-based approaches to test the mitigation potential of passive cooling strategies as suggested in [19], the main novelty of the study is in the hybrid thermal comfort modeling approach that uses a combination of static model and adaptive model based on the purpose of the specific building zone. Furthermore, the original contributions of the paper are that it simulates a calibrated model for renovated nearly zero-energy dwellings representing the renovated dwelling stock in Brussels for a concurrent heat wave and power outage using the latest real measured data during the hot summer of 2022. Furthermore, it provides real performance reference data for a renovated dwelling equipped with different passive measures during extreme heat events, and this is beneficial for policymakers, architects, engineers, consultants, and contractors to address the renovation challenges in existing buildings.

2. Methodology

The study was conducted in Brussels, Belgium. The climate in Brussels is classified as mixed humid (4A) according to ASHRAE 169 – Climatic data for building design standards [33]. The primary objective of building design in such heating-dominated areas has been to keep the indoor environment warm during the winter using airtight and highly insulated designs [31,34]. It will be difficult to prevent heat exposure risks during a concurrent heat wave and power outage due to the unavailability of active cooling solutions. As a result, the thermal performance of the reference dwelling was assessed using different passive strategies to assess their cooling potential to mitigate heat exposure. The workflow used in this study is shown in Fig. 2. The global study approach like data collection, heat wave identification, and KPIs is illustrated through a case study to demonstrate and ease the replicability of the work.

a A weather station was mounted on a lamp post at a height of 6 m to prevent vandalism and on a street with buildings on both sides and regular traffic at 4 km from the Brussels city center to characterize the hot summer weather and to detect the heat waves during the summer of 2022 as described in [35]. This is shown in Fig. 3(a).
b The thermal performance of a calibrated renovated nearly zero-energy dwelling from [30,36] was assessed for a concurrent heat wave and power outage using different passive cooling strategies like natural ventilation, cool roof, and louvres. The reference dwelling is shown in Fig. 3(b).
c A power outage in the building is simulated by switching off the mechanical ventilation, which would otherwise be operational in the building. The lighting and equipment are assumed to be switched off due to the concurrent power outage. Mechanical ventilation is then substituted using natural ventilation through window opening to maintain minimum hygienic levels.

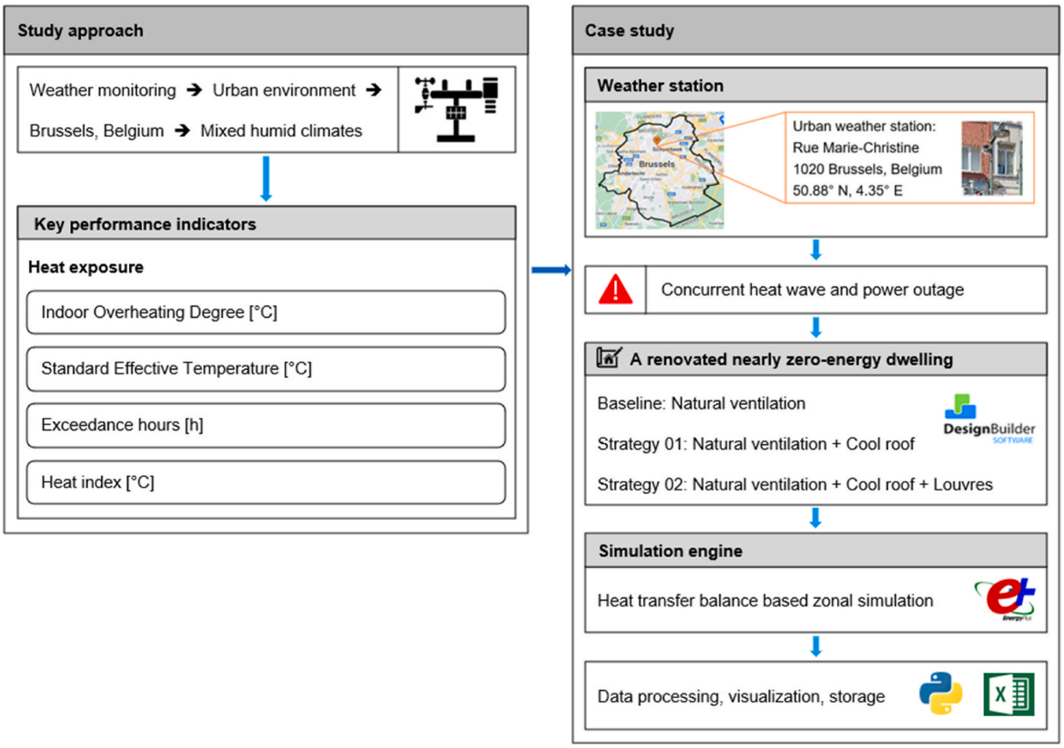

Fig. 2. Proposed workflow for thermal performance assessment in a renovated nearly zero-energy dwelling during a concurrent heat wave and power outage

d The heat exposure in the reference dwelling was characterized using Indoor Overheating Degree (IOD) [°C], Standard Effective Temperature (SET) [°C], Exceedance Hours (EH) [hours], and Heat Index (HI) [°C].

2.1. Study approach

2.1.1. Heat waves

Heat waves were identified using the methodology proposed by [37] and implemented in [38] using different thresholds. The approach from [37] was based on three thresholds estimated over a period of years, calculated from absolute values to percentiles of the distribution of daily mean temperatures. Since these values can be determined separately for different locations, the method can be applied to wider areas and climate zones. The heat wave threshold values were calculated using weather data from 2000 to 2020 from the Royal Meteorological Institute (RMI) Opendata Platform in [39] and extracted from a weather station in Uccle, approximately 11 km from Brussels, whereas the weather data used for heat wave detection in the analysis were collected from a local weather station in the City of Brussels at coordinates 50.86 °N and 4.35 °E. The heat wave thresholds calculated for the study location is as follows:

a. Spic (99.5%) is the threshold beyond which a heat wave is detected and calculated as 25.97 °C.
b. Sdeb (97.5%) is the threshold that determines when a heat wave begins and ends, and calculated as 22.63 °C.
c. Sint (95%) is the interruption threshold that allows the merging of two consecutive heat waves without a significant drop in temperature and calculated as 21.06 °C.

The global intensity [°C.days] is calculated by dividing the cumulative difference between the temperature and Sdeb throughout the event, divided by Spic-Sdeb difference as given in Eq. (1) from [18].

$$Global\ intensity = \frac{\sum (T_m - S_{deb})}{(S_{pic} - S_{deb})} \tag{1}$$

where T_m is the daily mean temperature in [°C]. The air temperature [°C] and relative humidity [%] values monitored during the measurement period is depicted in Fig. 4. The measurement indicates a reverse relationship between air temperature [°C] and relative humidity [%] during the monitored period, with increased temperature accompanied by decrease in relative humidity. A custom Python script from [40], which was developed based on [41], detected a 7-day heat wave from August 10, 2022, to August 16, 2022, as shown in Fig. 5. The y-axis depicts the amplitude of the heat wave in °C and x-axis depicts the total duration of the heatwaves in days.

2.1.2. Key performance indicators (KPIs)

The performance of the target variables evaluated in this study was quantified using different KPIs. This study evaluated the degree of discomfort caused by overheating using IOD from [8]. The IOD is a multizonal index that adds the total number of cooling degree hours divided by the total number of zonal occupied hours, as shown in Eq. (2).

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

Fig. 3. Illustration of the study setup: a. weather station installed in Brussels; b. reference renovated nearly zero-energy dwelling in Brussels.

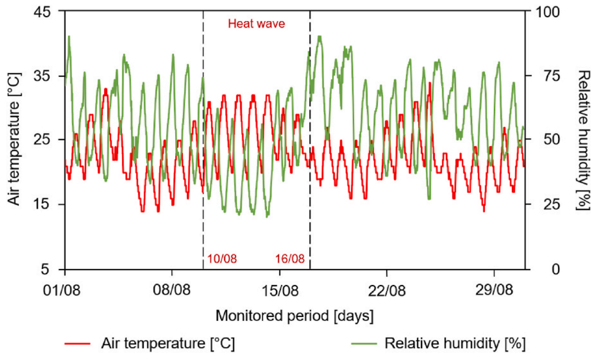

Fig. 4. Air temperature and relative humidity values monitored during the measurement period during August 2022.

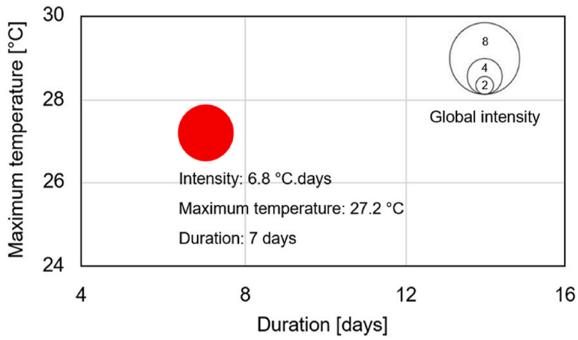

Fig. 5. The heat wave characteristics detected in Brussels from August 10, 2022, to August 16, 2022.

where Z is the number of total conditioned zones in the building, i is the occupied hour counter, $N_{occ}(z)$ is the total number of zonal occupied hours in zone z, $T_{in,z,i}$ is the indoor operative temperature [°C] in zone z at time step i, $T_{comf,upper,z,i}$ is the maximum comfort threshold in zone z at hour i. The overheating impact of the intense heat wave on the reference dwelling was categorized according to [42] as moderate impact if $IOD \leq 0.5°C$, strong impact if $0.5°C < IOD < 2°C$, and extreme impact if $IOD \geq 2°C$. An excel based tool for calculating IOD is available in [43].

The thermal comfort in the reference dwelling was evaluated using exceedance hours (EH). The number of occupied hours within a defined period during which the environmental conditions in an occupied area are outside of the specified limits is known as exceedance hours [h] [44]. This is shown in Eq. (3). The bedrooms in the reference dwelling are assessed using the static model based on studies from Refs. [45,46], which recommended an indoor temperature of not greater than 26 °C for the sleeping areas during summer. Furthermore, the results from [47] showed that even healthy people who do not have insomnia would be affected by excessively hot temperatures in sleeping areas. For Bedrooms, the static model using operative temperature limits was used as in Eq. (3). In contrast, for Office and Living + Kitchen areas, an adaptive model using operative temperature limits was used as in Eq. (4). The calculation methodology for exceedance hours is explained in ASHRAE 55 – Thermal environmental conditions for human occupancy [44].

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

where, $H_{disc} = 1;\ if\ |PMV| > 0.5.$

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

$$EH_{op} = \sum_{i=1}^{N_{occ}(z)} H_{disc} \tag{4}$$

where, $H_{disc} = 1;\ if\ T_{op,i} < T_{comf,lower,z,i}\ (or)\ T_{op,i} > T_{comf,upper,z,i}.$

$H_{disc} = 0;\ if\ T_{comf,lower,z,i} \leq T_{op,i} \leq T_{comf,upper,z,i}$

where, $T_{op,i}$ is the indoor operative temperature [°C] and H_{disc} is the discomfort hours [h].

The $T_{comf,upper,z,i}$ for IOD [°C] and EH [h] were derived from the International Organization for Standardization (ISO) 17772-1 –

Energy performance of buildings adaptive model category II limits [48]. Category II limits are recommended for new and renovated dwellings. Furthermore, the European Standard (EN) 16798-1 – Energy performance of buildings [49] recommends similar limits for category II dwellings. Eq. (5) and Eq. (6) show the upper and lower limits for adaptive model category II buildings [48]. These are computed based on the outdoor running mean temperature (T_{rm}).

$$T_{comf,upper,z,i} = 0.33 \times T_{rm} + 18.8 + 3 \tag{5}$$

$$T_{comf,lower,z,i} = 0.33 \times T_{rm} + 18.8 - 4 \tag{6}$$

SET considers the indoor air temperature [°C], relative humidity [%], mean radiant temperature [°C], air velocity [m/s], metabolic rate [W/m^2], and clothing factor [clo] as per [21]. SET is an ASHRAE 55 [44] recommended temperature index. The Center for the Built Environment (CBE) thermal comfort tool in [50] calculates the SET values. SET degree-hours [°C-hours] is the number of hours spent above the upper temperature limit expressed as a percentage of total occupied hours. Livable conditions are defined as SET between 12.2 °C and 30 °C in the LEED v4.1 credit for passive survivability [21]. Thermal survivability can be assessed using SET in hot and cold events [51]. To receive the LEED credit for residential buildings, the unlivable number of SET degree-hours above 30 °C for a seven-day power outage during an extremely hot event must not exceed 120 °C-hours for passive strategies.

The heat index from [52] is a hygrothermal comfort index used in the study to evaluate the indoor environment in the reference building. It is also known as apparent temperature and measures how it feels when relative humidity [%] and air temperature [°C] are considered. However, when relative humidity is high, the evaporation process is less effective, and the body cannot cool down as effectively, and it feels much hotter to the human body when the humidity in the air is considered. Heat index formula from [53] is used in this study. The heat index provides thresholds for how much heat the human body can withstand before becoming dangerous and a more precise representation of how it feels. The percentage of heat index hours [%] represents the number of hours that fall into each risk category as a percentage of total occupied hours [54].

This study assesses the building performance using various KPIs to evaluate thermal environment during a concurrent heat wave and power outage. While IOD and EH focus on operative temperature, SET incorporates relative humidity, air speed, metabolic rate, and clothing levels. Additionally, HI incorporates air temperature and relative humidity. A multi-indicator assessment was done based on existing simulation guidelines from IEA EBC Annex 80 – Resilient Cooling in Buildings like [55] that recommends various key performance indicators. Additionally, each KPI adds a unique perspective to the analysis. IOD is a time-integrated and multizonal index that gives the extent of overheating, SET incorporates human physiological factors to calculate the heat stress, EH indicates the intensity and duration of heat exposure, and HI provides a realistic measure of how it feels by combining air temperature and relative humidity.

2.2. Case study

This study used a renovated, nearly zero-energy renovated dwelling with a rectangular plan in Brussels as the reference model. The reference dwelling used in this study accurately represents 39 renovated, nearly zero-energy dwellings in Brussels, as described in [30]. Plans and layouts of these 39 dwellings were examined and the most common layout shape was long and narrow rectangles with narrow gardens. Based on the variance analysis of the energy use intensity of the thirty-nine households, the reference residence was determined to be the representative dwelling. The construction age (pre-World War I), energy efficiency (nearly zero-energy building renovations), building architecture (terraced row houses), surface area, and occupant demographics (single-family homes) were considered while selecting the representative dwelling. The model was created using DesignBuilder v7.1 and EnergyPlus simulation engine v9.1 as described in [56] and validated using walkthrough audits, in-situ measurements, and four years of energy use bills. The actual energy performance of renovated homes was evaluated over time, which helped in understanding the building performance and occupancy of the real building as described in [30]. It was renovated and labeled a nearly zero-energy building that adhered to passive house standards [57] after 2010. The requirements for Passive House Planning Package (PHPP) calculation in Belgium mandate that total space heating and cooling demand should be less than or equal to 15 kWh/m^2 for conditioned spaces, and a maximum number of hours exceeding 25 °C must be less than or equal to 5% [58,59]. Furthermore, before exploring renewable energy sources, the energy demand in the building should be kept as low as possible.

The reference dwelling has 3 floors and a total area of 173 m^2. The reference dwelling has a family of four, including two parents aged around forty-five years and two children aged ten and seven. The occupancy schedule was created per ISO 18523-2 – Energy performance of buildings [60]. The average internal equipment gain was estimated to be 8 W/m2 based on the running hours and power value, and the average lighting power density was 8 W/m^2 for bedrooms and 12 W/m^2 for living areas. An estimated metabolic rate of 1 met based on a seated, relaxed activity and a clothing factor of 0.5 clo based on light summer wear with a short-sleeved shirt and light trousers as per ISO 7730 – Ergonomics of the thermal environment [61]. Water consumption was 62 L/person/day, and domestic hot water (DHW) was 30 L/person/day at 60 °C from [30]. Furthermore, 40–60 min per day was the estimated time for cooking activities from [30]. The multizonal thermal spaces in the reference dwelling were divided into three categories: living areas, including the Office and Living + Kitchen; Sleeping areas, including the Bedrooms; and Short-presence areas, including the bathrooms and corridors.

Mechanical ventilation with a heat recovery unit is available in the reference dwelling. The reference dwelling is heated with natural gas, and no active cooling is available. Furthermore, the reference structure had natural ventilation. This reference model's quality was ensured by calibration following the ASHRAE Guideline 14 [62] using real monthly energy use data for electricity use collected over four years from 2016 to 2019. Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Square Error (CV (RMSE)) values were 2.7%, and 5.6% for the monthly electricity use were within acceptable ranges. Additional information on the energy characteristics, occupancy density, occupancy schedule, lighting intensity, lighting schedules, HVAC systems, and comfort setpoints can be found in [30]. Mechanical ventilation with a heat recovery unit is installed in the reference dwelling. Fig. 6 depicts the reference dwelling used in this study. The building envelope characteristics are listed in Table 1.

Triple-glazed is a passive strategy already used in the reference building. Most windows have triple glazing since they were retrofitted after 2010. The overall performance of the windows is good, with a low conductivity value of around 1 W/m^2K [30]. The window-to-wall ratio is 35%. Based on the exterior conditions and building configurations, the EnergyPlus simulation engine calculated the thermal environment in the reference dwelling. This study evaluated three passive building configurations for a concurrent heat wave and power outage. In Baseline, the reference dwelling was naturally ventilated at 1 ACH to maintain hygienic ventilation rates and air quality according to EN 16798-1 – Energy performance of buildings [49]. This value was set considering minimum ventilation requirements since natural ventilation depends on favorable wind conditions. The maximum and minimum setpoint temperatures for natural ventilation are set at 26 °C and 20 °C [48].

Furthermore, the building benefits from natural night ventilation as the windows are kept open throughout the day. Natural

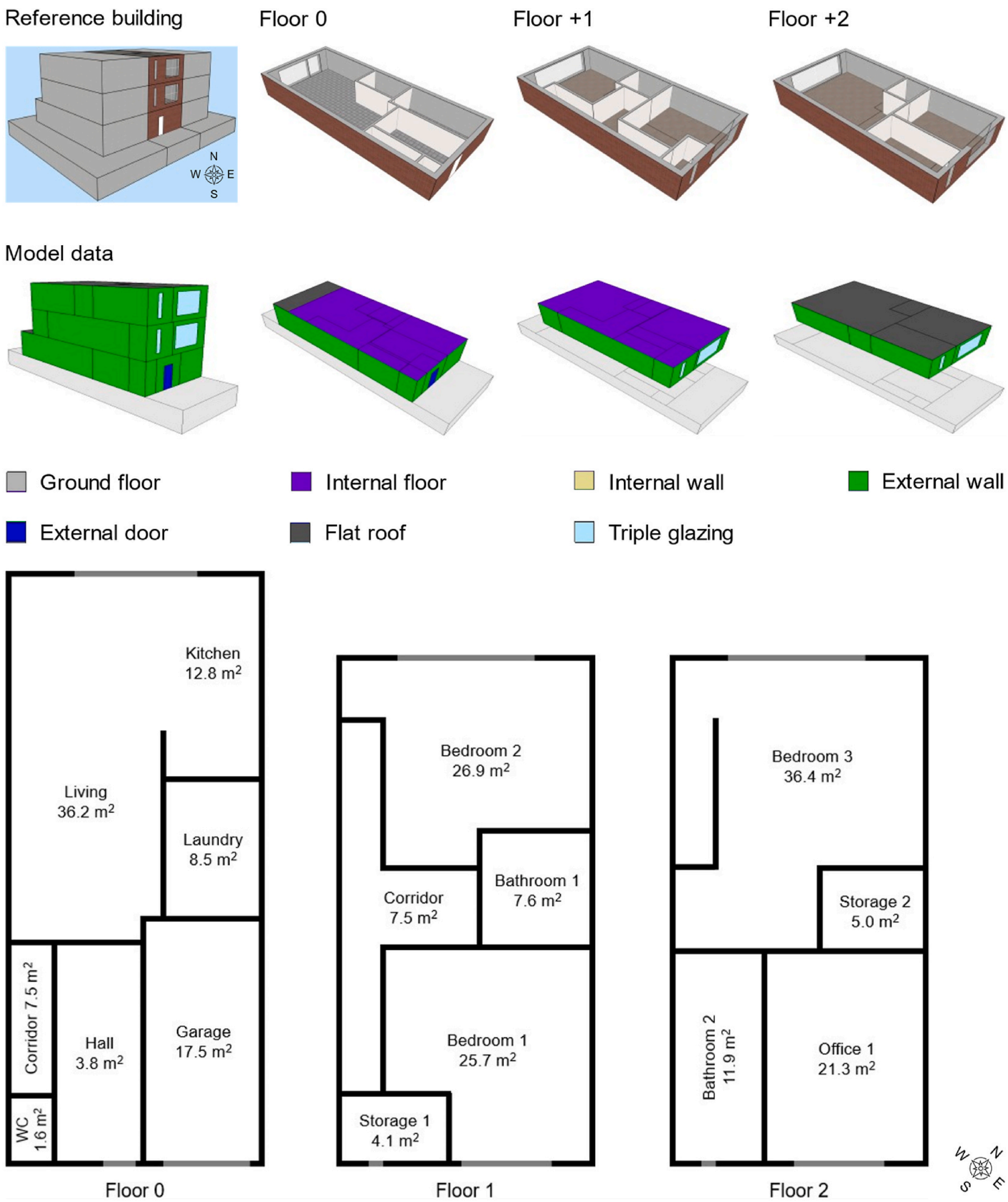

Fig. 6. The renovated nearly zero-energy dwelling energy performance simulation model.

Table 1
Composition of reference nearly zero-energy dwelling used in the study.

Envelope	Layers	Materials used	Thickness [m]	Thermal transmittance [W/m^{2}K]
Ground floor	Outer	Reinforced concrete with 2% steel	0.1200	0.300
	Third	Spray-on-R-12 insulation polyurethane foam	0.0796	
	Second	Cement screed	0.0100	
	Inner	Ceramic floor tiles	0.0050	
Internal floor	Outer	Perlite plastering	0.0150	0.800
	Fifth	Standard insulation	0.0228	
	Fourth	Reinforced concrete with 2% steel	0.1200	
	Third	Sandstone floor	0.0200	
	Second	Cement-bonded particle board	0.0100	
	Inner	Timber flooring	0.0150	
External floor	Outer	External rendering	0.0250	0.250
	Second	MV stone wool rolls	0.1482	
	Inner	Timber flooring	0.0050	
External roof	Outer	Asphalt	0.0100	0.300
	Third	MW glass wool rolls	0.1179	
	Second	Airgap	0.2000	
	Inner	Plasterboard	0.0130	
External wall	Outer	Brickwork	0.1000	0.400
	Second	Standard insulation	0.0818	
	Inner	Cast concrete of medium weight	0.1400	
Internal partition	Single	Cast concrete dense	0.1000	4.142
Doors	External	Painted oak	0.0350	2.823
Windows	External	Triple glazed, 3 triple pane layers filled with Air 6 mm		2.155

ventilation is included in the baseline rather than applying it as a passive strategy since natural ventilation is a default daily strategy in Belgium dwellings during summer [30]. The natural ventilation is opened and closed manually. When outdoor temperatures fall above 26 °C and below 20 °C, the windows are closed to avoid overheating and overcooling. In Strategy 01, a flexible elastomeric foam layer with white texture and color with a solar reflectance of 0.30 and thermal emissivity of 0.90 is added to the reference dwelling, as a cool roof was added to natural ventilation based on existing values from DesignBuilder. In Strategy 02, 6 steel louvre blades with 1 m projection and a 30° angle are installed at 0.3 m from each window, in addition to being naturally ventilated and a cool roof using a flexible elastomeric foam layer. Fixed louvres are a common solar shading strategy in Belgium [34,63]. The main benefit of using louvres for solar shading is that it is an eco-friendly option to decrease the extent of direct solar radiation, thereby reducing cooling needs. The louvre settings used in the study is shown in Fig. 7. The different configurations and passive strategies assessed in the study is listed in Table 2.

3. Results

This section presents the study results on how a concurrent heat wave and power outage impact a renovated, nearly zero-energy dwelling. The temporal distribution of indoor operative temperature [°C] in each zone is shown in Fig. 8. The temporal variations indicate significant variations in each individual zones, which is quantified using different KPIs. The maximum indoor operative temperature observed for Baseline was 30.6 °C and Strategy 01 was 30.5 °C. In comparison Strategy 02 indicated a value of 28.8 °C, a reduction of 5.9% and 5.6% compared to that of Baseline and Strategy 01. Similarly, the average indoor operative temperature across all zones for Baseline and Strategy 01 was 26.5 °C compared to 25.8 °C of Strategy 02, indicating a 2.6% reduction.

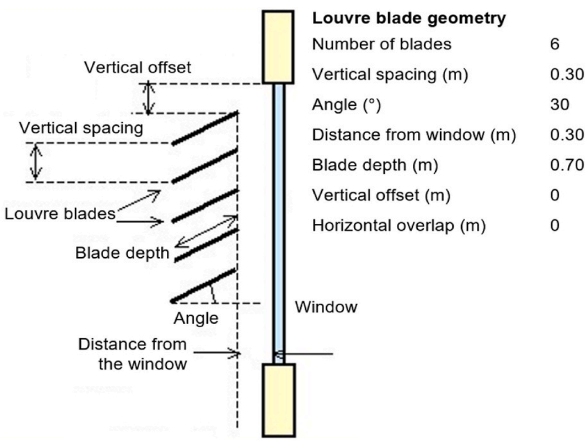

Fig. 7. Design of louvres on the reference nearly zero-energy dwelling windows adapted from DesignBuilder [64].

Table 2
Different configuration and passive strategies assessed in the study.

Configuration	Passive strategies
Baseline	Natural ventilation
Strategy 01	Natural ventilation + Cool roof
Strategy 02	Natural ventilation + Cool roof + Louvres

The analysis of indoor overheating for different passive measures during a concurrent heat wave and power outage is shown in Fig. 9. The indoor overheating results with impact on the built environment were highest at 0.59 °C for baseline configuration with natural ventilation, indicating a strong impact, 0.56 °C for Strategy 01 with natural ventilation and cool roof, 5% less than Baseline indicating a strong impact, and lowest at 0.19 °C for Strategy 02 with natural ventilation, cool roof, and louvres, 68% lower than Baseline indicating a moderate impact. Overall, Strategy 02 with a combination of natural ventilation, cool roof, and louvres exhibited lower IOD values compared to the two other scenarios, with a maximum difference of 1.01 °C and 0.98 °C, respectively, for Bedroom 2, which is the worst affected zone. The higher overheating in Bedroom 2 can be attributed to larger windows that contributes to higher solar gains.

The analysis of SET values for different passive measures during a concurrent heat wave and power outage is shown in Fig. 10. The analysis indicated that the renovated nearly zero-energy dwelling was within livable conditions according to LEED v4.1 credit for passive survivability and backup power with the hourly SET values within the upper limit of 30 °C [21,51]. There were no significant variations in Baseline and Strategy 01. Overall, Strategy 02 with a combination of natural ventilation, cool roof, and louvres exhibited lower SET values compared to the two other scenarios, with a maximum difference of 1.1 °C and 1 °C, at building level on August 16, 2022.

The analysis of the percentage of exceedance hours [%] for different passive measures during a concurrent heat wave and power outage is shown in Fig. 11, and Bedroom 2 was the worst affected zone in the reference dwelling. The percentage of exceedance hours [%] in Bedroom 2 due to overheating was highest at 46% for baseline configuration with natural ventilation, 46% for Strategy 01 with natural ventilation and cool roof was 46%, no less than Baseline with natural ventilation, and was lowest at 1% for Strategy 02 with natural ventilation, cool roof, and louvres. However, Strategy 02 introduced 4% exceedance hours due to overcooling. Overall, Strategy 02 with a combination of natural ventilation, cool roof, and louvres exhibited lower exceedance hour values compared to the two other scenarios, with a maximum difference of 0.84 and 0.83 in Predicted Mean Vote (PMV) values for Bedroom 2 on August 15, 2022.

The heat index thresholds for shaded areas without direct exposure to sun [65] are defined as: a. Heat index thresholds [65] are defined as: a. less than 27 °C: safe, b. from 27 °C to 32 °C: caution, c. from 32 °C to 41 °C: extreme caution, d. from 41 °C to 54 °C: danger, and over 54 °C: extreme danger. The analysis of the percentage of heat index hours [%] for different passive measures during a concurrent heat wave and power outage is shown in Fig. 12. The analysis provided insights into hygrothermal discomfort in the reference dwelling. The results for the worst affected zone, Bedroom 2, indicated that it was under caution for 54% of the occupied time for baseline configuration with natural ventilation, 54% of the occupied time for Strategy 01 with natural ventilation and cool roof, similar to Baseline, and 14% of the occupied time for Strategy 02 with natural ventilation, cool roof, and louvres, 40% lower compared to the other two configurations. Overall, Strategy 02 with a combination of natural ventilation, cool roof, and louvres exhibited lower heat index values compared to the two other scenarios. Additionally, Living + Kitchen areas are prone to hygrothermal exposure despite showing no signs of exceedance hours in Fig. 11 since the influence of relative humidity levels. To further improve hygrothermal exposure, measures to remove latent heat should be considered.

4. Discussions

This section presents the primary findings and limitations and makes suggestions to urban planners, engineers, and scientists for future practice and research based on the study findings.

4.1. Main findings and recommendations

Baseline with natural ventilation had limited potential in tackling heat exposure in the reference dwelling during a concurrent heat wave and power outage in Brussels, Belgium. Indoor overheating at 0.59 °C indicated a strong impact on the indoor environment. Exceedance hour analysis showed that the Bedroom 2 was the worst affected zone in the reference dwelling with an percentage of exceedance hours for 46% of the occupied time during the extreme event. Hygrothermal comfort analysis using heat index showed that the Bedroom 2 was in caution for 54% of the occupied time. SET values in the reference dwelling were within the upper limit of 30 °C for the entire event, maintaining the livable conditions per LEED v4.1 credit for passive survivability.

Adding a cool roof to natural ventilation in Strategy 01 did not yield any significant improvement in mitigating heat exposure in the reference dwelling, and this is in line with findings from Ref. [20] for multistory buildings. However, this can be attributed to the low solar reflectance coefficient of the cool roof material. Indoor overheating at 0.56 °C indicated a strong impact on the indoor environment. Exceedance hours due to overheating in the Bedroom 2 was 46% of the occupied time in Baseline. Hygrothermal comfort analysis using heat index indicated that the Bedroom 2 was in caution for 54% of the occupied time in Baseline. SET values in the reference dwelling were within the upper limit of 30 °C for the entire event, maintaining the livable conditions per LEED v4.1 credit for passive survivability.

Adding solar shading using window louvres to natural ventilation and a cool roof in Strategy 02 significantly improved heat

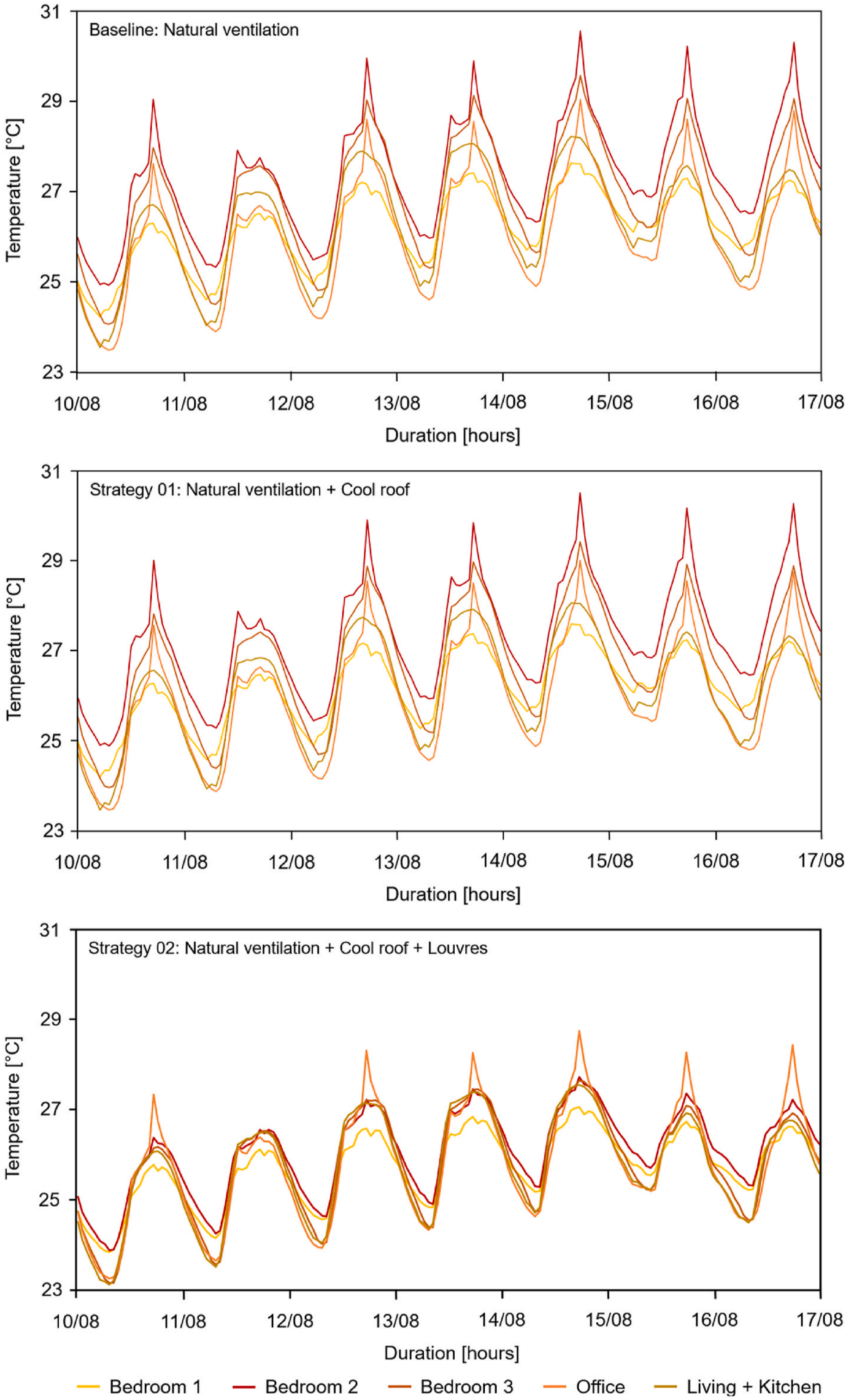

Fig. 8. Temporal distribution of indoor operative temperature [°C] for individual zones in the renovated nearly zero-energy dwelling for Baseline with natural ventilation, Strategy 01 with natural ventilation and cool roof, Strategy 02 with natural ventilation, cool roof, and louvres during a concurrent heat wave and power outage from August 10, 2022, to August 16, 2022.

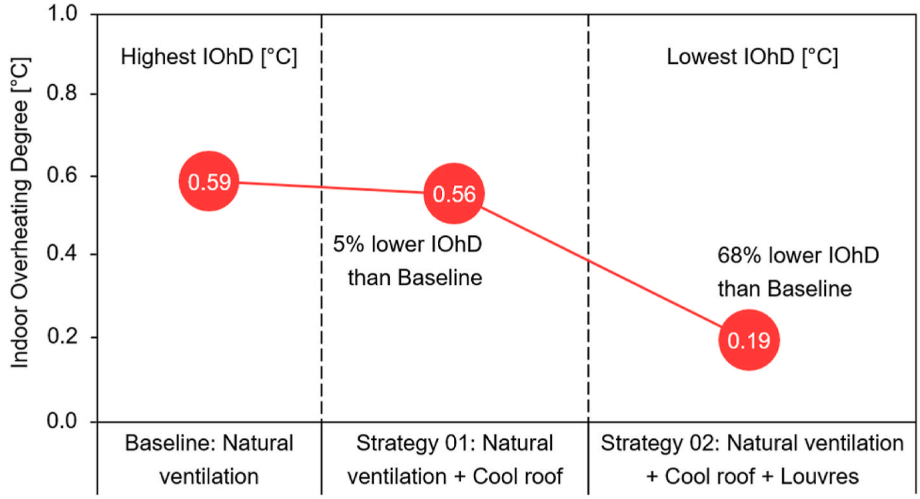

Fig. 9. Indoor Overheating Degree [°C] in the renovated nearly zero-energy dwelling for Baseline with natural ventilation, Strategy 01 with natural ventilation and cool roof, Strategy 02 with natural ventilation, cool roof, and louvres during a concurrent heat wave and power outage from August 10, 2022, to August 16, 2022.

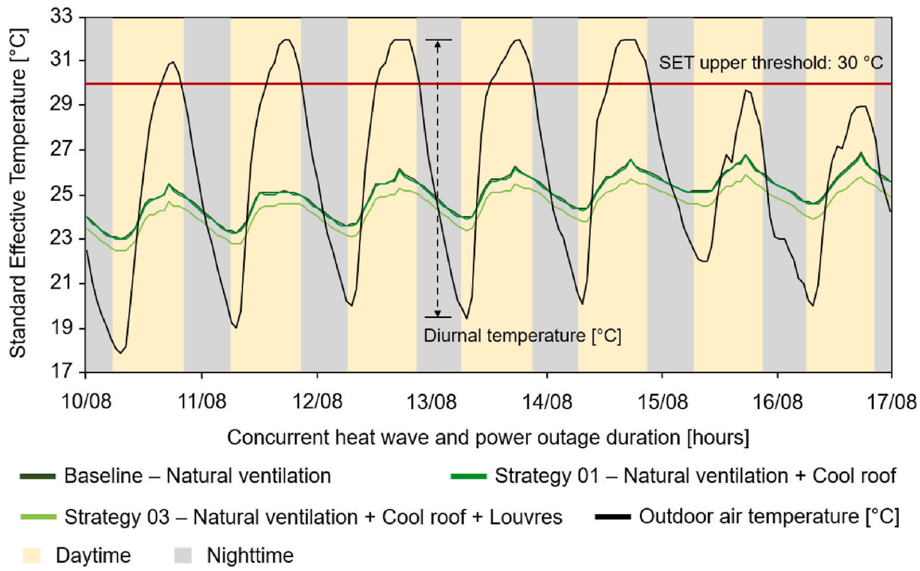

Fig. 10. Standard Effective Temperature [°C] in the renovated nearly zero-energy dwelling for Baseline with natural ventilation, Strategy 01 with natural ventilation and cool roof, Strategy 02 with natural ventilation, cool roof, and louvres during a concurrent heat wave and power outage from August 10, 2022, to August 16, 2022.

exposure mitigation in the reference dwelling. Indoor overheating fell to 0.19 °C, indicating a moderate impact on the indoor environment. Percentage of exceedance hours fell to 1% of the occupied time in the Bedroom 2. In line with this, the hygrothermal comfort analysis using heat index showed Bedroom 2 was only in caution for 14% of the occupied time compared to other configurations. Like the previous configurations, SET values were within the upper limit of 30 °C for the entire event, maintaining the livable conditions per LEED v4.1 credit for passive survivability.

4.2. Recommendations

The wide range of thermal exposure in all bedrooms in the reference dwelling suggests that design and operation strategies for the most vulnerable bedrooms should be carefully considered. Moving to relatively safer bedrooms should be considered during extreme events to avoid heat exposure risks for occupants in more exposed bedrooms. Future studies should assess the effects of different solar reflectance values for cool roofs on building performance. Additionally, other shading structures like overhangs and sidefins, alongside the impact of setting position like angles of solar shades, should be assessed, as this could be an efficient strategy to mitigate high indoor temperatures during compound events like heat waves and power outages. Moreover, dynamic shading could be introduced to reduce winter energy penalty due to decreased solar gains.

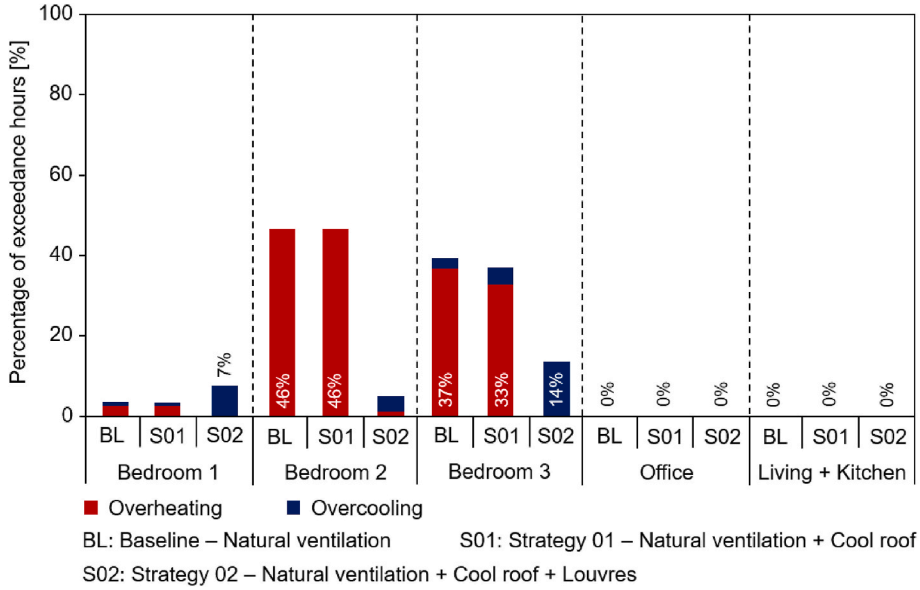

Fig. 11. Percentage of exceedance hours [%] in the renovated nearly zero-energy dwelling for Baseline with natural ventilation, Strategy 01 with natural ventilation and cool roof, Strategy 02 with natural ventilation, cool roof, and louvres during a concurrent heat wave and power outage from August 10, 2022, to August 16, 2022.

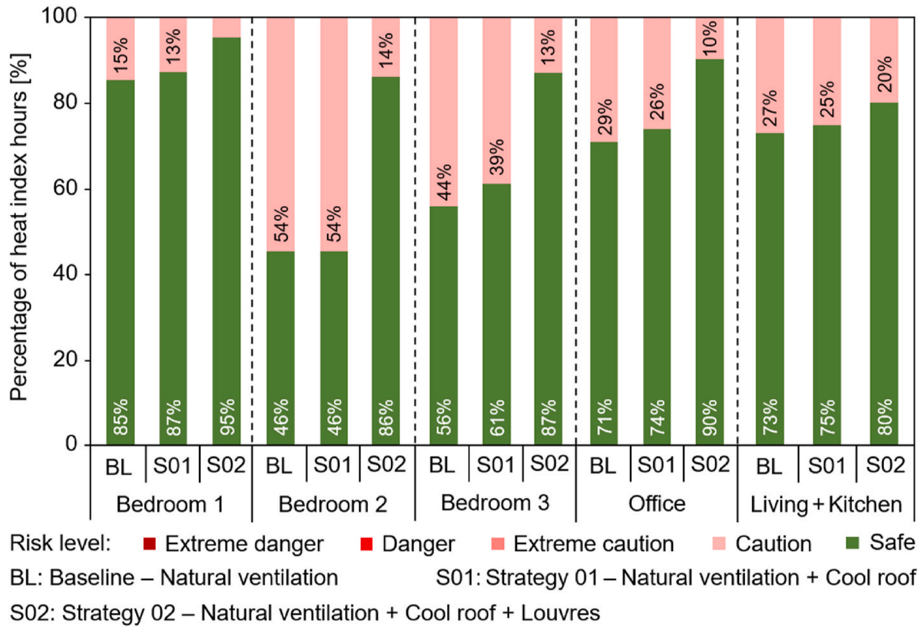

Fig. 12. Percentage of heat index hours [%] in the renovated nearly zero-energy dwelling for Baseline with natural ventilation, Strategy 01 with natural ventilation and cool roof, Strategy 02 with natural ventilation, cool roof, and louvres during a concurrent heat wave and power outage from August 10, 2022, to August 16, 2022.

4.3. Study limitations

The study assessed passive measures by retaining cool air and/or expelling excess heat through natural ventilation, limiting excess heat gains through a cool roof, and limiting excess heat gains through window louvres in a renovated reference dwelling. However, other strategies are available, such as window-related (e.g., low-e window films, window curtains, storm windows) and insulation-related (e.g., ceiling insulation, wall insulation, cool wall) strategies. Such passive measures should be included in future studies. Furthermore, when considering the benefits of natural ventilation, it is important to consider privacy considerations related to leaving the windows open at night. Other important aspects to be considered in the future work should include supplementing the simulation study with real field measurements for further analysis. In addition, cost consideration must be considered for these strategies.

5. Conclusions

In this study, the heat exposure risks in a renovated nearly zero-energy dwelling are estimated and compared for different passive cooling strategies during a concurrent heatwave and power. The strategies included passive ones like natural ventilation, cool roofs, and solar shading. A comparison is made to understand how these strategies mitigate heat exposure in the reference dwelling during extreme heat events. The paper emphasizes the importance of assessing heat exposure risks to assist policymakers in developing long-term mitigation solutions to counter the negative impacts of climate change on the built environment. These policies have the potential to significantly improve occupant comfort while helping the construction industry in its efforts to build heat-resistant buildings. The effectiveness of passive measures in heat exposure mitigation is augmented by their additional benefits, like higher energy efficiency and lower financial costs. The findings indicated that a combination of passive measures like night ventilation, cool roofs, and window louvres effectively mitigate the heat exposure risks to a large extent during a concurrent heat wave and power outage.

However, the cooling potential of passive strategies should be further assessed for heat waves of larger intensity and duration and power outages of prolonged duration in future studies. Future work should also focus on heat-related mortality and morbidity among urban populations in response to concurrent heat waves and power outages in the present and future periods and across diverse climate zones on the growing heat risk posed by major infrastructure failures in European cities. The current work and future studies will inform various passive mitigation strategies and behavioral adaptations to reduce extreme heat risks in urban areas during prolonged power outages. Furthermore, the current study is conducted on a renovated nearly zero-energy dwelling, which should perform better than old buildings in extreme conditions. Future studies should also assess older buildings, as they form a considerable portion of the residential building stock and are also supposed to be the most vulnerable in extreme weather.

The research can contribute to revisions in the Belgian Passive House Standard. By sharing learned lessons and representative performance data from the reference dwelling, the study can also contribute to larger initiatives and renovation projects in Belgium and more in mixed humid climates in Europe. During early design stages, comparisons can be made to assess the passive design assumptions. Currently, no building codes in Europe mandate overheating in an indoor environment during extreme heat events. Even the most stringent non-mandated building rating system, like The Living Building Challenge from the United States, did not mention power outages during heat waves. The guidelines and mandates for heat exposure must be developed in the European context, focusing on climate zones considering time-integration and the extent of heat exposure. Hence, the study results will contribute to the policy recommendations from the International Energy Agency (IEA) Annex 80 - Resilient Cooling of Buildings. The paper identified low-energy and low-carbon retrofit strategies that will improve the capacity to withstand the thermal impacts of extreme heat events on the built environment. The passive strategies assessed in this study will contribute to the existing knowledge base from IEA Annex 80 by supporting the transition to low-energy and low-carbon cooling solutions that will mitigate the overheating issues in buildings.

CRediT authorship contribution statement

Deepak Amaripadath: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elie Azar:** Writing – review & editing, Validation, Methodology. **Manoj Kumar Singh:** Writing – review & editing, Validation, Methodology. **Shady Attia:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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References

[1] R. Rahif, M. Hamdy, S. Homaei, C. Zhang, P. Holzer, S. Attia, Simulation-based framework to evaluate resistivity of cooling strategies in buildings against overheating impact of climate change, Build. Environ. 208 (Jan. 2022) 108599, https://doi.org/10.1016/j.buildenv.2021.108599.
[2] S. Attia, C. Gobin, Climate change effects on Belgian households: a case study of a nearly zero energy building, Energies 13 (20) (2020), https://doi.org/10.3390/en13205357.
[3] O.O. Elrawy, S. Attia, The impact of climate change on Building Energy Simulation (BES) uncertainty - case study from a LEED building in Egypt, IOP Conf. Ser. Earth Environ. Sci. 397 (1) (Nov. 2019) 012005, https://doi.org/10.1088/1755-1315/397/1/012005.
[4] M.R. Gaterell, M.E. McEvoy, The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings, Energy Build. 37 (9) (Sep. 2005) 982–995, https://doi.org/10.1016/j.enbuild.2004.12.015.
[5] L. Borghero, E. Clèries, T. Péan, J. Ortiz, J. Salom, Comparing cooling strategies to assess thermal comfort resilience of residential buildings in Barcelona for present and future heatwaves, Build. Environ. 231 (2023) 110043, https://doi.org/10.1016/j.buildenv.2023.110043.
[6] S. Vardoulakis, et al., Impact of climate change on the domestic indoor environment and associated health risks in the UK, Environ. Int. 85 (Dec. 2015) 299–313, https://doi.org/10.1016/j.envint.2015.09.010.
[7] S. Attia, Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation, Butterworth-Heinemann, Oxford, UK, 2018, https://doi.org/10.1016/C2016-0-03166-2.
[8] 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.
[9] M. Rebetez, O. Dupont, M. Giroud, An analysis of the July 2006 heatwave extent in Europe compared to the record year of 2003, Theor. Appl. Climatol. 95 (1) (Jan. 2009) 1–7, https://doi.org/10.1007/s00704-007-0370-9.
[10] B. Anderson, M. Bell, Lights out: impact of the August 2003 power outage on mortality in New York, NY, Epidemiology 23 (Mar. 2012) 189–193, https://doi.org/10.1097/EDE.0b013e318245c61c.
[11] K.J. Lomas, S.M. Porritt, Overheating in buildings: lessons from research, Build. Res. Inf. 45 (1–2) (Feb. 2017) 1–18, https://doi.org/10.1080/09613218.2017.1256136.
[12] M. Rajput, G. Augenbroe, B. Stone, M. Georgescu, A. Broadbent, S. Krayenhoff, E. Mallen, 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.
[13] 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.
[14] S.S. Clark, M.V. Chester, T.P. Seager, D.A. Eisenberg, The vulnerability of interdependent urban infrastructure systems to climate change: could Phoenix experience a Katrina of extreme heat? Sustain. Resilient. Infrastructure 4 (1) (Jan. 2019) 21–35, https://doi.org/10.1080/23789689.2018.1448668.
[15] NCC, Belgian National Risk Assessment," National Crisis Center, Brussels, Belgium, 2018 [Online]. Available: https://crisiscenter.be/en/what-does-national-crisis-center-do/risk-assessment-and-protection-critical-infrastructures/belgian. (Accessed 5 January 2023).
[16] WMO, This Heatwave Is the New Normal, World Meteorological Organization, 2022 [Online]. Available: https://public.wmo.int/en/media/news/%E2%80%9C-heatwave-new-normal%E2%80%9D-says-wmo-secretary-general. (Accessed 15 October 2022).
[17] T. Aduralere, J. Isaacs, D. Fannon, Passive survivability in residential buildings during heat waves under dynamic exterior conditions, in: Proc. Of 7th International Building Physics Conference IBPC, Syracuse, USA, 2018, https://doi.org/10.14305/ibpc.2018.ms-1.06.
[18] S. Flores-Larsen, C. Filippín, F. Bre, New metrics for thermal resilience of passive buildings during heat events, Build. Environ. 230 (Feb. 2023) 109990, https://doi.org/10.1016/j.buildenv.2023.109990.
[19] C. Zhang, et al., Resilient cooling strategies – a critical review and qualitative assessment, Energy Build. 251 (2021) 111312, https://doi.org/10.1016/j.enbuild.2021.111312.
[20] 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.
[21] 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.
[22] A. Baniassadi, J. Heusinger, D.J. Sailor, Energy efficiency vs resiliency to extreme heat and power outages: the role of evolving building energy codes, Build. Environ. 139 (Jul. 2018) 86–94, https://doi.org/10.1016/j.buildenv.2018.05.024.
[23] Z. Zeng, W. Zhang, K. Sun, M. Wei, T. Hong, Investigation of pre-cooling as a recommended measure to improve residential buildings' thermal resilience during heat waves, Build. Environ. 210 (Feb. 2022) 108694, https://doi.org/10.1016/j.buildenv.2021.108694.
[24] D.J. Sailor, A. Baniassadi, C.R. O'Lenick, O.V. Wilhelmi, The growing threat of heat disasters, Environ. Res. Lett. 14 (5) (May 2019) 054006, https://doi.org/10.1088/1748-9326/ab0bb9.
[25] L. Hanna, P. Tait, Limitations to thermoregulation and acclimatization challenge human adaptation to global warming, Int. J. Environ. Res. Publ. Health 7 (Jul. 2015) 8034–8074, https://doi.org/10.3390/ijerph120708034.
[26] K. Sun, W. Zhang, Z. Zeng, R. Levinson, M. Wei, T. Hong, Passive cooling designs to improve heat resilience of homes in underserved and vulnerable communities, Energy Build. 252 (Dec. 2021) 111383, https://doi.org/10.1016/j.enbuild.2021.111383.
[27] K. Amada, J. Kim, M. Inaba, M. Akimoto, S. Kashihara, S. ichi Tanabe, Feasibility of staying at home in a net-zero Energy House during summer power outages, Energy Build. 273 (2022) 112352, https://doi.org/10.1016/j.enbuild.2022.112352.
[28] 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.
[29] EPBD, "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)," EUR-Lex. [Online]. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031. Accessed on: April. 17, 2024.
[30] 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.
[31] D. Amaripadath, M.Y. Joshi, M. Hamdy, S. Petersen Jr., Stone Brian, S. Attia, Thermal resilience in a renovated nearly zero-energy dwelling during intense heat waves, J. Build. Perform. Simulat (Sep. 2023) 1–20, https://doi.org/10.1080/19401493.2023.2253460.
[32] M. Leroy, Y. Dupont, T. Braeye, N. Bossuyt, N. Sierra Bustos, "Belgian Mortality Monitoring (Be-MOMO)," Sciensano, Brussels, Belgium. Available: https://epistat.sciensano.be/momo/.
[33] ANSI/ASHRAE, ASHRAE Standard 169: Climatic Data for Building Design Standards, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA, 2013.
[34] D. Amaripadath, R. Rahif, W. Zuo, M. Velickovic, C. Voglaire, S. Attia, 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.
[35] D. Amaripadath, R. Paolini, D.J. Sailor, S. Attia, Comparative assessment of night ventilation performance in a nearly zero-energy office building during heat waves in Brussels, J. Build. Eng. 78 (2023) 107611, https://doi.org/10.1016/j.jobe.2023.107611.
[36] S. Attia, Benchmark model for nearly-zero-energy terraced dwellings, Harvard Dataverse (2021), https://doi.org/10.7910/DVN/GJI84W.
[37] G. Ouzeau, J.M. Soubeyroux, M. Schneider, R. Vautard, S. Planton, Heat waves analysis over France in present and future climate: application of a new method on the EURO-CORDEX ensemble, Clim. Serv. 4 (Dec. 2016) 1–12, https://doi.org/10.1016/j.cliser.2016.09.002.
[38] A. Machard, C. Inard, J.M. Alessandrini, C. Pelé, J. Ribéron, 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.
[39] RMI, Opendata Meteo, Royal Meteorological Institute, Brussels, Belgium, 2022 [Online]. Available: https://opendata.meteo.be/. (Accessed 8 December 2022).

[40] 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.
[41] A. Machard, AMachard/Assembling-Future-Weather-Files-Including-heatwaves: v1.0.0, Zenodo, 2022, https://doi.org/10.5281/zenodo.7300024.
[42] S. Flores-Larsen, F. Bre, M. Hongn, A performance-based method to detect and characterize heatwaves for building resilience analysis, Renew. Sustain. Energy Rev. 167 (Oct. 2022) 112795, https://doi.org/10.1016/j.rser.2022.112795.
[43] R. Rahif, S. Attia, "IOhD (Calculation & Illustration), IOcD (Calculation & Illustration), AWD (Calculation & Illustration), ACD (Calculation & Illustration), CCOhR (Calculation), CCOcR (Calculation), Zonal OpT (Illustration), and HWs (Illustration), Zenodo, 2022, https://doi.org/10.5281/zenodo.7326901.
[44] ANSI/ASHRAE, ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA, 2017.
[45] T. Cao, Z. Lian, J. Zhu, X. Xu, H. Du, Q. Zhao, Parametric study on the sleep thermal environment, Build. Simulat. 15 (5) (May 2022) 885–898, https://doi.org/10.1007/s12273-021-0840-5.
[46] L. Lan, L. Pan, Z. Lian, H. Huang, Y. Lin, Experimental study on thermal comfort of sleeping people at different air temperatures, Build. Environ. 73 (Mar. 2014) 24–31, https://doi.org/10.1016/j.buildenv.2013.11.024.
[47] K. Okamoto-Mizuno, K. Mizuno, Effects of thermal environment on sleep and circadian rhythm, J. Physiol. Anthropol. 31 (1) (May 2012) 14, https://doi.org/10.1186/1880-6805-31-14.
[48] 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.
[49] 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.
[50] 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.
[51] A. Wilson, Passive survivability, building green [Online]. Available: https://www.buildinggreen.com/op-ed/passive-survivability, 2005.
[52] 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.
[53] K. Sun, M. Specian, T. Hong, Nexus of thermal resilience and energy efficiency in buildings: a case study of a nursing home, Build. Environ. 177 (2020) 106842, https://doi.org/10.1016/j.buildenv.2020.106842.
[54] 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.
[55] C. Zhang, O.B. Kazanci, S. Attia, R. Levinson, S.H. Lee, P. Holzer, A. Salvati, A. Machard, M. Pourabdollahtootkaboni, A. Gaur, B. Olesen, P. Heiselberg, IEA EBC Annex 80 - dynamic simulation guideline for the performance testing of resilient cooling strategies: version 2, DCE Technical Reports No. 306 (2023), https://doi.org/10.13140/RG.2.2.12309.19687.
[56] D.B. Crawley, et al., EnergyPlus: creating a new-generation building energy simulation program, Energy Build. 33 (4) (Apr. 2001) 319–331, https://doi.org/10.1016/S0378-7788(00)00114-6.
[57] Performance Énergétique des Bâtiments, La performance énergétique des bâtiments - La PEB, une réglementation à 3 volets, Envir. Brussels, Belgium [Online] (Accessed 10 January 2023), https://environnement.brussels/pro/reglementation/textes-de-loi/reglementation-sur-la-performance-energetique-des-batiments-peb, 2023.
[58] 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.
[59] 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.
[60] ISO, ISO 18523-2, Energy Performance of Buildings - Schedule and Condition of Building, Zone and Space Usage for Energy Calculation – Part 2: Residential Buildings, International Standards Organization, Geneva, Switzerland, 2016.
[61] ISO, ISO 7730: Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, International Standards Organization, Geneva, Switzerland, 2005.
[62] 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.
[63] D. Amaripadath, R. Levinson, R. Rawal, S. Attia, Multi-criteria decision support framework for climate change-sensitive thermal comfort evaluation in European buildings, Energy Build. 303 (2024) 113804, https://doi.org/10.1016/j.enbuild.2023.113804.
[64] DesignBuilder, "Local shading - Louvres," DesignBuilder, Gloucs, UK. [Online]. Available: https://designbuilder.co.uk/helpv7.0/Content/_Local_shading_Louvres.htm. Accessed on: April. 13, 2024.
[65] NWS, "Heat Index Chart" National Weather Service, USA. [Online]. Available at: https://www.weather.gov/ffc/hichart. Accessed on: May 3, 2024.