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Thermal resilience in a renovated nearly zero-energy dwelling during intense heat waves

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ABSTRACT
Overheating risk is expected to rise in dwellings as heat waves continue increasing in intensity and duration. This paper presents a simulation-based study on thermal resilience in a benchmark renovated nearly zero-energy dwelling during intense heat waves in Belgium. Data analysis using thermal simulations of the reference dwelling with and without active cooling was used to assess overheating risk. The analysis indicated that the reference dwelling with active cooling was resilient to heat waves for over 91% of the occupied hours. Furthermore, the existing building-level renovation strategies alone will not be sufficient to mitigate overheating in renovated dwellings and require active cooling. However, active cooling came with an energy penalty of 37.69 kWh/day during the monitored period, and any potential benefits of active cooling should factor in the excess energy use. The presented findings lead to recommendations for future building renovation practices and identified needs for further research.

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Overheating; nZEB; indoor environment; active cooling; building renovation; energy penalty

1. Introduction

The impacts of the ongoing climate crisis and its associated heat waves with high temperatures across many countries have been documented in (Pörtner et al. 2022). The global mean air temperature has increased over the past one hundred years due to human-induced climate change brought about by issues like fossil fuel usage, deforestation and changes in agricultural practices (Masson-Delmotte et al. 2018). The Intergovernmental Panel on Climate Change (IPCC) reports have unequivocally provided the connection between climate change and heat waves (Pörtner et al. 2022). Resilient building design and construction are urgently needed to prepare for climate change and the disruptions brought on by weather extremes (Attia 2023). Resilient building cooling systems are a crucial strategy to reduce risks to occupants because building disturbances will have significant and lasting health and economic effects (Gupta and Kapsali 2016). Moreover, due to climate change, there is an urgent need for resilient cooling systems in buildings to provide comfort even during extreme weather conditions (Holzer and Cooper 2019). Findings from previous studies like Attia and Gobin (2020) pointed out the vulnerability of free-running timber dwellings to overheating in Belgium due to climate change.

Many societies in the world have experienced a string of severe and deadly heat waves since the start of the twenty-first century. Baccini et al. (2008) indicated an increased mortality risk of 3.12% in the Mediterranean region and 1.84% in the north-continental regions of Europe, with an estimated temperature increase of 1°C above a location-specific threshold. For example, the heat wave of 2003 resulted in about 70,000 additional deaths, mainly in France, Germany, and Italy, according to the World Health Organization (WHO) and numerous national reports (Marx et al. 2021). Additionally, the heat waves that swept through England and Wales in the summer of 2022 reported an additional death toll of 3,271 people (ONS 2022). Figure 1 shows the heat wave related additional mortalities that occurred in the past decades in the United Kingdom (ONS 2022), France (Fouillet et al. 2006; Hughes et al. 2016), India and Pakistan (Hughes et al. 2016), Japan (Hughes et al. 2016), Australia (Hughes et al. 2016), California in the United States (Hughes et al. 2016;

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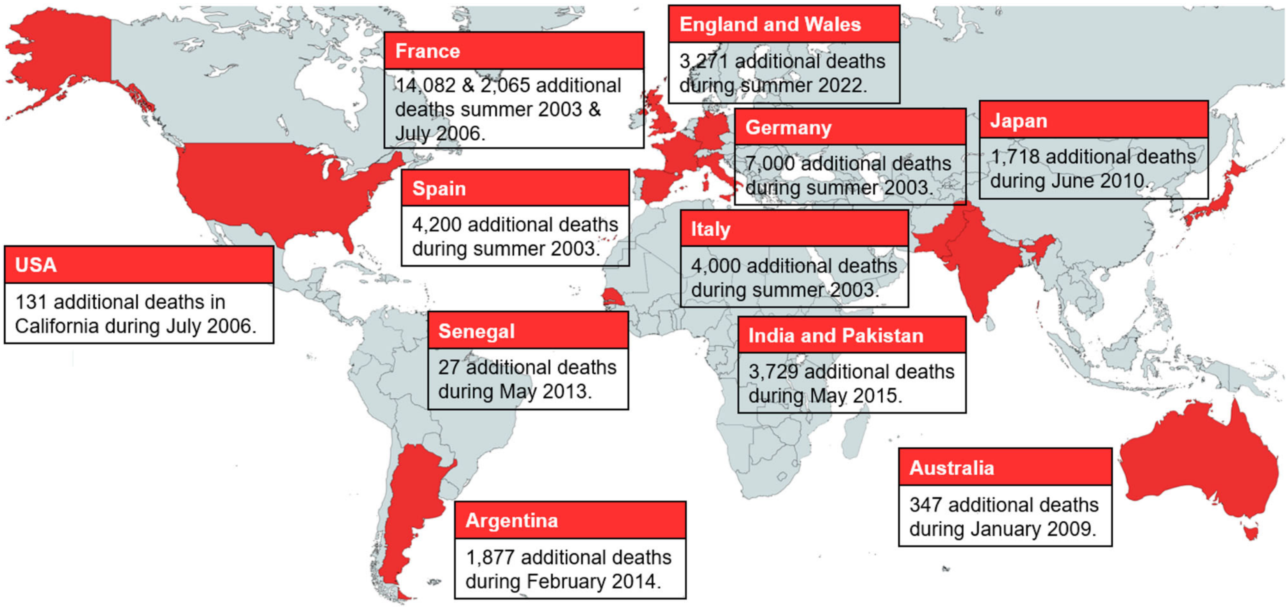

Figure 1. Heat wave-related mortalities around the globe during the past decades. Map generated using MapChart (2022).

Edwards et al. 2006), Germany (De Bono et al. 2004), Spain (De Bono et al. 2004), Italy (De Bono et al. 2004), Argentina (Chesini et al. 2022), and Senegal (Sy et al. 2021). These mortality rates are representative numbers as these may have been calculated using different methods in different regions and may not be directly comparable.

Table 1 provides the key findings from 15 recent studies on the thermal building performance of dwellings during hot summer months. Studies from (Pathan et al. 2017; Vellei et al. 2017; Baborska-Narożny et al. 2017; Mavrogianni et al. 2017; Porritt et al. 2012; Pyrgou et al. 2017) were conducted in mixed humid (4A) climate zone, similar to the study locations. Studies (Morey et al. 2020; Sakka et al. 2012; Zinzi et al. 2020; Flores-Larsen et al. 2022; Zhou et al. 2020; Ji et al. 2022; Stone Jr et al. 2021b) and studies (Rajput et al. 2022; Stone Jr et al. 2021a) were conducted in other humid climate zones and dry climate zones, respectively. The existing literature emphasizes the risks of overheating in the residential sector and the significance of developing effective mitigation strategies that may prevent overheating in dwellings. The existing literature points towards a potential increase in air-conditioning use to mitigate overheating in the built environment (Sakka et al. 2012; Zinzi et al. 2020). Energy-efficient measures aimed at reducing heating energy use, such as an increase in the building envelope's insulation level, contribute to overheating during summer months, deteriorating the thermal performance in dwellings (Porritt et al. 2012; Pyrgou et al. 2017). However, expert opinions from (Taylor et al. 2023) recommend that adequate ventilation and shading can mitigate small increases in summertime temperatures after certain retrofits. The study further pointed out that to have more convincing evidence, further research into how energy-efficient design affects overheating in various settings and with various occupant behaviour patterns is required.

The existing studies from Table 1 were based on the unique assumption of comfort models and limits applied to the reference building while not differentiating them based on the purpose of building zones. Studies like Porritt et al. (2012) evaluated the thermal environment using hours of exceedance that predicted comfort as a binary factor – comfortable vs. uncomfortable (Salimi et al. 2021). Pyrgou et al. (2017) used a percentile-based methodology for calculating heat waves using temperature data over a year. However, the methodology developed by Ouzeau et al. (2016) and adopted by IEA EBC Annex 80 recommends that a distribution of mean daily temperature over several years must be used while determining the heat wave thresholds. Multiple scientific reports like (WMO 2022; AdaptNSW 2022) indicated that more intense and prolonged heat waves would become the norm. Hence, it is essential to understand the impacts of heat waves on the built environment in a world where climate change's effects are becoming more visible. The relevance of this study is based on the following aspects:

(1) As heat waves happen more frequently and intensely, they affect the occupant's comfort. By understanding the impact of heat waves on indoor overheating, strategies can be developed to mitigate the harmful effects of extreme heat on the indoor built environment and occupant well-being.
(2) The focus is on indoor overheating in a dwelling since (i) people spend most of their time at home, especially older people who are more susceptible to

Table 1. Summary of recent literature on heatwave impacts on building performance.

Location and Climate	Study type	Core focus	Operation	Key findings	Reference
Studies from mixed humid climates (4A)					
London (4A), UK	Observational with field measurements and surveys	Overheating	Air-conditioned Free-running	Dwellings built after 1996, under higher energy efficiency standards, tend to have indoor temperatures that were significantly higher and remained above thresholds for a longer period than older homes.	Pathan et al. (2017)
Exeter (4A), UK	Observational with field measurements and surveys	Overheating	Free-running	Overheating happened frequently and disproportionately in dwellings with vulnerable occupants, even during summers without extreme or prolonged heat waves, which is a significant find.	Vellei et al. (2017)
Leeds (4A), UK	Observational with field measurements and surveys	Overheating	Free-running	Due to inadequate shading for excessively large windows and poor ventilation control, the study apartments were prone to overheating. However, overheating was significantly reduced through the efficient use of windows and continuous mechanical extract ventilation (MEV).	Baborska-Narożny et al. (2017)
London (4A), UK	Observational with field measurements and surveys Modeling with EnergyPlus	Overheating	Air-conditioned	The monitoring data showed that under the current climate, London homes, particularly bedrooms, are already at risk of overheating during hot spells. The occupant behaviour should align with model assumptions to obtain reliable modeling outputs for overheating analysis.	Mavrogianni et al. (2017)
London (4A), UK	Modeling with EnergyPlus	Overheating	Free-running	Controlling window openings during the hottest periods while keeping curtains closed during the day was the most cost-effective measure. Heating energy-saving measures poorly impact overheating by being ineffective or making it worse.	Porritt et al. (2012)
Perugia (4A), Italy	Modeling with EnergyPlus	Overheating	Air-conditioned	High thermal insulation levels in the envelope raised the risk of indoor overheating in study dwellings. Temperature values between 24 and 28°C were achieved due to active cooling systems.	Pyrgou et al. (2017)
Studies from other humid climate zones					
Central England (4A) and (5A), UK	Observational with field measurements	Overheating	Free-running	Recently built dwellings showed much higher mean temperatures than those from earlier times. Temperatures above thresholds were more persistent in newer dwellings than in older ones.	Morey et al. (2020)
Athens (3A), Greece	Observational with field measurements	Overheating	Free-running	Thermal comfort evaluations from 50 low-income non-air-conditioned houses during the summer of 2007 indicated very high indoor temperatures up to 40°C and a rise of 4.2°C in mean temperature during July.	Sakka et al. (2012)
Rome (3A), Italy	Observational with field measurements Modeling with simulations	Overheating Energy use	Air-conditioned Free-running	The average operating temperature increased by more than 5°C due to the combined effects of the heat wave in an urban setting. Heat waves significantly worsen the thermal comfort conditions in free-floating buildings.	Zinzi et al. (2020)
Buenos Aires (3A), Argentina	Modeling with EnergyPlus	Overheating	Free-running	Relatively brief heat waves can also significantly impact the indoor environment, so they shouldn't be ignored when analyzing a building's resilience.	Flores-Larsen et al. (2022)
Zurich (5A), Switzerland	Observational with field measurements Modeling with simulations	Overheating	Air-conditioned Free-running	Thermal comfort in urban environments was moderately improved by precooling the building before the heat wave. The combination of precooling and moisture desorption was more energy-efficient than air-conditioning.	Zhou et al. (2020)
Toronto (5A), Ottawa (6A), Montreal (6A), Canada Houston (2A), Baltimore (4A), USA	Modeling with EnergyPlus	Overheating	Intermittent air-conditioning	The building operation with closed interior blinds and open windows was appropriate for cold climatic areas, and the building operation with closed external shades and open windows was suitable for hot climatic areas.	Ji et al. (2022)
Atlanta (3A), Detroit (5A), USA	Modeling with simulations	Heat exposure	Free-running	Heat exposure is more common for low-income and high-income households due to the lack of air conditioning. When air conditioning fails, extreme heat inside buildings can reach dangerously high levels.	Stone Jr. et al. (2021b)
Studies from dry climate zones					
Phoenix (1B), USA	Modeling with EnergyPlus	Heat exposure	Free-running	The heat exposure in the reference buildings was high due to inadequate HVAC and/or power outages. The extreme heat impacts can be reduced by adaptation strategies like installing battery-operated cooling systems and onsite renewable energy for evaporative cooling.	Rajput et al. (2022)
Phoenix (1B), USA	Modeling with EnergyPlus	Heat exposure	Free-running	Homes with intermittent access to mechanical air conditioning will be exposed to a high heat exposure risk due to a rise in summer cooling needs in parallel with rising summer temperatures.	Stone Jr. et al. (2021a)

overheating exposure (NHBC 2012), and (ii) overheating during sleep time at home has been reported as a severe public health risk (Zero Carbon Hub 2015; Kovats and Hajat 2008).

(3) The study was focused on mixed humid climates in Belgium because (i) in terms of population, seven out of 15 largest cities in the EU and UK fall within mixed humid climates (4A) and constitute up to 57% of the total population (Eurostat 2022), and (ii) In terms of GDP, five out of 15 largest cities in the EU and the UK, fall within mixed humid climates (4A) and constitute up to 56% of the total GDP (Economie 2022).

(4) The nearly zero-energy building requirements have been in effect in Belgium since 2010. These standards are modeled after the passive house standard, where high energy performance is advised, and numerous dwellings are renovated to meet the nearly zero-energy building requirements with nearly zero or very low energy consumption (Attia et al. 2022).

(5) The study findings can be used to increase the understanding of overheating risks in renovated dwellings during heat waves and use this understanding to support the transition at the regional and national levels in Belgium and, to a larger extent, in mixed humid climates (4A) of Europe like London, Madrid, Milan, Paris, etc.

Based on these observations, the following research questions were formulated and addressed in this paper:

1. How can heat waves in Belgium be detected and categorized?
2. How resilient is the renovated nearly zero-energy dwelling against intense heat waves in Belgium?

This study expanded the scope of previous works from Table 1 to include thermal resilience assessment. This study evaluated thermal resilience in a renovated nearly zero-energy dwelling with and without active cooling during and after an intense heat wave. The novelty of this paper is based on the following aspects. This paper combines adaptive and PMV/PPD comfort model thresholds for the reference dwelling. This modeling approach for the reference dwelling was designed after considering findings from sleep studies like (Cao et al. 2022; Lan et al. 2014; Okamoto-Mizuno and Mizuno 2012). During the literature review, to the best of our knowledge, we did not find any other studies that used this design approach for overheating evaluation during heat waves. The study also characterized overheating in the reference dwelling for seven days before the heat wave and seven days after. Analyzing the period before and after the heat waves will help to test the potential of passive strategies as mitigative measures and to determine the time required for the building to get back to the designed thresholds after events like heat waves in future studies (Attia et al. 2021).

2. Methodology

An overview of the methodology used in this paper is shown in Figure 2. The workflow used in this study is as follows:

1. The heat waves were identified and classified according to Ouzeau et al. (2016) for the different study locations across Belgium over the past decades from 2001 to 2020, and the most intense heat wave was selected for building performance analysis.
2. Degree-hours were used to measure building resilience against heat waves, calculated by adding the total temperature values above the minimum and critical thresholds. This was used as an indicator since it considers the degree of variation in indoor operative temperature above the defined thresholds.
3. The overheating in the reference dwelling was characterized by Indoor Overheating Degree (IOD) (Hamdy et al. 2017a) and exceedance hours [h] for configurations with and without active cooling. The PMV/PPD and adaptive thresholds used complies with threshold limits from (ISO 17772-1 2017).

The heat waves across Belgium were detected using a custom Python code (Joshi et al. 2022) based on (Machard 2022). The building simulation model was created using DesignBuilder v7.1, a graphical user interface for the EnergyPlus simulation engine v9.1.

2.1. Study scope

The research was conducted in different study locations in Belgium, in mixed humid climates (4A), according to the classification from (ASHRAE 169 2013). In such heating-dominated regions, the design of buildings is primarily focused on heat preservation inside the building during winter. This is achieved using airtight and highly insulated design principles (Amaripadath et al. 2023). As a result, relying solely on existing building-level passive cooling measures will make it difficult to prevent overheating issues during heat waves. Passive design strategies like the envelope and the ability of occupants to acclimatize are excluded from the boundary conditions of the study. There is an aging population in Europe who are vulnerable to cardiovascular and

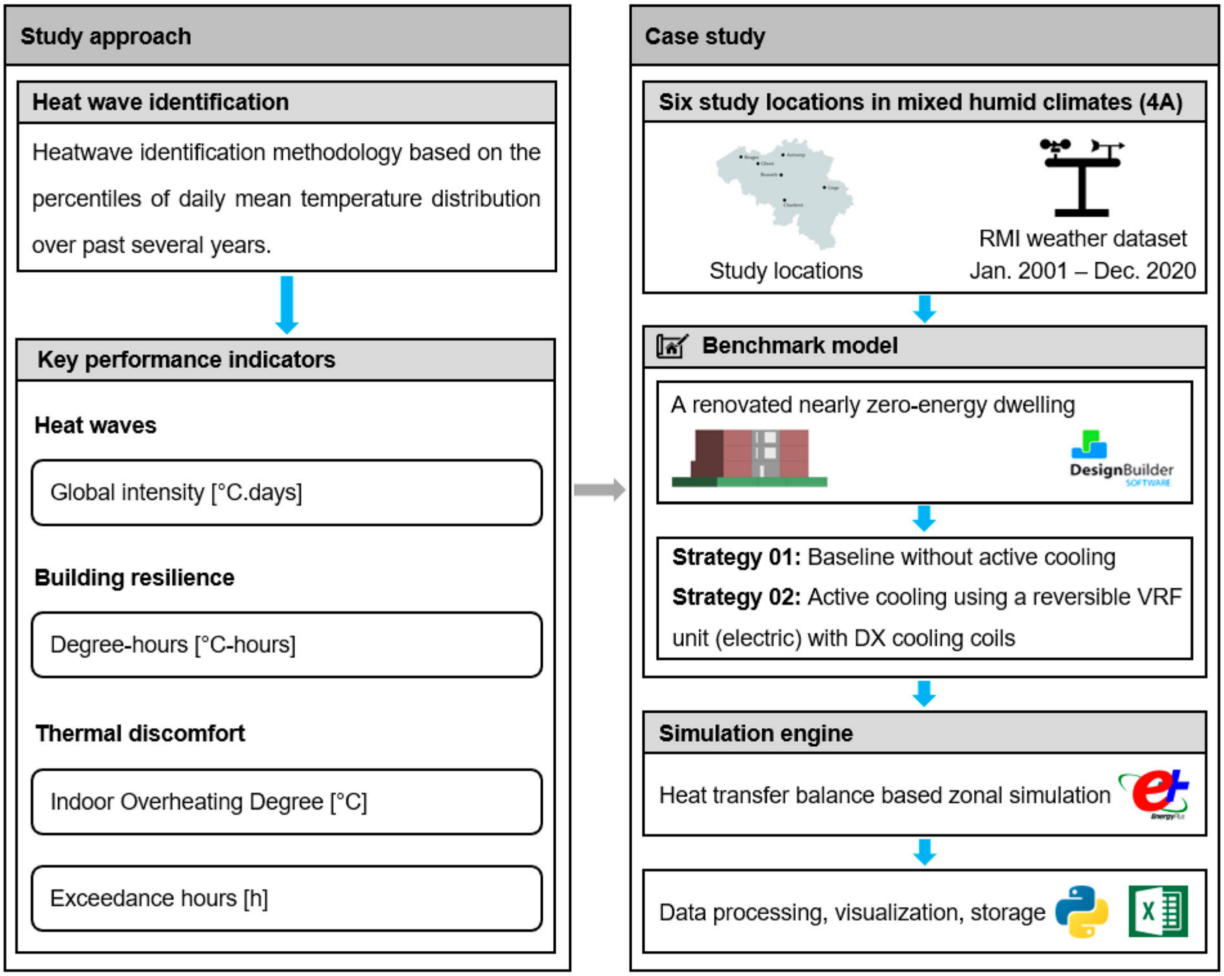

Figure 2. Proposed study workflow.

respiratory syndrome (Michelozzi et al. 2009). Their ability for acclimatization is low. The boundary conditions align with IEA EBC Annex 80.

2.2. Study approach

2.2.1. Heat wave identification

Regarding the identification of heat waves, the absence of a standard definition for heat waves today makes it difficult to analyze these events in great detail and compare them to previous, present, and future events in different regions. The factors which allow the detection and qualification, like the duration and thresholds., vary greatly. However, heat waves can be typically defined as periods with warm temperatures above the normal observed levels for several consecutive days (Ouzeau et al. 2016). Aligned with this observation, currently, there are two different definitions used to identify heat waves across Belgium: a. the Royal Meteorological Institute (RMI) defines heat waves as a period of five consecutive days with maximum daily temperatures of 25°C or more (summer days), including three days of 30°C or higher (tropical days) (Brits et al. 2009), b. the federal heat plan, 'heat waves and ozone peaks' defines heat waves as a period with a predicted minimum temperature of 18.2°C or more for three days and a maximum temperature of 29.6°C or higher (Brits et al. 2009). However, these methods do not consider the local climate of each region (Brits et al. 2009). Therefore, this study's heat wave identification method was based on percentiles of daily mean temperature distribution over the past several years to identify the thresholds (Ouzeau et al. 2016) IEA EBC Annex 80 adopted.

This method was based on three thresholds changed from absolute values to percentiles of the daily mean temperature distribution over several years (Ouzeau et al. 2016). This makes the method applicable to more data sets, as these values were computed independently for each study location. The thresholds (Ouzeau et al. 2016) used were Spic (99.5 percentile), beyond which a heat wave was detected; Sdeb (97.5 percentile), which determines when a heat wave begins and ends; and Sint (95 percentile), which allows the merging of two consecutive

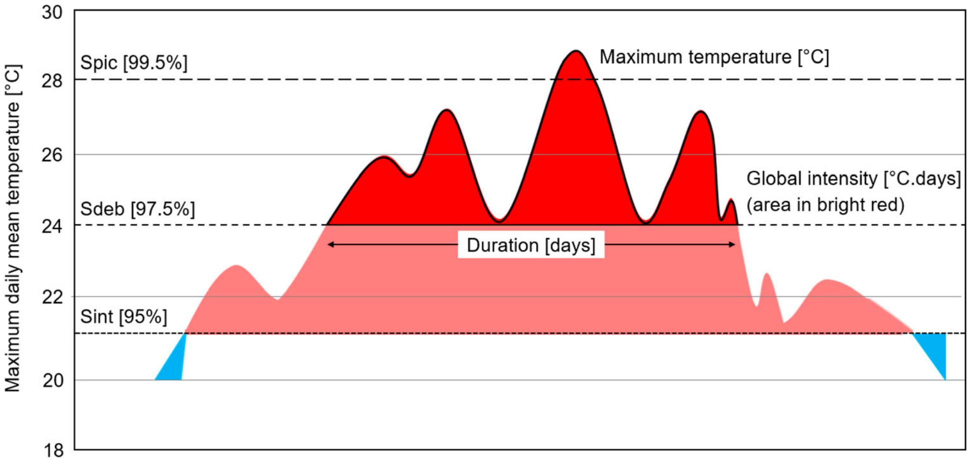

Figure 3. Heat wave detection thresholds (Ouzeau et al. 2016).

heat waves without a significant drop in temperature. Once the thresholds were estimated for individual study locations, heat waves were detected when the temperature exceeded the Spic. The global intensity [°C.days] was calculated by dividing the cumulative difference between the temperature and Sdeb throughout the event, divided by the Spic-Sdeb difference, represented by the bright red area in Figure 3.

2.2.2. Key performance indicators

2.2.2.1. *Heat wave intensity.* One of the key findings from (WMO 2022) was that most locations would see a three to tenfold increase in dangerous heat wave days by the end of the century. A report from (WMO 2022) found that heat waves will become more frequent, intense and last longer. Therefore, for overheating evaluation on the reference dwelling, a heat wave was selected based on the global intensity [°C.days], which is a measure of maximum temperature [°C] and duration [days].

2.2.2.2. *Thermal resilience.* The reference dwelling is Passive House certified, and the very high energy performance requirements of Passive House serve as an adequate indicator for passive survivability in the reference dwelling during extreme heat events (USGBC 2023). The reference dwelling has operable windows to meet the ventilation requirements during a concurrent heat wave and power outage, where mechanical ventilation will not be functional. The resilience of a building's cooling system is defined as the ability of the building's cooling system to withstand or recover from disturbances caused by disruptions and to adopt the necessary strategies after failure to mitigate building performance degradation due to deterioration of indoor environmental quality and/or increased need for space cooling energy (Attia et al. 2021).

The reference dwelling is designed for an acceptable value from 19°C recommended by (EN 16798-1 2019), a minimum designed value of 26°C recommended by (EN 16798-1 2019), and a critical thermal value of 30°C recommended by the Health and Safety Executive (HSE) (HSE 2010). In a changing climate, quantifying a building's thermal resilience during extreme events is critical (Homaei and Hamdy 2021; Mirzabeigi et al. 2022). The sum of the difference between the hourly operative and standard reference temperatures is used to calculate degree-hour values (Coskun 2010). In this case, the minimum design value of 26°C and the critical value of 30°C are standard reference temperatures.

2.2.2.3. *Indoor overheating.* Indoor Overheating Degree (IOD) was used to calculate the extent of discomfort caused by overheating (Hamdy et al. 2017a; Amaripadath et al. 2022). The IOD is a multizonal index that adds the total number of cooling degree hours divided by the total number of zonal occupied hours. The IOD values were calculated using equation (1).

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

where Z is the total number of 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 in zone z at time step i in (°C), $T_{comf,upper,z,i}$ is the maximum comfort threshold in zone Z at hour i in (°C).

2.2.2.4. *Thermal discomfort.* Exceedance hours (EH) is the number of occupied hours within a defined period during which the environmental conditions in an occupied space are outside the specified limits (ASHRAE 55 2017; Carlucci and Pagliano 2012; Attia et al. 2023).

Equations (2) and (3) show the equations for calculating exceedance hours for the PMV model (EH_{PMV}) and adaptive model (EH_{op}) respectively.

$$EH_{PMV} = \sum_{i=1}^{N_{occ}(z)} H_{disc} \tag{2}$$

where, $H_{disc} = 1$; if $|PMV| > 0.5$, $H_{disc} = 0$; if $|PMV| \leq 0.5$

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

where, $H_{disc} = 1$; if $T_{op,i} > T_{comf,upper,z,i}$, $H_{disc} = 0$; if, $T_{op,i} \leq T_{comf,upper,z,i}$

where, H_{disc} is the discomfort hours [h], $T_{op,i}$ is the indoor operative temperature [°C]. The $T_{comf,upper,z,i}$ was derived from ISO 17772-1 adaptive model category II limits (ISO 17772-1 2017) for the Office room and Living room + Kitchen in the reference dwelling, which was recommended for new buildings. Similar limits are recommend ed in (EN 16798-1 2019). Equation (4) shows the upper limit (ISO 17772-1 2017) based on the outdoor running mean temperature (T_{rm}).

$$T_{comf,upper,z,i} = 0.33 \times T_{rm} + 18.8 + 3 \tag{4}$$

The $T_{comf,upper,z,i}$ was derived from ISO 17772-1 PMV/PPD model category II limits for the Bedrooms in the reference dwelling was 26°C for the upper limit recommended for new and renovated dwellings (ISO 17772-1 2017). The Bedrooms in the reference dwelling were evaluated using PMV/PPD limits since numerous studies link sleep quality with the thermal environment. The study findings from (Altena et al. 2022) suggest that the ambient temperature inside the sleep areas should be kept preferably close to 19°C and if this is not possible, then between 20°C to 25°C, but never more than 26°C during heat waves. The field experiment results from (Cao et al. 2022) recommended an indoor temperature not greater than 26.1°C for summertime sleeping areas. The ideal sleep temperature of 26°C from (Lan et al. 2014) was very close to the recommended value of 26.1°C in (Cao et al. 2022). There were studies like (Okamoto-Mizuno and Mizuno 2012) that observed excessively high temperatures in sleeping areas will affect even healthy individuals. The impact of the most intense heat wave on the indoor environment of the reference dwelling using IOD (Hamdy et al. 2017a; Amaripadath et al. 2022) was categorized by (Flores-Larsen et al. 2022) as:

1. moderate impact, if $\text{IOD} \leq 0.5^{\circ}\text{C}$
2. strong impact, if $0.5^{\circ}\text{C} < \text{IOD} < 2^{\circ}\text{C}$
3. extreme impact, if $\text{IOD} \geq 2^{\circ}\text{C}$

2.3. Case study

2.3.1. Climate data

For heat wave identification, data from RMI weather stations were used. The weather data used in this study were retrieved from the RMI Opendata Platform (RMI 2022). Data availability time frames vary depending on the weather station, e.g. weather data for Ghent extracted from Melle between January 2001 and March 2003 was unavailable. The study locations and weather stations used for data extraction for the study locations are shown in Figure 4.

2.3.2. Reference dwelling

The benchmark structure was a nearly zero-energy renovated dwelling after 2010 and was labeled as a nearly zero-energy building adhering to passive house standards (Hamdy et al. 2017b). The PHPP calculation model for dwellings in Belgium (Hamdy et al. 2017b; Attia et al. 2020; PMP 2011) mandates that the total energy demand for space heating and cooling must be less than or equal to 15 kWh/m⊃2 of conditioned floor area, and the total primary energy use should be less than or equal to 45 kWh/m⊃2. Furthermore, comfort is indicated as a 5% maximum of hours exceeding 25°C. The selected reference dwelling accurately represents 39 renovated nearly zero-energy dwellings in Brussels (Zero Carbon Hub 2015). The model was developed and validated through walkthrough audits, in-situ measurements, and four years of energy use bills. The reference dwelling has three floors with a total surface area of 173 m^2. The building model was designed as follows (Attia et al. 2022):

1. Occupancy: a family of two parents around forty-five years old and two children of ten and seven years, respectively. The occupancy schedules were formulated with ISO 18523-2 (ISO 2016).
2. Clothing factor: light summer wear with 0.5 clo (ISO 7730 2005).
3. Metabolic activity: standing relaxed activity with 0.9 met (ISO 7730 2005).
4. Internal equipment gains: 8 W/m^2 based on the running hours and power value.
5. Lighting gains: 8 W/m^2 based on commonly used types and the number of lamps.
6. Water usage: 62 L/person/day.
7. Domestic Hot Water (DHW): 30 L/person/day at 60°C.
8. Processes: cooking activities were deduced to reach around 40–60 min/day.

Airflow rates for each zone were calculated based on the outside air definition method in DesignBuilder, which

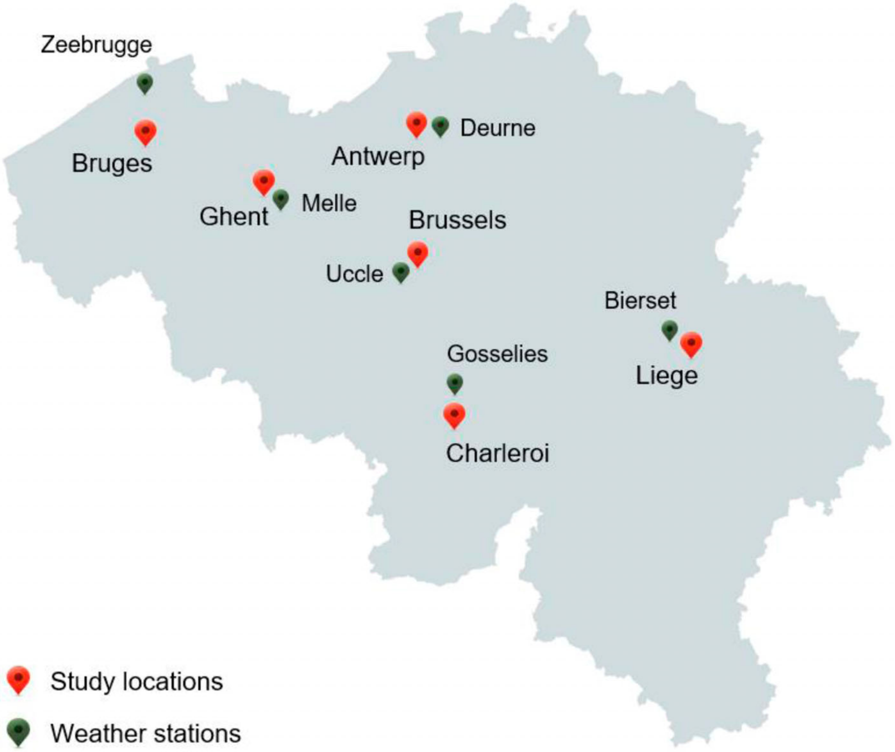

Figure 4. Belgian study locations and the weather stations used for data extraction used in the study.

defines the maximum mechanical ventilation rate using minimum fresh air requirements per person (DesignBuilder 2023). The minimum fresh air rate per person was 8.33 l/s/person per the requirements from (EN 16798-1 2019), and the number of occupants was 4. The airflow rate in m^3/s is calculated as in equation (5).

$$\text{Air flow rate} = \frac{\text{Minimum Fresh Air} \times \text{Number of occupants}}{1000} \quad (5)$$

From equation (5), the airflow rate is 0.033 m^3/s. The mechanical ventilation is scheduled to operate 24/7 during the monitored period. The window-to-wall ratio was 33%. The quality of the reference benchmark model was assured through calibration as per (ASHRAE 14 Guideline 14 2014) using real monthly energy use data for natural gas and electricity use collected over four years from 2016 to 2019 (Attia et al. 2022). The Mean Bias Error (MBE) and Coefficient of the Variation of the Root Mean Square Error (CV(RMSE)) values of monthly electricity use were 2.7% and 5.6%, within the acceptable ranges. The building composition is as follows:

- The ground floor has four layers and is made of Reinforced concrete with 2% steel (0.12 m), Spray-on-R-12 insulation polyurethane foam (0.0796 m), Cement screed (0.01 m), and Ceramic floor tiles (0.005) from the outer to the inner layer.
- The internal floor has six layers and was made of Perlite plastering (0.015 m), Standard insulation (0.0228), Reinforced concrete with 2% steel (0.12 m), Sandstone floor (0.02 m), Cement bonded particle board (0.01 m), and Timber flooring (0.015 m) from the outer to the inner layer.
- The external roof has four layers and was made of Asphalt (0.01 m), MW glass wool rolls (0.1179 m), Air gap (0.20 m), and Plasterboard (0.013 m) from the outer to the inner layer.
- The external wall has three layers and was made of Brickwork (0.10 m), Standard insulation (0.0818 m), and Cast concrete of medium weight (0.14 m) from the outer to the inner layer.
- The reference building has triple-glazed windows. The performance of the windows is good, with a low conductivity value of around 1 W/m^2K.

The reference dwelling simulation model and floor layout are shown in Figure 5. The reference dwelling is oriented with a southeast facade. Additional details on the reference dwelling can be found at (Attia et al. 2022; Attia 2021). A general description and model characteristics are listed in Table A.1 and Table A.2 in Appendix A.

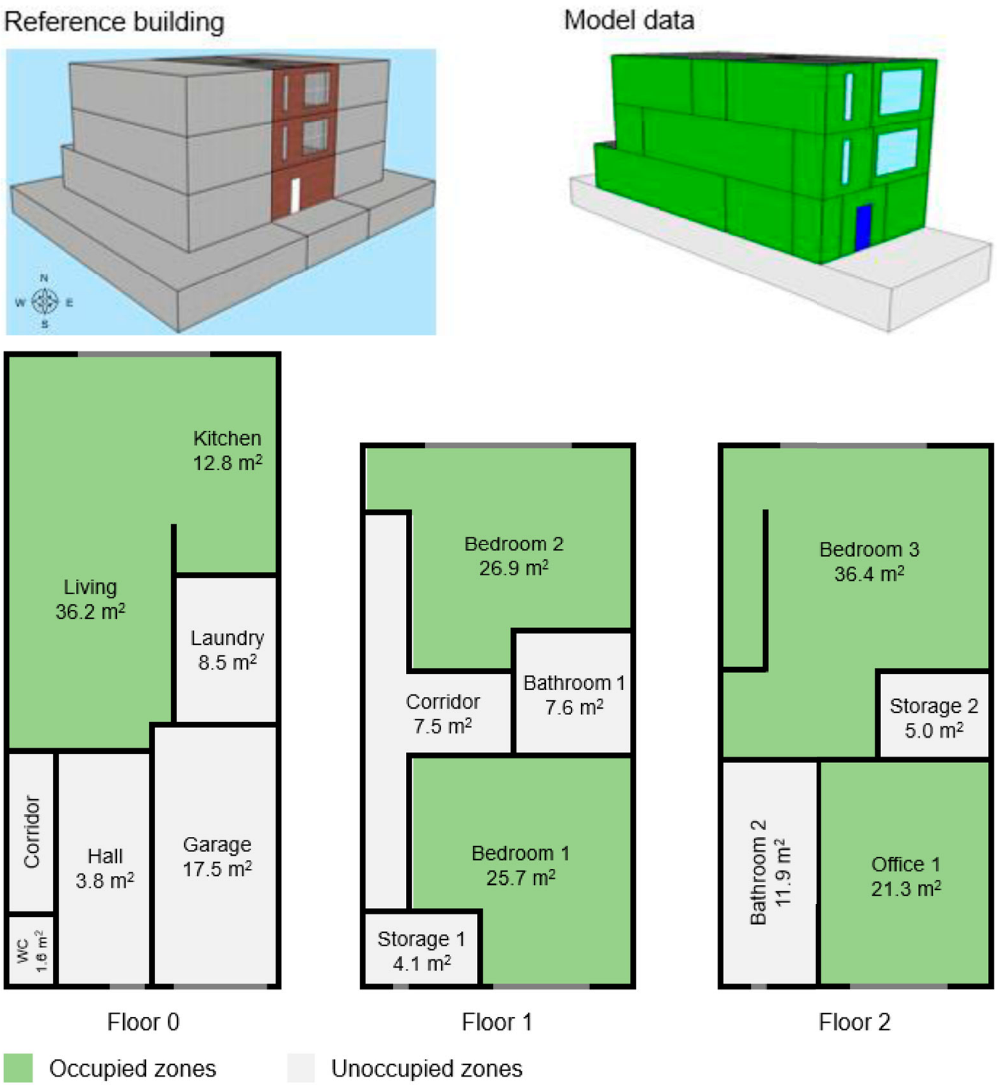

Figure 5. The renovated nearly zero-energy dwelling simulation model and floor layout.

Two building configurations were evaluated in this study as follows:

a. Strategy 01 without active cooling: In the baseline configuration, active cooling was unavailable. The reference dwelling was mechanically ventilated during the summer period.
b. Strategy 02 with active cooling: Active cooling was implemented using a reversible VRF unit (electric) with DX cooling coils. A VRF unit was preferred over other systems because VRF systems are more energy efficient than conventional systems (Enterprise 2022; Rumsey et al. 2021). The sizing of the VRF system was performed with a climate change-sensitive approach (Amaripadath et al. 2023) using design day calculation according to (ISO 15927-2 2009). The design data for cooling consisted of a maximum dry-bulb temperature of 37°C, a minimum dry-bulb temperature of 21°C, and a coincident wet-bulb temperature of 21.3°C (Żuławińska 2022; Vecellio et al. 2022).

3. Results

3.1. *How can heat waves in Belgium be detected and categorized?*

The heat waves across the study locations and average summer temperatures from 2001 to 2020 are shown in Figure 6.

The most intense heat waves [°C.days] from each study location, along with the occurrence [year], maximum temperature [°C], and duration [days], are geolocated on the Belgian map and are shown in Figure 7.

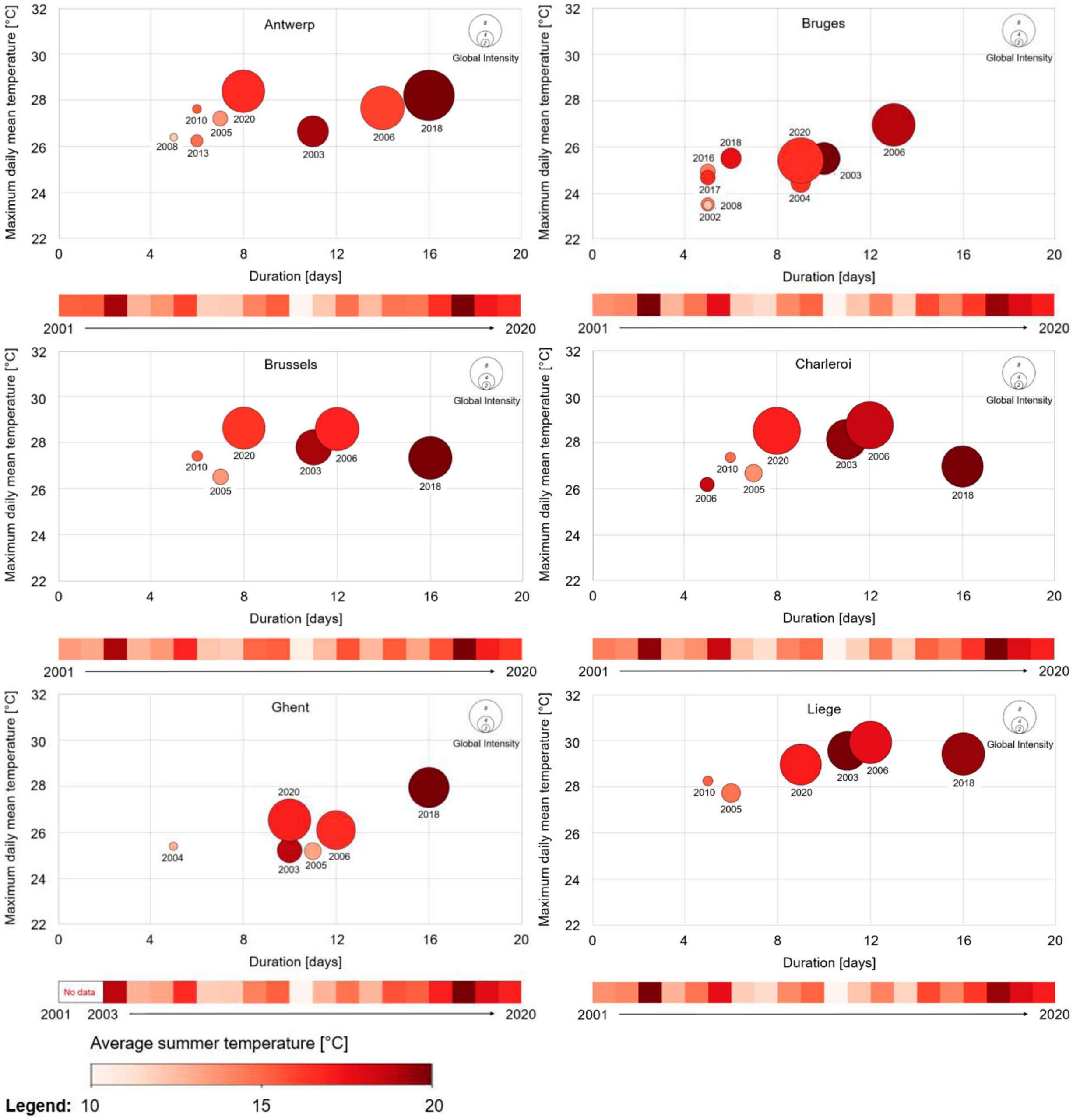

Figure 6. Heat waves identified and classified across the study locations in Belgium from 2001 to 2020.

3.2. How resilient is the renovated nearly zero-energy dwelling against intense heat waves in Belgium?

The operative temperature in the reference dwelling for Strategy 01 without active cooling and Strategy 02 with active cooling before, during, and after the heat wave is shown in Figure 8. The analysis of Strategy 02 with active cooling for building resilience showed that the reference dwelling has a low overheating exposure risk indicating that the building is less vulnerable to the heat wave. The impact of overheating during the heatwave is minimal to 0.01°C, which indicates that the reference dwelling is resistant to overheating exposure severity. The system's failure to maintain the designed minimum operative temperature of 26°C is evident from Figure 8. However, these are short-term failures, and the dwelling adapts to designed minimum thermal conditions.

During the heat wave, Strategy 02 does not go into failure mode above the critical thermal condition of 30°C, whereas Strategy 01 fails to maintain the operative temperature at acceptable levels. The degree-hours for each strategy above the designed minimum value

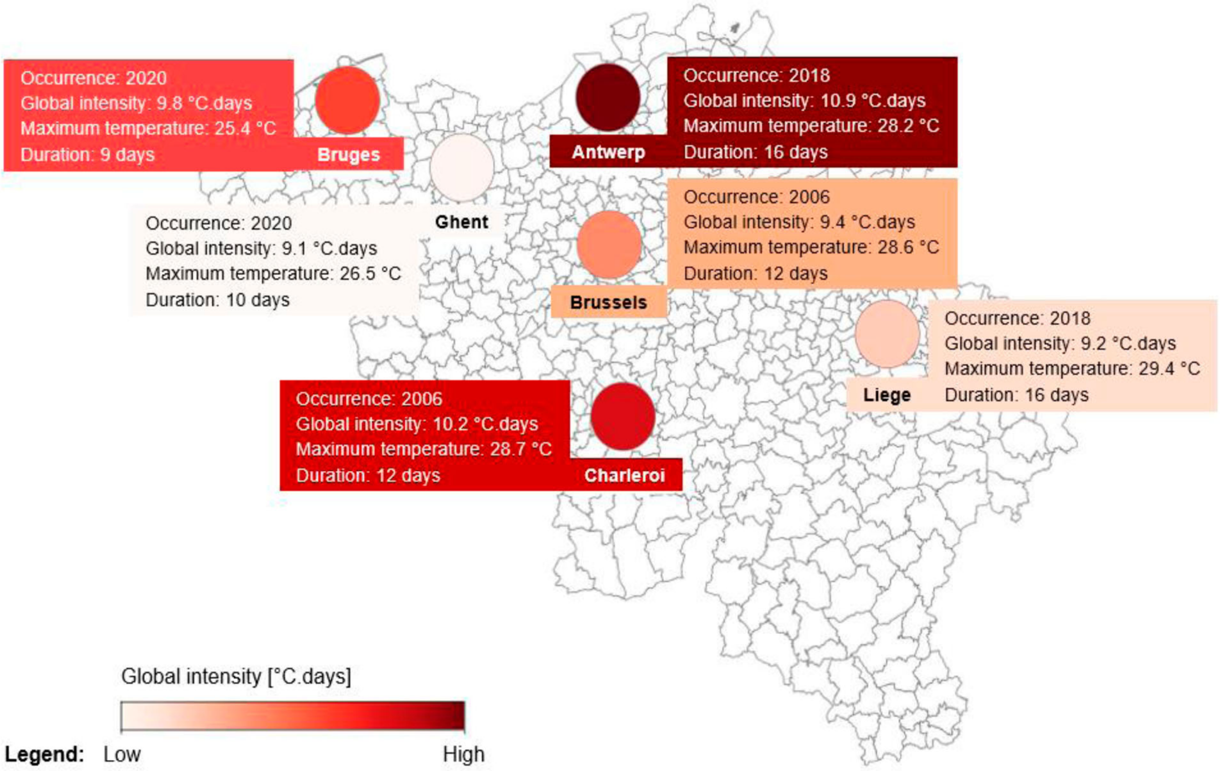

Figure 7. The most intense heat waves with occurrence [year], global intensity [°C.days], maximum temperature [°C], and duration [days] geolocated on the study locations in Belgium from 2001 to 2020.

of 26°C and critical value of 30°C are listed in Table 2. The table shows a 100% decrease in degree-hours before and after the heat wave and a 98% decrease during the heat wave for Strategy 02 for the designed minimum value of 26°C. For the critical value of 30°C, Strategy 02 shows a 100% decrease in degree-hours during the heat wave.

3.3. *How does overheating vary in the renovated nearly zero-energy dwelling with and without active cooling during intense heat waves?*

Overheating was evaluated for the reference dwelling at the building and zone level before, during, and after the most intense heat wave in Antwerp, Belgium, from July 23, 2018, to August 07, 2018. Seven days were evaluated before and after the heat wave to consider the recoverability rate of the reference dwelling as per the IEA EBC Annex 80 dynamic simulation guideline (Zhang et al. 2023). The IOD computed for each occupied zone in the reference dwelling is shown in Figure 9. The IOD for Strategy 01 without active cooling was lower than Strategy 02 with active cooling after the heatwave by 0.01°C since the whole building was assessed using PMV/PPD limits for Strategy 02 with active cooling. In contrast, the Office room and Living + Kitchen were assessed using adaptive limits for Strategy 01 without active cooling.

The percentage of exceedance hours to the total occupied hours in the reference dwelling zones is shown in Figure 10. There is a decrease in the percentage of exceedance hours [%] for the Bedrooms and Living + Kitchen for Strategy 02 with active cooling compared to Strategy 01 without active cooling with $|PMV| > 0.5$. In contrast, there is an increase in the percentage of exceedance hours in the Office room since it was calculated using a stringent $|PMV| > 0.5$ for Strategy 02 with active cooling compared to Strategy 01 without active cooling, which uses a more flexible upper adaptive operative temperature limit.

4. Discussions

4.1. *Findings and recommendations*

1. The evaluation of heat waves across Belgium indicated that heat waves were increasing in duration and intensity each year. The most intense heat wave detected in Belgium had an intensity of 10.9°C.days, 16 days, and occurred in 2018. These findings aligned with the observations from (WMO 2022; AdaptNSW 2022), which indicated longer and more intense heat waves in the future.

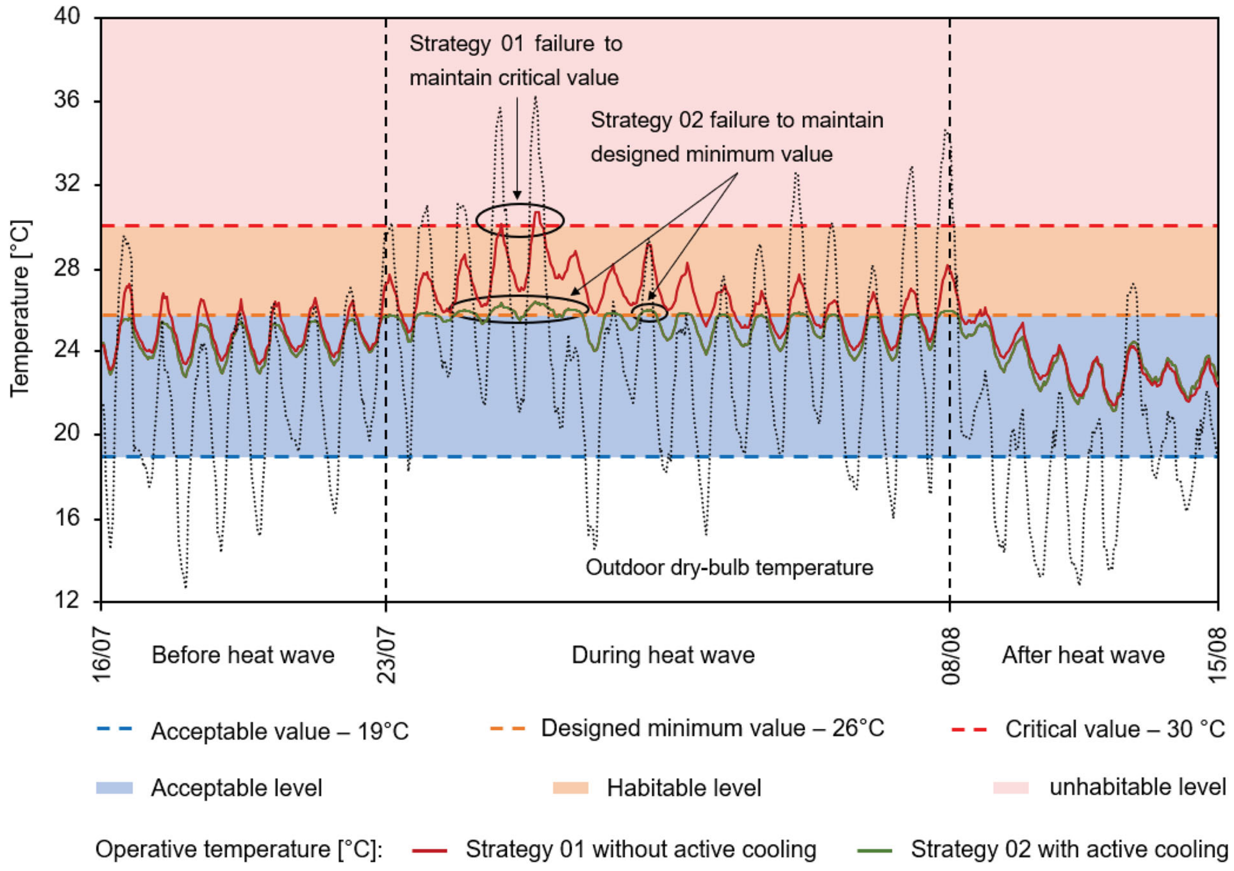

Figure 8. Characterization of thermal resilience of cooling strategies in reference dwelling before, during, and after the intense heat wave in Antwerp, Belgium, from July 16, 2018, to August 14, 2018.

Table 2. Thermal resilience quantification using degree-hours [°C-hours] for cooling strategies outside each temperature threshold before, during, and after the intense heat wave in Antwerp, Belgium, from July 16, 2018, to August 14, 2018.

	Above designed minimum value: 26°C			Above critical value: 30°C		
Event	Strategy 01	Strategy 02	Decrease [%]	Strategy 01	Strategy 02	Decrease [%]
Before heat wave [16/07 – 22/07]	13.29	0	100	0	0	–
During heat wave [23/07 – 07/08]	333.34	4.96	98	2.75	0	100
After heat wave [08/07 – 14/08]	0.72	0	100	0	0	–

2. From the analysis, Strategy 02, with active cooling proposed for the reference dwelling, is resilient to heat waves. This is evident from the percentage decrease in degree-hours for Strategy 02 from 98% to 100% before, during, and after the heat wave. Furthermore, the resilience of the cooling system can be improved by setting a design temperature that is lower than desired minimum thermal conditions.
3. Bedroom 2 is the worst discomfort zone, while the Office room is the least discomfort zone regarding the percentage of exceedance hours in the Baseline since the zones were analyzed using PMV/PPD and adaptive limits, respectively. Hence, it is advised to spend more non-sleeping hours in the Office room during heat waves, and sleeping hours should be shifted to Bedroom 1, which is relatively safer than other bedrooms in the reference dwelling. Additionally, the thermal safety zones like Bedroom 1 and Office room with minimal overheating exposure, add to the robustness of the reference dwelling.
4. The most intense heat wave in Belgium from 2001 to 2020 had a strong impact with an IOD of 0.60°C for Strategy 01 without active cooling and a moderate impact with an IOD of 0.01°C for Strategy 02 with active cooling on the indoor environment. This indicated a decrease in the extent of overheating during heat waves while using Strategy 02 with active cooling.

Figure 9. Indoor Overheating Degree [°C] in different occupied zones in the reference nearly zero-energy dwelling before, during, and after the most intense heat wave in Antwerp, Belgium, from July 16, 2018, to August 14, 2018.

5. The percentage of exceedance hours decreased in the Bedrooms and increased in the Office room for Strategy 02 with active cooling compared to Strategy 01 without active cooling. This increase was since the exceedance hours for the Office room were calculated using stringent criteria of $|PMV| > 0.5$ for Strategy 02 compared to Strategy 01, which was calculated using more flexible criteria of upper adaptive operative temperature limit.
6. To conduct a comprehensive heat wave analysis, characterization of urban microclimate is inevitable. UHI should be characterized using: a. weather stations

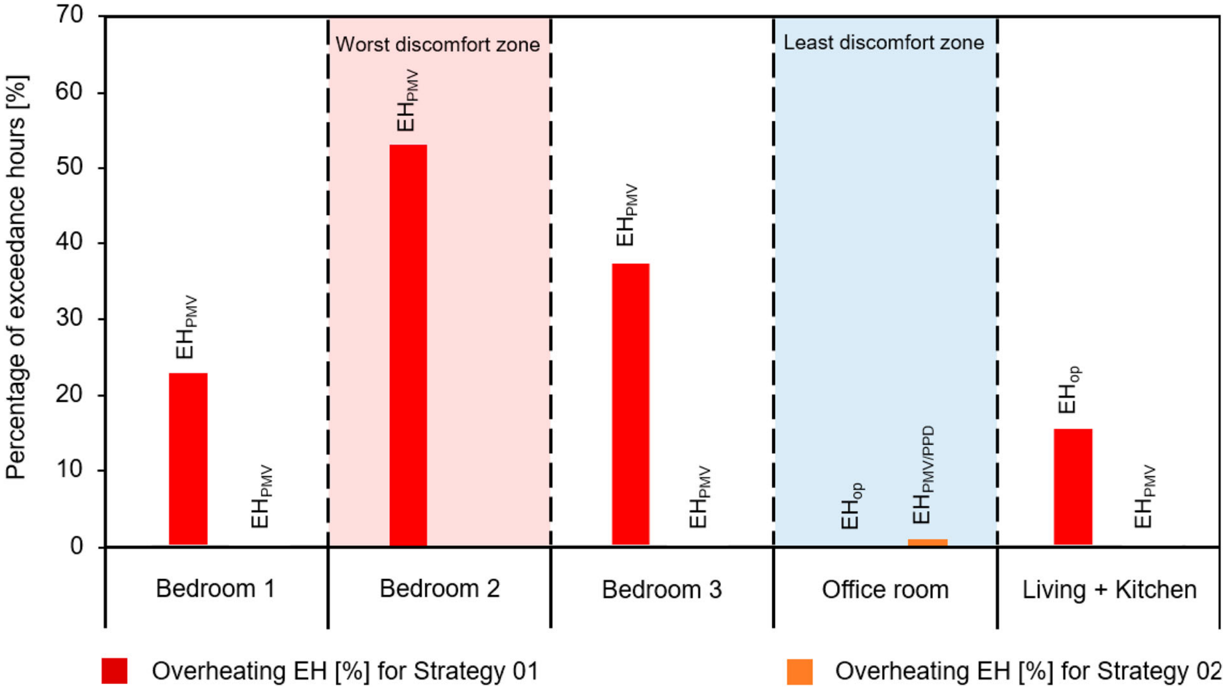

Figure 10. Percentage of overheating exceedance hours [%] in the reference dwelling zones during the intense heat wave in Antwerp, Belgium, from July 23, 2018, to August 07, 2018.

in the most vulnerable locations in the cities considering air temperature, solar radiation, surface topology, and population density, or b. simulation tools like the Urban Weather Generator (UWG) that calculates hourly urban air temperature and humidity based on data collected from an operational weather station outside of the city (Bueno et al. 2013).

7. The total site energy use for Strategy 01 was 8.72 kWh/day, and for Strategy 02 was 46.41 kWh/day during the monitored period from July 16, 2018, to August 14, 2018. While considering the comfort benefits of Strategy 01 with active cooling, it is also important to address the energy penalty and consequent environmental impacts due to greenhouse gas (GHG) emissions. The excess site energy use due to active cooling amounts to 37.69 kWh/day. This site energy value corresponds to the primary energy use of 94.225 kWh_{PE}/day using a conversion factor 2.5 (Carlier 2016; IBGE 2017) and GHG emission of 25.44 kg.CO_2e/day using a conversion factor of 0.270 kg.CO_2e/kWh (Encon 2022), since the fuel source is electricity. Therefore, any potential benefits of using Strategy 02 over Strategy 01 should factor in the excess energy use, GHG emissions, and financial impact. Implementing passive design adaptations can reduce the energy demand for active cooling systems, and they are not mutually exclusive.
8. Active cooling systems are limited not only by their enhanced carbon emissions but by their ineffectiveness during heat wave conditions should the electrical grids fail, as was the case in several heat wave events highlighted in Figure 1. Future studies should evaluate the resilience during a concurrent heat wave and power outage and how integrating onsite renewables and storage capacities will contribute to the recoverability during such an event. However, this limitation can be offset through (i) onsite power generation through renewable energy systems (Rajput et al. 2022) and (ii) urban heat island mitigation like urban tree canopies (Middel et al. 2015; Skelhorn et al. 2014).

4.2. *Strengths and limitations*

The strengths of this paper are based on several aspects:

1. This paper provides the policymakers with evidence on the increasing intensity and duration of heat waves across the study locations in Belgium over the past decades. The study is important to building scientists, urban modelers, building designers, maintenance engineers, and energy engineers to shape sustainable solutions for mitigating and adapting to heat waves.
2. This study's heat wave identification methodology was based on three different thresholds that were percentiles of the daily mean temperature distribution over several years. The existing definition from

RMI in Belgium was based on the absolute values of the maximum daily temperature observed in the Uccle weather station, which was unsuitable for a study involving multiple study locations.
3. This study used a reference dwelling model calibrated according to (ASHRAE Guideline 14 2014) that was representative of renovated nearly zero-energy dwellings with monthly energy use values. In terms of building resilience and overheating assessments, this increased the reliability of the model outputs with the real-world outputs.

The main limitations of this study are:

1. The study considered cooling strategies at the building level. The study did not evaluate neighborhood-level measures, also called urban heat island mitigation strategies like urban tree canopies. Findings from existing studies like (Middel et al. 2015; Skelhorn et al. 2014) found that a 1% increase in urban tree cover results in a 0.14°C to 0.2°C drop in temperature in humid and arid areas. This should be considered in future studies.
2. The study was based on the free-running and air-conditioned operation of the reference dwelling. However, active measures also can be used alongside passive measures in mixed-mode operations to reduce energy use for active cooling as much as possible. The performance of mixed-mode operation during heat waves should be addressed in future studies.

4.3. Implications for practice and work

1. UHI effects in the cities exacerbate the detrimental effects of heat waves. UHI effect will intensify as the structure, spatial extent, and population density change and grow in urban areas unless the cities are equipped with adequate adaptive measures. Cities or metropolises with a large population and an industrial economy will be particularly affected by UHI (Skelhorn et al. 2014). Therefore, the measurement and reporting of UHI magnitudes should be carried out according to existing best practices to ensure the authenticity of the monitored data (Rizwan et al. 2008; Stewart 2011).
2. According to current adaptive model category II equations from (ISO 17772-1 2017), the upper comfort limit exceeds 30°C during intense heat waves. However, this might not be comfortable in a real building and requires further investigation. The HSE had previously outlined a higher acceptable temperature of roughly 30°C for more sedentary activities and up to 27°C for strenuous activities (HSE 2010).
3. As the temperature rises, heat waves will become more frequent and intense (Wuebbles 2017; Shevchenko et al. 2022). The increasing frequency of heat waves will increase deaths and illnesses from heat exposure, particularly among vulnerable populations like the elderly, children, economically disadvantaged, and people with chronic health conditions, unless communities adapt to these events (Sarofim et al. 2016). Hence, tracking heat waves as a visible effect of climate change and as a risk factor is vital.

5. Conclusions

The paper reiterates the importance of analyzing heat wave impacts on overheating in renovated dwellings to aid policymakers in shaping sustainable solutions to the detrimental effects of extreme short-term events on the built environment. This study evaluated heat wave impacts in terms of thermal resilience and overheating in a calibrated dwelling that was representative of renovated, nearly zero-energy dwellings in mixed humid climates (4A). The building thermal resilience was analyzed before, during, and after Belgium's most intense heat wave from 2001 to 2020. The results showed that the most intense heat wave would strongly impact the building resilience with Strategy 01 without active cooling and much less for Strategy 02 with active cooling. This finding was supported by an overheating analysis that showed a strong impact for Strategy 01 without active cooling with an IOD of 0.60°C and a moderate impact for Strategy 02 with active cooling with an IOD of 0.01°C.

All reference dwelling zones evaluated in the study showed a decrease in the exceedance hours with Strategy 02 except the Office room compared with Strategy 01 during the intense heat wave due to different comfort models used for the assessment. The study findings indicated that the existing building-level renovation strategies alone would be insufficient and that nearly zero-energy dwellings will require active cooling with climate change-sensitive sizing to reduce the overheating impact of heat waves on the indoor environment. Therefore, implementing resilient active cooling systems in buildings should be focused on mitigating the impact of heat waves on overheating in nearly zero-energy dwellings. To accelerate and contribute toward the EU objective of reducing emissions by 55% by the 2030s, the paper suggests increased integration of renewables and renovation of traditional building systems. This integration will help decrease the stress on existing electricity grids to meet the increasing energy demand during heat waves.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The Python code used for heatwave identification, classification, and visualization is available at: doi.org/10.5281/zenodo.7326894 (Joshi et al. 2022).

Declaration of competing interest

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.

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Appendix A

The general characteristics of the reference dwelling are listed in Table A1.

The model characteristics and assumptions are listed in Table A2.

The VRF unit has a COP of 3.3 for cooling from the existing energy efficiency standards (Legal Information Institute 2022).

Table A1. The general description of the reference dwelling.

Building characteristics	Values
Number of floors [-]	3
Total area [m^2]	173
Occupants [-]	4
Total volume [m^3]	873
External wall area [m^2]	122
Roof area [m^2]	91
Floor area [m^2]	259
Window area [m^2]	41
Window U-value [W/m^2K]	1.20
Window G-value [-]	0.60
Wall surface absorptance (-)	0.90
Walls U-value [W/m^2K]	0.40
Roof U-value [W/m^2K]	0.30
Ground U-value [W/m^2K]	0.30
Attic floor U-value [W/m^2K]	0.80
Airtightness (at 50 Pa $m^3/h.m^2$) [ACH]	1.58

Table A2. The DesignBuilder model inputs.

Active cooling	Strategy 02
Production	Reversible VRF unit (electric)
Distribution	DX cooling coils
Target zones	Bedrooms, Office room, Living + Kitchen
Cooling	Setpoint: 26°C, Setback: 50°C
Nominal COP	3.3 (Legal Information Institute 2022)
Fuel type	Electricity
Sizing factor	1
Schedule	On: 24/7
Mechanical ventilation	**Strategy 01 and Strategy 02**
Target zones	Bedrooms, Office room, Living + Kitchen
Ventilation rates	8.33 l/s/person (CEN 2019)
AHU type	Constant Air Volume
AHU fans	Constant volume fans
Nominal COP	0.7
Schedule	On: 24/7