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Thermal resilience in the built environment: A critical review

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ABSTRACT

With the increasing frequency and severity of extreme weather events including heatwaves and cold snaps, enhancing thermal resilience has become a critical priority for the built environment. Existing studies offer advanced knowledge on building overheating risk, resilient cooling, and related adaptation strategies, but often remain fragmented and focused on isolated topics. Despite this growing body of research, no comprehensive review has yet synthesized these developments. This paper presents a comprehensive review of more than 100 peer-reviewed journal articles on thermal resilience in the built environment, covering definitions, application domains, disturbance categories, scenario construction, and performance evaluation methods. The review critically examines current research trends from a broader perspective and reveals the diversity in current approaches. This paper further proposes a cross-scale framework linking urban and building thermal resilience and offers practical recommendations for different stakeholders. It also advocates integrating climate resilience with net-zero targets for the transition to a robust and future-ready built environment.

1. Introduction

In recent years, extreme weather events have become increasingly frequent and severe in the context of climate change. Among these, extreme temperature events such as heatwaves and cold snaps, particularly when combined with power outages, pose substantial threats to human comfort and health. Exposure to extreme temperatures can lead to numerous health issues, and it leads to increased morbidity and mortality, especially among vulnerable populations, including the elderly and low-income communities (Gronlund et al., 2018; Yadav et al., 2023). The extreme weather events also present serious risks to energy systems and urban infrastructure (Javanroodi et al., 2023).

Buildings provide critical protection through their envelopes and service systems, protecting occupants from external environmental conditions. Since the late 20th century, concerns regarding overheating in buildings, defined as discomfort caused by accumulated indoor heat, have been increasingly recognized (Lomas and Porritt, 2017). Numerical studies have examined evaluation methods, metrics, criteria, and improvement strategies for overheating (Rahif et al., 2021; Attia et al., 2023); some of these have even been incorporated into official standards and guides, e.g., the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 (ASHRAE, 2023), the Chartered Institution of Building Services Engineers (CIBSE) TM52 (CIBSE, 2013) and TM59 (CIBSE, 2017).

Recently, with the development of International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Programme Annex 80: Resilient Cooling of Buildings, the concept of thermal resilience and resilient cooling have gained increasing attention. While research on overheating has traditionally emphasized long-term thermal discomfort across the summer season, thermal resilience places greater emphasis on short-term shocks caused by extreme weather and on the dynamic processes of adaptation and recovery in response to such events. The scope of thermal resilience extends beyond the overheating concerns of free-running buildings to mechanical cooling buildings, and further to neighbourhood and urban scale. Thermal resilience also broadens the disturbance spectrum to include diverse extreme events, including cold snaps and power outages that may compromise indoor habitability.

A growing body of research has investigated these aspects through various case studies. For example, several simulation studies have analysed building performance under heatwaves and power outages (Baniassadi et al., 2018; Sengupta et al., 2023b, 2023a) and under winter cold snaps (Guo et al., 2024; Sheng et al., 2023). Empirical

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monitoring has also been used to evaluate thermal safety during actual extreme events (López-García et al., 2022). Beyond the building scale, research has also examined outdoor and urban-scale thermal conditions under extreme weather scenarios (Huang et al., 2023; Khorat et al., 2024; Xia and Hu, 2024). These case studies are context-dependent, focusing on specific climatic regions. They highlight the importance of thermal resilience under diverse conditions and provide useful insights, but more systematic and integrative approaches are still needed to generalize the findings across broader contexts.

In parallel, several review papers have attempted to synthesize the emerging knowledge on thermal resilience, as summarized in Table 1. While these reviews provide important stepping stones, they tend to prioritize specific perspectives. For example, the reviews by Attia et al. (2021) and Zhang et al. (2021) focus on conceptual framing and resilient cooling strategies categorization, providing foundational overview of the problem and outlining potential solution pathways. Siu et al. (2023) take a methodological perspective and offer rigorous insights into simulation workflows and resilience assessment. Hong et al. (2023) propose a high-level research agenda by addressing ten key questions for future inquiry. However, despite these valuable contributions, such perspectives—including definitions, simulation tools, measures and research agendas—have rarely been examined within a unified structure to reveal their interdependencies. In addition, some aspects such as urban-scale interactions and grid flexibility have received relatively limited attention in previous building-level reviews.

Therefore, this paper explores thermal resilience in the built environment from a broader and more integrative perspective. Rather than examining thermal resilience through a single isolated lens, this study holistically synthesizes the key components that shape thermal resilience, including definitions, system boundaries, disruptive events, scenarios and performance evaluation, within a unified analytical framework. Furthermore, this paper extends the analytical scope beyond the building boundary to situate buildings within their interconnected built environment, capturing broader contextual factors such as neighbourhood-scale dynamics and microclimatic interactions. By synthesizing evidence from over 100 peer-reviewed journal articles published in recent years, this paper promotes a comprehensive and holistic approach to its understanding and application of thermal resilience. The objectives of this study are:

- To systematically review existing definitions, metrics, and methodologies used to evaluate thermal resilience in the built environment, identifying the diversity and limitations in current research trends.
- To explore the integration of thermal resilience concepts across multiple scales, proposing a cross-scale framework that links urban and building thermal resilience.
- To identify and synthesize a broader set of indicators that enable a more systematic and interdisciplinary assessment of thermal resilience.
- To identify critical research gaps and propose future directions for both academic investigation and practical implementation by diverse stakeholders.

Table 1
Summary of previous review articles on thermal resilience.

Reference	Focus
(Attia et al., 2021)	Introduced and structured the concept of resilient cooling
(Zhang et al., 2021)	Defined the concept of resilient cooling and qualitatively assessed a range of cooling strategies
(Siu et al., 2023)	Reviewed the previous modelling and simulation research on quantifying the thermal resilience of buildings
(Hong et al., 2023)	Highlighted ten critical questions about thermal resilience of buildings and occupants

2. Review methodology

2.1. Search strategy and criteria

The focus of this review is on thermal resilience of the built environment, while other forms of resilience, such as those related to earthquakes, fires, or floods, are outside the scope of this study. The scale of analysis extends from the building level, as emphasized by Attia et al. (2021), to the neighbourhood level, addressing not only indoor environments but also the surrounding built environment and its connection to open spaces. Furthermore, this study focuses mainly on engineering- and performance-based thermal resilience research. Based on this focus, the search terms used are listed in Table 2. The search was performed in the Scopus database on July 24, 2025, and only peer-reviewed journal articles were included.

Fig. 1 presents the flowchart of the review process. During the screening process, the exclusions often involved topics unrelated to the built environment (e.g., coral thermal resilience), studies focusing solely on social or health resilience, or those addressing other types of extreme events. Following full-text review, manual searches, and snowballing, a total of 113 articles were read in full and included in the final analysis of this study.

2.2. Analysis of the search results

Fig. 2 shows the distribution of the selected articles by publication year. The number of related publications has increased rapidly since 2011, which likely corresponds with the increasing frequency and intensity of extreme climate events in recent years. The majority of articles were published in *Building and Environment* and *Energy and Buildings*.

Among the 113 reviewed articles, except for a small number of theoretical studies, literature reviews, and methodological framework articles, 92 are case studies focused on one or more site-specific applications. Fig. 3 presents the geographic distribution of these case studies. The case studies are concentrated in the United States (n=25), Belgium (n=10), China (n=10), Canada (n=9), and other European countries, including Spain, Italy, Germany, and the United Kingdom. Although less frequent, relevant studies have also emerged from the Global South, including Argentina (Flores-Larsen and Filippín, 2021; Flores-Larsen et al., 2023), Brazil (Krelling et al., 2023, 2024), Honduras (Gamero-Salinas et al., 2021), India (Vellingiri et al., 2020; Henna et al., 2021; Verma et al., 2025), Libya (Aruta et al., 2025) and Pakistan (Mehmood et al., 2022, 2023), indicating growing attention to thermal resilience in diverse climatic and socioeconomic contexts.

Fig. 4 categorizes the case studies according to ASHRAE climate zones and shows a clear focus on warm and mixed climates, particularly 4A (Humid Subtropical/Humid Continental - Warm Summer) and 3A (Humid Subtropical - Warm Summer). This trend may reflect increasing concerns that traditionally mild summer climates are becoming hotter under climate change, raising the urgency for thermal resilience strategies in these zones.

2.3. Analysis of the papers

The content of the included papers was organized and analysed using thematic synthesis (Thomas and Harden, 2008), which involved line-by-line coding, the development of descriptive themes, and the generation of analytical themes that interpret and extend beyond the original findings. The resulting synthesis informed the structure of the following section, organized around five key thematic domains: (1) how thermal resilience is defined across studies; (2) the spatial and functional domains of thermal resilience studies; (3) the classification and definition of disturbance events; (4) the contextualization of thermal resilience scenarios; and (5) the methods, tools and metrics used to evaluate thermal resilience.

Fig. 5 illustrates the overall structure of this review.

Table 2
Scoping review search strategy.

Concept	Terms	Justification
Thermal resilience	("thermal resilien*" OR "heat resilien*")	Directly discusses thermal or heat-related resilience
	(("climat* resilien*") AND ("overheating" OR "overcooling" OR "undercooling" OR "heatwave" OR "heat wave" OR "cold wave" OR "cold snap" OR " extreme" OR "shock" OR "outage"))	Broader climate resilience with a focus on thermal-related events or power disruptions.
Built environment	(building OR dwelling OR house OR office OR school OR neighbourho*d OR district OR communit*)	Built environment at the building and neighbourhood scale

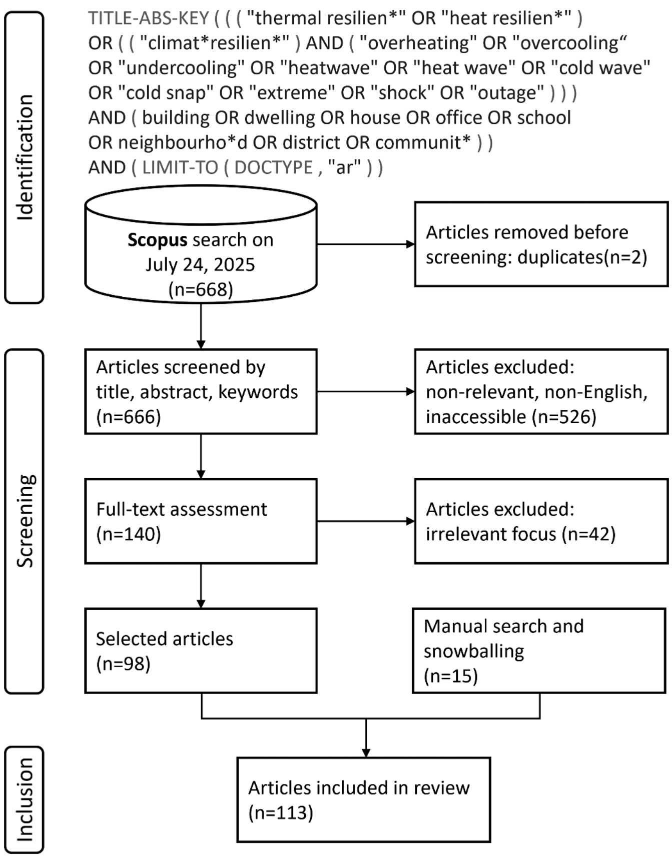

Fig. 1. The flowchart of the review process.

3. Findings

3.1. Evolving definitions of thermal resilience

The term resilience originates from the Latin word *resilire*, and was originally used in material science to describe a material's ability to absorb energy from bending or deformation without breaking. In the built environment field, Leichenko (2011) extended this concept to define urban resilience as the capacity of a city or urban system to withstand a wide range of shocks and stresses. These shocks and stresses are not limited to specific categories but can include natural disasters, urban ecology challenges, and economic disruptions.

When extended to the thermal domain, this concept shifts the research focus from simply preventing overheating or overcooling toward understanding the dynamic capacity of buildings to cope with such thermal extremes. Although many studies have attempted to quantify resilience, relatively few have provided clear and precise definitions, and existing definitions vary widely in scope. To illustrate these trends, this study synthesizes different types of thermal resilience definitions used in the built environment literature, as shown in Fig. 6. A widely referenced benchmark is the framework proposed by Attia et al. (2021), identifying four key stages along the resilience curve: vulnerability (sensitivity to risk), resistance (absorption), robustness (adaptation after failure), and recovery (remedy). This definition has also been adopted in IEA EBC Annex 80 and applied in a number of subsequent studies (Flores-Larsen et al., 2023; Krelling et al., 2023).

Nonetheless, not all studies have universally adopted this full structure as a standardized definition of resilience. Instead, many have focused on only selected parts of the process and therefore adopt narrower interpretations of thermal resilience.

One group of studies applies a minimal, resistance-only definition, and focuses solely on the ability to 'withstand and maintain' performance during a shock (Borghero et al., 2023; Rostami and Bucking, 2024; Sengupta et al., 2024a; Sheng et al., 2023). These definitions

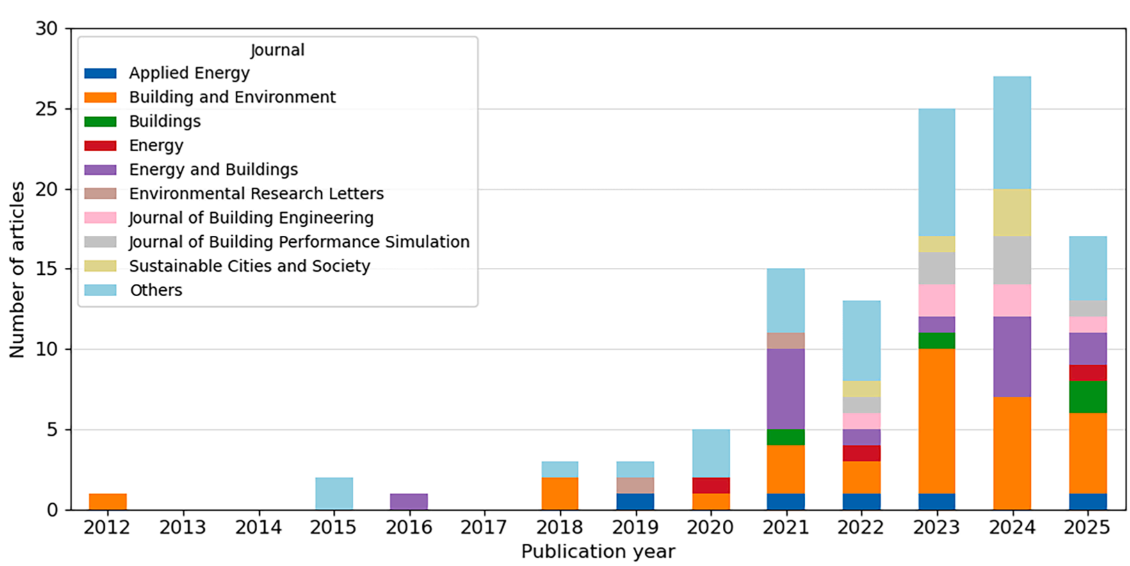

Fig. 2. Number of articles according to publication year and journal.

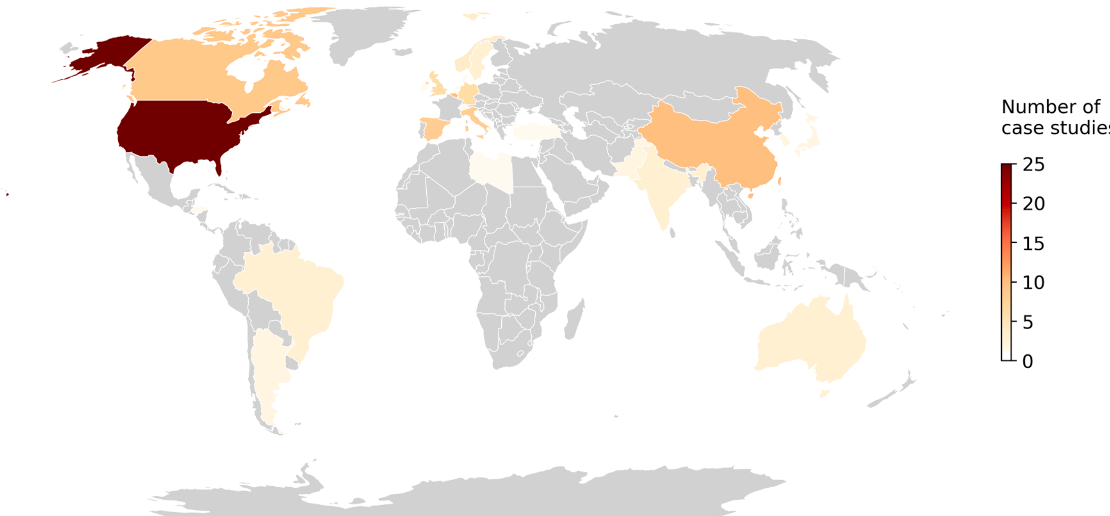

Fig. 3. Number of case studies according to the study region.

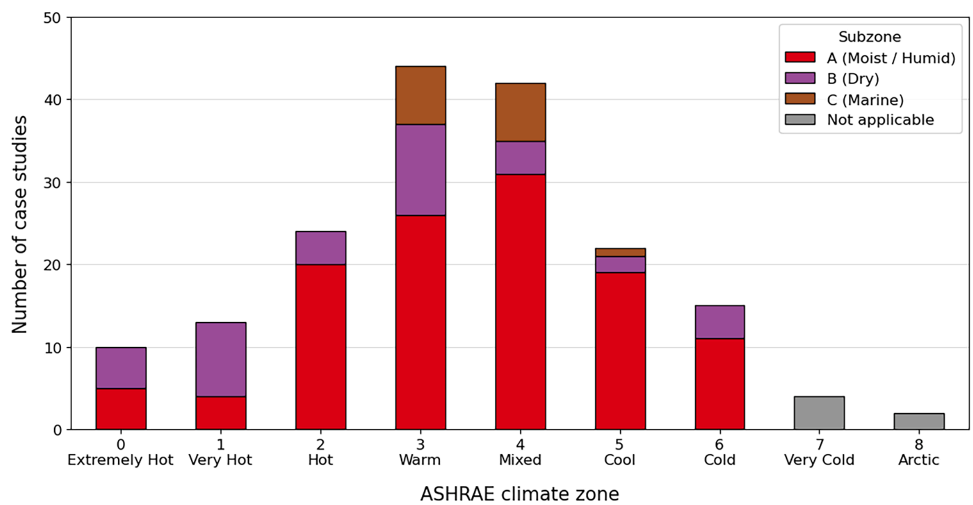

Fig. 4. Number of case studies according to ASHRAE climate zones.

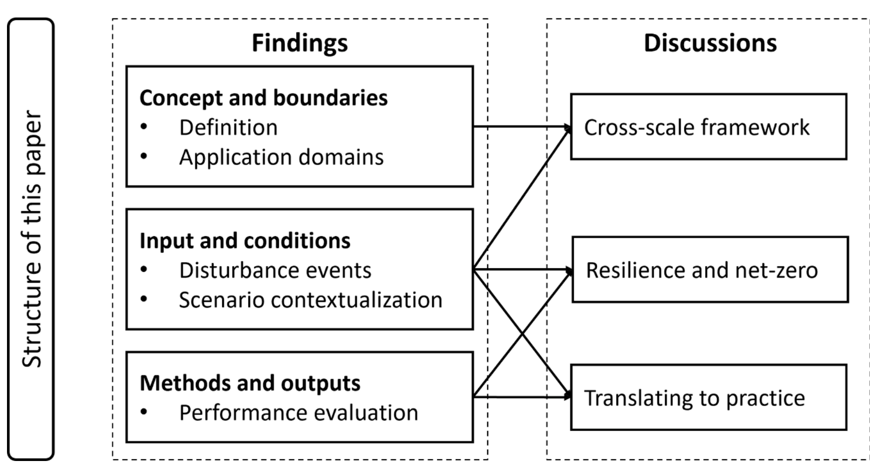

Fig. 5. The structure of this review paper.

address only system stability around the disturbance point, without considering performance degradation or recovery.

A second group of studies expands this minimal definition by incorporating a "recovery" or "return" component (Siu et al., 2023; Liyanage et al., 2024; Borghero et al., 2023; Guo et al., 2024; Sengupta et al., 2023b, 2024a; Schünemann et al., 2021a; Ji et al., 2024),

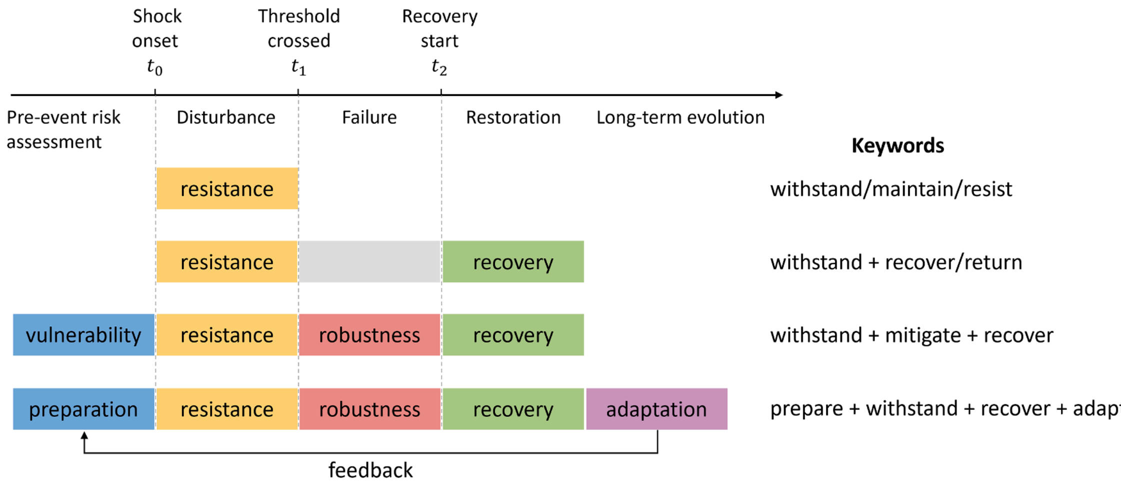

Fig. 6. Different types of thermal resilience definitions in literature. (Adapted from(Attia et al., 2021)).

recognizing the system's ability to regain acceptable conditions after a shock. However, these definitions still do not address how the system behaves during the failure period (robustness stage), i.e., how the system buffers performance degradation, stabilizes under reduced functionality, or maintains minimally acceptable conditions before recovery occurs.

These groups of definitions are largely aligned with the logic of engineering resilience, which focuses on maintaining or returning to a stable equilibrium in response to specific shock events. Even within this engineering framework, Attia et al. (2021) recognize the necessity of adaptation over time and consideration of long-term climate change. Building on this, recent studies have increasingly adopted a broader, ecological-oriented perspective (Krelling et al., 2024; Paneru et al., 2024). This perspective emphasizes not only a system's capacity for long-term adaptation and transformation under future climatic shifts, but also the importance of proactive planning and design strategies in the pre-disturbance phase. Within this perspective, resilience is understood as an iterative and evolutionary process: under the pressure of continuous climate change, built domains undergo continuous retrofitting and functional upgrades. Each disturbance and failure provides new feedback, informing subsequent design improvements and operational adjustments that collectively enhance the system's adaptive potential over time.

3.2. Application domains: from buildings to urban systems

The selection of research objectives in thermal resilience fundamentally reflects the definition of system boundaries. Different study subjects exhibit varying spatial typologies (e.g., indoor or outdoor environments), physical characteristics (e.g., building envelope performance), internal occupant profiles and behavioural patterns, internal technical systems (e.g., HVAC configurations), and external contextual factors (e.g., urban microclimate and urban morphology). These factors collectively influence the resilience of a system.

At the building level, over 52 % of research focuses on residential buildings. This emphasis is driven by the prevalence of residential buildings, long occupancy durations, and higher susceptibility to nighttime overheating (Attia et al., 2023). In the field of residential buildings, specific areas of focus include disadvantaged housing, particularly low-income residences with poor building conditions and limited access to cooling resources (Lee et al., 2024; Sun et al., 2021; Zeng et al., 2022), housing in the Global South, which frequently experiences higher ambient temperatures and more severe climatic conditions while operating within resource-constrained contexts (Flores-Larsen and Filippín, 2021; Verma et al., 2025), and informal settlements (Vellingiri et al., 2020) that rely on substandard building materials and face severe energy-poverty challenges, placing these residents at significantly greater risk. Another key area of interest is traditional vernacular buildings (Henna et al., 2021; Yan et al., 2024), where studies explore how indigenous design strategies enhance passive resilience and evaluate their continued effectiveness under intensifying heat stress. The emerging net-zero energy buildings or nearly net-zero buildings represent another key research focus. Studies investigate whether advanced energy-saving and net-zero technologies can effectively mitigate overheating risks (Amaripadath et al., 2023; Bucking et al., 2022; O' Donovan et al., 2021; Sengupta et al., 2023a) and maintain energy neutrality (Kazmi et al., 2022). These studies highlight potential trade-offs between energy efficiency and thermal resilience.

Besides residential buildings, buildings that accommodate vulnerable populations, such as hospitals (Lomas and Giridharan, 2012), nursing homes (Ji et al., 2023; Sheng et al., 2023; Sun et al., 2020), and child or elderly care centres (Hosseini et al., 2024; Nik and Hosseini, 2023; Pagliano et al., 2016), also receive significant attention in resilience studies due to the physiological susceptibility of their occupants (e.g., patients, children, the elderly), which makes these groups more vulnerable to the impacts of extreme weather events.

Specialized building types include community centres (Villa et al., 2024b), which serve as temporary shelters for the surrounding community during extreme events. Since these facilities need to accommodate large populations for extended periods during extreme events, they often require a higher level of adaptive capacity to ensure thermal resilience.

Beyond individual buildings, studies at the neighbourhood scale investigate the performance of resilience on building clusters and communities (Flores-Larsen and Filippín, 2021; Li et al., 2023; Liu et al., 2023; Sola-Caraballo et al., 2024). Some of these studies examine the influence of socioeconomic and physical characteristics on resilience outcomes (Paneru et al., 2024; Sun et al., 2021). Some studies claim a community-scale perspective, but they rely on a representative archetype building approach rather than capturing the full complexity of neighbourhood interaction (Krelling et al., 2023; Moazami et al., 2019).

However, most neighbourhood-scale studies remain heavily focused on indoor thermal resilience, often neglecting the potential impact of urban heat island (UHI) effects and microclimatic conditions on overall thermal resilience. Outdoor and transitional spaces (Diz-Mellado et al., 2021, 2023b; Gherri and Matoti, 2024), such as courtyards, shaded walkways, and parks, are frequently oversimplified as passive "heat exposure backgrounds" rather than being recognized as active contributors to resilience. Conversely, anthropogenic heat discharged from building mechanical systems during extreme heat events can further intensify local temperatures, particularly in dense urban districts (Luo et al., 2020).

While the fundamental physical interactions between buildings and their surrounding microclimates have been extensively documented in the literature (Bouyer et al., 2011; Gros et al., 2016; Hong et al., 2021), detailed investigations into how these dynamic couplings behave under extreme weather conditions and influence system-level thermal resilience are beginning to emerge. For example, Shi et al. (2025) demonstrated that incorporating microclimatic conditions in compound heatwave and power outage scenarios can reveal resilience differences that would otherwise be underestimated by up to 13 %. Gao et al. (2023) identified optimal thresholds for building height and density, and proximity to industrial areas and water bodies for neighbourhood morphology to improve heat resilience. Nature-based solutions (e.g., optimized green spaces) may simultaneously improve microclimatic conditions through shading, evapotranspiration, and reduced wind speeds, effectively alleviating indoor thermal discomfort during heatwaves (Berardi et al., 2020; Lu et al., 2023). These developments highlight the need for more systematic investigation into how building clusters and their surrounding outdoor environments jointly contribute to mitigating and adapting to extreme conditions.

3.3. Characterization of disruptive events in thermal resilience

The prerequisite for resilience lies in the vulnerability exhibited by the system after experiencing a disturbance, deviating from its original normal operational state. For thermal resilience, the sources of stress refer to disturbances that affect the thermal comfort of the built environment. The main stressors include:

3.3.1. Heatwaves

There is no unified definition for heatwave events. Traditionally, local meteorological offices define heatwaves as consecutive days with above-normal temperatures; however, the specific temperature thresholds and duration criteria vary widely due to regional climate differences. In thermal resilience research, two main trends in heatwave definitions exist: one follows the local meteorological office's approach (Borghero et al., 2023; Flores-Larsen and Filippín, 2021; Huang et al., 2023; Liu et al., 2024), while the other adopts Ouzeau’s method, which is also proposed by IEA EBC Annex 80 (Amaripadath et al., 2023; Elnagar et al., 2024; Flores-Larsen et al., 2023; Guo et al., 2024; Krelling et al., 2024; Sengupta et al., 2023a, 2023b; Sheng et al., 2023). Ouzeau’s method identifies heatwaves based on three thresholds: a detection threshold beyond which an event is recognized; a threshold that defines the beginning; and the end of the heatwave and an interruption threshold (Ouzeau et al., 2016). To better reflect local conditions and adaptability, these thresholds are typically set as percentiles of the recent daily average temperature distribution, although the exact time span defined as “recent” and the chosen percentiles differ considerably in the literature.

Some studies define heatwaves independently by stipulating a minimum duration and using average, maximum, or minimum temperatures exceeding a preset threshold, e.g., (Baniassadi and Sailor, 2018; Liyanage et al., 2024). Other research relies directly on short-term field measurements (Amaripadath et al., 2024b; Sun et al., 2020) or historical heatwave events (Liu et al., 2023; Narayanan et al., 2024). The different definitions of heatwaves may make the comparisons and synthesis across studies complicated.

Some studies further classify heatwaves to recognize varying levels of impact on thermal resilience, to enable the assessment of the potential risks to the built environment based on external temperature conditions. Existing classification methods primarily include: Ouzeau’s categorization by duration, maximum temperature, and intensity (Amaripadath et al., 2023; Sengupta et al., 2023b); Sengupta et al. (2023a, 2024)’s normalized degree of shock (*doS*) combining severity and duration; Liu et al. (2024)’ four-type classification (short/moderate, short/intense, long/moderate, long/intense).

3.3.2. Cold snaps

Although heatwaves have been the primary focus in thermal resilience studies under the context of global warming, extreme cold events, commonly referred to as cold snaps or cold waves, can also lead to significant indoor thermal discomfort and pose serious risks to energy supply and human health.

Nevertheless, only six of the reviewed articles have investigated the impact of cold snaps on thermal resilience. Similar to heatwaves, there is no unified definition for cold snaps. The methodologies developed for defining heatwaves can often be adapted to characterize cold snaps. For example, Guo et al. (2024) used Ouzeau’s method, originally designed for identifying heatwaves, and adapted it by incorporating three corresponding low-temperature thresholds and temperature percentiles to detect cold snap; Sheng et al. (2023) focused on an actual historical event, the 2021 Winter Storm Uri; Villa et al. (2024a) simulated extreme cold scenarios using the multi-scenario extreme weather simulator; Liyanage et al. (2024a) applied a method proposed by Lavaysse et al. (2018) considering both daily maximum and minimum temperatures and the magnitude to identify periods of extreme cold; Xiao and Yuizono (2022) and Diz-Mellado et al. (2023a) applied field measurements to characterize these events.

3.3.3. Power outages and system failures

Besides climatic disruption, power outages and system failures are typically simulated as scenarios for evaluation, as they directly interrupt active thermal control systems and thus impact indoor thermal conditions. In most studies, these events are treated as binary (i.e., on or off), with systems being directly disabled in models or shut down in test environments without requiring complex definitions. However, no unified standard exists for incorporating these disturbances into thermal resilience studies, particularly regarding the outage duration. In most cases, studies adopt a simplified approach by defining fixed outage durations on an hourly or daily basis, typically ranging from several hours to 7 days (Sengupta et al., 2023a; Ismail et al., 2023; Homaei and Hamdy, 2021; Rostami and Bucking, 2024). Few case studies use actual outage data (Bucking et al., 2022; Rostami et al., 2024).

These simplified assumptions limit the accuracy of assessments. Factors such as whether an outage begins during the day or night (Baniassadi et al., 2019; Sengupta et al., 2023a) and the co-occurrence frequency with heatwaves (Bucking et al., 2022) can substantially affect evaluation outcomes. Accurately determining the start time is crucial for evaluating building flexibility or the effectiveness of pre-cooling strategies. However, only a few studies have attempted a more detailed differentiation of outages or system failures. For example, Wang et al. (2021) examined planned rotational outages to determine the maximum tolerable duration to avoid overheating risks. Sengupta et al., (2023a) have differentiated system shocks from simple outages by refining fault durations (ranging from 2 to 10 hours) and specifying the occurrence time of the shocks. Despite these examples, systematic investigations integrating real-world fault or operational data remain limited; there is a need for future research to explore outage occurrence timing, duration, and frequency in greater depth.

3.3.4. Compound events

Extreme events are often interdependent in both space and time, and the risks associated with compound disturbances are typically greater than the sum of their individual components (Zscheischler et al., 2018). In the field of climate events and disaster management, the terms “compound” and “cascade” are widely used, but they emphasize different aspects: “compound” highlights the concurrence of multiple extremes, while “cascade” refers to cause–effect chains that propagate through systems (Pescaroli and Alexander, 2018; Sulfikkar Ahamed et al., 2023).

Although extreme weather events and power outages are, in principle, better conceptualized as cascading risks (Xu et al., 2025), for example, heatwaves and cold snaps affect both electricity supply and demand and also increase the likelihood of power outages (Liang et al., 2025), the terminology in the thermal resilience studies remains vague. Most of the reviewed articles describe the multiple overlapping events using general expressions such as “coincide” or “combination” when framing their simulation scenarios (Baniassadi et al., 2018; Sengupta et al., 2023a; Sun et al., 2021). Only one article explicitly refers to compound events (Sheng et al., 2023), and none use the terminology of cascade events. At the building scale, this treatment may be understandable, as the focus is typically on the vulnerability arising from overlapping stressors rather than on simulating the full cascading sequence.

Despite this, there is currently no consensus on how to systematically define or model such events. While historical compound extremes are sometimes used as references, most studies still rely on simplified assumptions, typically modelling power outages as either fully overlapping with heatwaves (Homaei and Hamdy, 2021; Ismail et al., 2023; Liyanage et al., 2024; Ozkan et al., 2019; Sheng et al., 2023; Sun et al., 2021; Wijesuriya et al., 2024) or occurring at specific stages (e.g., peak or midpoint) (Baniassadi et al., 2018, 2022a; Rostami and Bucking, 2024; Samuelson et al., 2020; Sengupta et al., 2023b).

3.4. Scenario construction and contextualization

The disturbances described above directly impact thermal conditions and act as immediate stressors to building and urban systems. Nevertheless, incorporating these shocks within broader contextual scenarios, including future climate conditions and urban morphology patterns, is crucial for comprehensive modelling and informing long-term planning, design, and policy development for thermal resilience.

Similar to common practices in building performance research on weather data, historical meteorological records are used as an essential baseline for understanding past extreme events and their effects on thermal conditions. To account for future uncertainties, researchers frequently incorporate climate projections derived from the Intergovernmental Panel on Climate Change (IPCC) scenarios to explore resilience under varying emission pathways and temporal milestones (e.g., 2030s, 2050s, 2080s) and select the worst case to provide a reference for “stress testing” system resilience. The year 2050 is frequently identified as a key temporal milestone. However, given that 2050 is now less than a few decades away and that the typical design life of a building often spans 50 to 70 years, focusing solely on the climate conditions of 2050 may be insufficient to capture the full lifecycle risks for new or retrofitted buildings.

Researchers often rely on standardized weather files such as typical meteorological year (TMY) or test reference year (TRY), but such files are being generated from representative months, which may smooth out extreme weather events and reduce the reliability for assessing scenarios like extreme heatwaves (Siu et al., 2023). Some studies have questioned the accuracy of relying solely on "typical" weather data in building performance simulations (Crawley and Lawrie, 2019; Moradi et al., 2023). To address this limitation, certain standards and studies have proposed improvements. The CIBSE overheating standard recommends using design summer year (DSY) (CIBSE, 2013, 2017), which are based on a 20-year period and include three types: a moderately hot year with a one-in-seven-year return period, the year with the most intense heat, and the year with the longest-lasting heat event, to better capture a range of warmer summer conditions (CIBSE, 2025). IEA EBC Annex 80 researchers have also developed heatwave year (HWY) weather files that integrate the frequency, duration, and magnitude of extreme temperature events for resilience studies (Machard et al., 2024). Other researchers have applied probability distribution methods to identify extreme cold year (ECY) or extreme warm year (EWY) to allow a more robust simulation of adverse weather scenarios and quantify the associated uncertainties (Nik, 2016; Nik and Moazami, 2021; Hosseini et al., 2024). Moreover, Villa et al. (2024b, 2024a) have introduced the multi-scenario extreme weather simulator (MEWS) that directly generates weather files for heatwave assessments by incorporating extreme weather event variations based on stochastic dynamic processes into existing files. These advanced weather file methodologies also account for longitudinal temporal dimension, providing specific climate scenarios from historical conditions to future projections.

In addition to temporal considerations, spatial resolution also needs to be considered for the microclimate variation. Various downscaling methods can reduce the grid resolution of urban climate data to as fine as 250 meters (S. Li et al., 2024; Liu et al., 2023). For finer resolution particularly when examining local impacts in outdoor or semi-outdoor spaces such as courtyards and plazas, researchers can apply other microclimate simulation tools, such as ENVI-met (Gherri et al., 2021; Gherri and Matoti, 2024; Li et al., 2023; Schünemann et al., 2023; Sola-Caraballo et al., 2024), Urban Tethys-Chloris (UT&C) (Baniassadi et al., 2022a, 2022b), or obtain microclimate data through field measurements (Diz-Mellado et al., 2023b, 2021; Hong et al., 2021; Huang et al., 2023; Sharifi et al., 2016). Despite their ability to provide highly detailed spatial data, these methods generally cover only short periods due to computational constraints and limited field measurement durations, which make it difficult to conduct comprehensive, long-term evaluations of thermal environment resilience.

Most existing building thermal resilience studies address longitudinal temporal dynamics and geospatial microclimatic variations independently. While some building energy and thermal performance evaluation studies have explored their joint consideration to achieve a higher level of spatiotemporal granularity (Mauree et al., 2018; Salvati and Kolokotroni, 2023), such integrated approaches can be further extended to the assessment of extreme weather events. However, researchers must be cautious of the cascading uncertainties from combined temporal and spatial transformations.

When selecting the critical simulation and analysis time period for thermal resilience assessment, methodological guidance remains limited in the literature. Power outage scenarios are often defined in a simplified manner, and although the beginning and end of extreme weather events can be rigorously identified (e.g., using Ouzeau’s method), the broader simulation window required to capture the preparation and recovery processes along the resilience curve is rarely made explicit. Moreover, as different building types exhibit different sensitivities to extreme weather characteristics and system disruptions, sensitivity or multi-scenario analyses are needed to identify appropriate simulation time periods to provide robust guidance for future research.

To ensure transparency and reproducibility, researchers typically specify the scenario settings in the methodology section. Studies often evaluate multiple scenarios and time scales, but the abundance of scenario data and model outputs makes it hard to effectively synthesize and interpret the results. Researchers must balance the use of multi-scenario, multi-model methods with interpretability to objectively assess the resilience of buildings and urban thermal environments.

3.5. Performance evaluation of thermal resilience

3.5.1. Evaluation methods and tools

There are several methods for assessing resilience performance in the built environment: onsite measurement, building performance simulation (BPS), and a combination of both approaches.

Onsite measurement can capture various indoor and outdoor environmental parameters and allow for greater accuracy in assessing the actual thermal conditions and indoor environmental quality. However, measuring radiation temperature, which is critical for evaluating operative temperature and thermal comfort, remains challenging as it requires additional instruments, and measurements can vary considerably across different locations in the same space (Lee and Jo, 2025). Few outdoor environments have measured globe temperature and various radiation values (Huang et al., 2024, 2023; Yan et al., 2024), while indoor radiation temperature measurement specifically aimed at resilience evaluation is limited (Guo et al., 2024).

On the other hand, BPS has gained consensus as a robust tool for assessing thermal resilience (Hong et al., 2023; Kesik et al., 2022; Siu et al., 2023). However, when applying these tools, it is important to recognize their potential limitations in resolution with respect to the specific research objectives and scope. These BPS tools can perform full-year or partial-year simulations at hourly or sub-hourly resolutions, which is generally sufficient for capturing indoor thermal dynamics. However, when evaluating system-level responses to transient events, such as power outages or sudden HVAC failures, more detailed dynamic simulations operating at minute- or even second-level intervals should be used. This ensures higher accuracy in representing equipment-level dynamics and control behaviours under extreme conditions (Sengupta et al., 2023a). Besides, temperature variation within spaces, such as higher temperatures near windows or heat sources, is difficult to model with sufficient granularity, since most BPS models assume well-mixed air within zones. Moreover, when ventilation strategies are applied, coupling with computational fluid dynamics (CFD) models may be required to resolve localized airflow patterns and accurately assess thermal comfort under extreme weather scenarios.

The combination of onsite measurements and energy modelling can involve either grey-box models (Yoon and Wu, 2024) or calibrating BPS models with measured data. The former approach faces limitations in analysing retrofit measures, as parameter estimation of physical properties like resistance and conductance is challenging (Deb and Schlueter, 2021). On the other hand, calibrating BPS models is essential to validate model performance, particularly under extreme scenarios. For example, Schünemann et al. (2021b) proposed a calibration framework for overheating assessments under multiple conditions to achieve greater robustness. For power outages and system failures, calibration can be performed by using controlled system shut-offs (Sengupta et al., 2023a).

3.5.2. Resilience metrics

Several previous works have classified resilience metrics into different dimensions, such as resistance, robustness, and recovery stages (Krelling et al., 2023), occupant vulnerability, system vulnerability, financial and energy performance (Hong et al., 2023), passive and active resilience metrics (D'Agostino et al., 2023). Other frameworks distinguish between thermal stress indicators and resilience metrics, where the former reflect vulnerability (e.g., overheating or heat stress) and the level of discomfort in a building, while the latter capture adaptive and recovery processes (Siu et al., 2023; Tavakoli et al., 2022). Despite many reviewed studies labelling their indicators as "resilience metrics," some simply describe vulnerability rather than the full resilience process over time. Therefore, this paper aims to link existing metrics with the resilience curve to analyse how effectively they characterize the full resilience process. Fig. 7 illustrates an abstract resilience curve under a heatwave scenario; for cold waves, the performance trend would reverse. In this schematic, the y-axis typically represents thermal performance indicators (summarized in Table 3). The metrics related to the resilience curve are summarized in Table 4.

The basic temperature indicators (e.g., air temperature and operative

Table 3
Performance metrics for the resilience curve.

Metrics	Main inputs	Usage in the reviewed literature
Temperature/air temperature/operative temperature	T_a, T_r	(Flores-Larsen and Filippín, 2021; Liu et al., 2023; Pagliano et al., 2016; Wang et al., 2021) (among many others, only representative studies shown)
Wet-bulb globe temperature (WBGT)	T_a, T_w, T_g,	(Amaripadath et al., 2024b; Huang et al., 2024; Yan et al., 2024)
Physiological equivalent temperature (PET)	T_a, T_r, RH, v, clo, met	(Diz-Mellado et al., 2023a, 2023b; Gherri et al., 2021; Huang et al., 2024; Li et al., 2023)
Predicted mean vote (PMV)	T_a, T_r, RH, v, clo, met	(Huang et al., 2024; Park et al., 2024; Sun et al., 2021; Xiao and Yuizono, 2022)
Adaptive predicted mean vote (aPMV)	T_a, T_r, RH, v, clo, met	(Guo et al., 2024)
Universal thermal comfort index (UTCI)	T_a, T_r, RH, v	(Diz-Mellado et al., 2023b; Huang et al., 2024, 2023; Sola-Caraballo et al., 2024)
Standard effective temperature (SET)	T_a, T_r, RH, v, clo, met	(Guo et al., 2024; Lee et al., 2024; Park et al., 2024; Sengupta et al., 2024b, 2024a; Sheng et al., 2023; Sun et al., 2021)
Heat index (HI)	T_a, RH	(Amaripadath et al., 2024b; Birge et al., 2025; Flores-Larsen and Filippín, 2021; Hong et al., 2021; Lee et al., 2024; Liyanage et al., 2024; Sheng et al., 2023; Sun et al., 2020; Wijesuriya et al., 2024)
Discomfort index (DI)	T_a, RH	(Baniassadi et al., 2018; Baniassadi and Sailor, 2018)

T_a = air temperature/dry bulb temperature; T_r = mean radiant temperature; T_w= wet bulb temperature; T_g = globe thermometer temperature; RH = relative humidity; v=air speed/wind velocity; clo = clothing insulation; met = metabolic rate (activity level)

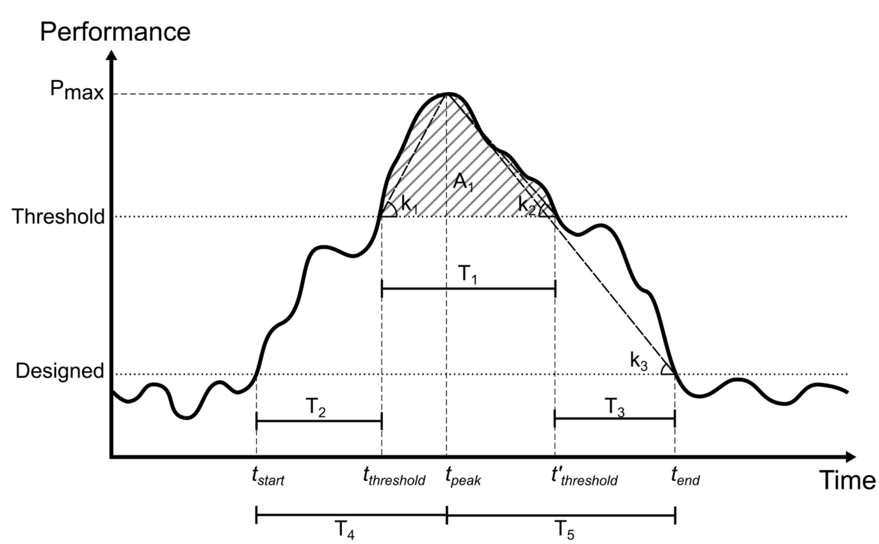

Fig. 7. Resilience curve and the related metrics. (Adapted from (Attia et al., 2021; Homaei and Hamdy, 2021; Krelling et al., 2023)).

Table 4
The summary of resilience-curve-related metrics.

Metric Name	Equation/Definition	Usage and specification in Literature
T_1: The amount of time that performance level is above the threshold (the duration of time that a building remains habitable/safety)		
Hours of exceedance(H_e)	$H_e = \int_{t_1}^{t_2} f(T_{op}(t) - T_{op,\ threshold})dt$ where $f(x) = 1,\ if\ x > 0,\ or\ 0\ otherwise$	$T_{op,\ threshold}$ =26°C, referenced in ISO 17772-1 adaptive model category II limits (Amaripadath et al., 2023) $T_{op,\ threshold}$ =27°C, x>1 for adaptive model and 0 for static model (Amaripadath et al., 2024b) Not specify (Gamero-Salinas et al., 2021)
Heat discomfort hours	-	Threshold limit: (80 % acceptability limit according to the adaptive comfort model ASHRAE 55–2017) (Mehmood et al., 2023, 2022)
Hours of safety	-	Threshold limit: 15°C (59°F) for the winter storm, heat index 33°C (91°F) for the heatwave (Wijesuriya et al., 2024)
Passive survivability	-	$T_{op,\ threshold}$ = 30°C (Ozkan et al., 2019; Sengupta et al., 2023b) Threshold limit: heat index range (Liyanage et al., 2024) (typically applied in power outage scenarios)
Unmet load hours	$ULH = \int_{t_1}^{t_2} f(T(t) - T_{threshold})dt$ where $f(x) = 1,\ if\ x > 0.5,\ or\ 0\ otherwise$	Threshold limit: the thermostat set-points (Almeida et al., 2023)
Heat index hazard hours (HIHH)	$HIHH = \int_{t_1}^{t_2} f(HI(t) - HI_{threshold})dt$ where $f(x) = 1,\ if\ x > 0,\ or\ 0\ otherwise$	$HI_{threshold}$ = 27°C for caution and 39°C for danger (Sun et al., 2021)
Hours above caution (HAC)	-	$HI_{threshold}$ = 26°C for caution (Birge et al., 2025)
Predicted mean vote exceedance hours (PMVEH)	$PMVEH = \int_{t_1}^{t_2} f(PMV(t) - PMV_{threshold})dt$ where $f(x) = 1,\ if\ x > 0,\ or\ 0\ otherwise$	$PMV_{threshold}$=±0.7 (grid-on scenario) or ±3 (grid-off scenario) (Sun et al., 2021) $PMV_{threshold}$=±0.5(Amaripadath et al., 2023)
T_1/T: The percentage of time that performance level is above the threshold		
Percentage of exceedance hours	$EH\ \% = \frac{EH}{\int_{t_1}^{t_2} dt} \times\ 100\ \%$	(Sengupta et al., 2024b, 2023a; Villa et al., 2024a)
Thermal vulnerability (TV)	-	$T_{op,\ threshold}$ =30°C (Krelling et al., 2023, 2024)
T_2: The amount of time that performance level is below the threshold before reaching it		
Hours of safety	$t = t_{threshold} - t_{start}$	(Guo et al., 2024; Ismail et al., 2023; Sheng et al., 2023)
Time to heat index caution (THIC)	-	(Birge et al., 2025)
$(T_2 + T_3)/T$: The percentage of time that performance level is below the threshold		
Thermal autonomy (TA)	$TA = \frac{\int_{t_1}^{t_2} f(T_{op}(t) - T_{op,\ threshold})dt}{\int_{t_1}^{t_2} dt} \times\ 100\ \%$ where $f(x) = 1,\ if\ x < 0,\ or\ 0\ otherwise$	Thresholds limit: 18 °C to 26 °C (Kesik et al., 2022; Krelling et al., 2023) 18 °C to 25 °C (Ozkan et al., 2019) SET 12.2°C and 30°C (Krelling et al., 2024)
T_4: The amount of time between start and peak.		
Absorptivity time	$t_{abs} = t_{peak} - t_{start}$	Comfort limit: SET 28°C (Sengupta et al., 2024a)
T_5: The amount of time between peak and end.		
Recovery time	$t_{rec} = t_{end} - t_{peak}$	Comfort limit: SET 30°C(Krelling et al., 2024) SET 28°C (Sengupta et al., 2024a) 26°C (Krelling et al., 2023)
Recovery capacity	-	Comfort limit: 24°C (Sengupta et al., 2023b)
P_{max}: Maximum performance level reached in the given time period		
Maximum temperature	T_{max}	(Krelling et al., 2023, 2024)
Thermal peak shedding (TPS)	$\Delta\ T_{max} = T_{max,base} - T_{max,\ test}$	(Yoon and Wu, 2024)
t_{peak}: The moment when performance reaches its maximum value		
Thermal peak time shift (TPTS)	$\Delta\ t_{peak} = t_{peak,base} - t_{peak,\ test}$	(Yoon and Wu, 2024)
A_1: The accumulated excess performance above the threshold (usually measured in degree hour)		
Unmet degree hour (UDH)	$UDH = \int_{t_1}^{t_2} [T(t) - T_{threshold}]_+ dt$	Threshold limit: Cooling setpoint (Baniassadi et al., 2022b; Sun et al., 2021; Zeng et al., 2022) $T_{threshold}$ = 24°C (Sengupta et al., 2023a) $T_{threshold}$ = 24 °C, 25 °C and 28 °C (Sengupta et al., 2024b, 2023b)
Over temperature degree hours	-	$T_{threshold}$ = 26°C (Schünemann et al., 2021a, 2021b) $T_{threshold}$ = 27°C (Schünemann et al., 2020)
Degree hours of discomfort index	$DIDH = \int_{t_1}^{t_2} [DI(t) - DI_{threshold}]_+ dt$	$DI_{threshold}$ = 26°C (Baniassadi et al., 2018)
Standard effective temperature unmet degree hours (SETUDH)	$SETUDH = \int_{t_1}^{t_2} [SET(t) - SET_{threshold}]_+ dt$	$SET_{threshold}$ = 30°C (86°F) (Lee et al., 2024; Park et al., 2024) $SET_{threshold}$ = 28°C (Sengupta et al., 2024b, 2024a) $SET_{threshold}$ = 28.12°C (Al-Assaad et al., 2025) $SET_{threshold}$ = 12.2°C (54°F),30°C (86°F) (Guo et al., 2024; Sheng et al., 2023) $SET_{threshold}$ = 28°C (Grid-on), 30°C (Grid-off) (Sun et al., 2021)

(*continued on next page*)

Table 4 (*continued*)

Metric Name	Equation/Definition	Usage and specification in Literature
Weighted exceedance	$We = \int_{t_1}^{t_2} [T(t) - T_{threshold}]_+ dt$	Analysed in a daily basis (Liu et al., 2023)
A_1/T		
Indoor overheating degree (IOD)	$IOD = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{fr,i,z} - TL_{comf,i,z}\right)_+ \cdot t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}}$ The summation of positive values of the difference between zonal indoor operative temperature and the zonal thermal comfort limit averaged over the sum of the total number of zonal occupied hours	(Hamdy et al., 2017; Amaripadath et al., 2023; Borghero et al., 2023; Flores-Larsen et al., 2022; Krelling et al., 2024; Rahif et al., 2022; Amaripadath et al., 2024b; Liu et al., 2024; Gamero-Salinas et al., 2021; Flores-Larsen et al., 2023; Elnagar et al., 2024)
Ambient warmness degree (AWD)	$AWD \equiv \frac{\sum_{i=1}^{N}\left[\left(T_{a,i} - 18^\circ C\right)_+ \cdot t_i\right]}{\sum_{i=1}^{N} t_i}$ The accumulation of amplitude and the duration of each occurrence against a base temperature(outdoor)	(Hamdy et al., 2017; Borghero et al., 2023; Rahif et al., 2022; Flores-Larsen et al., 2023)
Overheating escalation factor (α_{IOD})	$\alpha_{IOD} = \frac{IOD}{AWD}$	(Borghero et al., 2023; Flores-Larsen et al., 2023; Hamdy et al., 2017)
$A_1{}'$: The accumulated excess performance with penalty multipliers		
Weighted unmet thermal performance (WUMTP)	$WUMTP = \sum_{i=1}^{12} S_i W_{P,i} W_{H,i} W_{E,i}$ [Degree hours]	(Homaei and Hamdy, 2021; Ji et al., 2023)
Thermal resilience index (TRI)	$TRI = WUMTP_{baseline} / WUMTP_{retrofit}$	(Ji et al., 2023)
k_1, k_2, k_3: How fast the system responds to extreme events and absorb/recovery from the shock		
Absorptivity rate	$\Delta ABS = \frac{SET_{max} - SET_{threshold}}{t_{peak} - t_{threshold}}$	(Al-Assaad et al., 2025)
Recovery rate	$\Delta REC = \frac{SET_{max} - SET_{threshold}}{t'_{threshold} - t_{peak}}$	(Al-Assaad et al., 2025)
Agility factor (AF)	$af^{t+1} = 1 - \frac{\text{abs}\left(E^{t+1}_{\text{extreme}} - E^{t+1}_{\text{baseline}}\right)}{\text{abs}\left(E^{t}_{\text{extreme}} - E^{t}_{\text{baseline}}\right)}$ $AF = \sum_{t=2}^{t_{\text{end}}} \frac{af^t}{t_{\text{end}} - 1}$	(Nik and Moazami, 2021)
Others		
Resilience score	$Score = IOD_W + \left[\frac{He_{hours}(\%) + WBGT_{hours}(\%) + HI_{hours}(\%)}{100}\right]$	(Amaripadath et al., 2024b)

temperature) are widely used due to their simplicity. While air temperature is easily obtainable, it primarily reflects convective heat transfer. In contrast, operative temperature offers higher validity for human thermal sensation by accounting for radiative heat exchange. More detailed parameters that link environmental factors (such as air temperature, air velocity, and relative humidity) with personal variables (such as clothing insulation and activity level) are also used to better predict occupants' thermal sensation and comfort under extreme events (Enescu, 2017). The selection of appropriate metrics should match the research context, for instance, humidity-sensitive indices are preferable in hot humid climates. Moreover, although most of these metrics, except for universal thermal climate index (UTCI), are based on steady-state assumptions, using sufficiently short timesteps (e.g., 10–15 minutes) allows them to approximate the temporal evolution of the thermal resilience curve.

Beyond the selection of suitable metrics, the interpretation of resilience outcomes largely depends on how comfort thresholds are defined and applied. Although some resilience curves distinguish between designed conditions (e.g., set points), minimum habitable conditions (habitable but not comfortable), and critical conditions (not habitable), most reviewed literature used only a single threshold and did not distinguish between habitable and critical thresholds. This is understandable because of the complexity of human thermal comfort, it is challenging to define a distinct "failure point" as one might in purely engineering contexts. Certain performance indicators classify comfort on multiple levels, for example, the heat index (HI) uses five categories (safe, caution, extreme caution, danger, extreme danger). In practice, resilience metrics often depend on these indicator-specific thresholds, which may be derived from local weather conditions or regulatory guidelines, and vary across different studies.

Some indicators, such as wet bulb globe temperature (WBGT), physiological equivalent temperature (PET), and UTCI, are mostly used to evaluate outdoor thermal comfort and lack predefined threshold values. They tend to serve as descriptive indicators (e.g., reporting maximum or average values) rather than capturing the dynamic evolution of a resilience curve. Therefore, outdoor resilience evaluations often remain limited to general vulnerability assessments.

The resilience curve can be depicted in various dimensions. At temporal dimensions, one common approach focuses on the duration of threshold exceedance, i.e., Hours of exceedance(H_e). This approach is widely adopted in regulatory documents (e.g., CIBSE TM52 and TM59) and they also set specific limits on the duration or percentage of time exceeding a thermal threshold, for example, CIBSE TM59 restricts exceedance to below 3 % of the occupied hours for residential buildings.

Additionally, the time to reach the threshold, time to reach the peak, time to recover to the threshold, and time to recover to normal conditions, offer another perspective on how long a system remains functional under extreme weather events. In principle, longer intervals before reaching the threshold or peak suggest stronger robustness, whereas shorter intervals for returning to threshold or normal conditions indicate greater recovery capacity. However, these parameters are rarely discussed in detail, and there are no clear guidelines on acceptable ranges. They are typically used for comparisons between different resilient measures rather than providing a definitive quantitative criterion for classifying a system as "resilient."

Another dimension uses integral or area-under-the-curve metrics (e.g., degree-hours) that capture both severity and duration. However, because they multiply temperature deviation by time, a brief but extremely high exceedance may have the same integral value as a moderate but prolonged exceedance. Hamdy et al.(2017) proposed the indoor overheating degree (IOD), which divides the time integral by the total duration to reduce reliance on exposure length alone. Subsequent work introduced impact categories (i.e., moderate if IOD $\leq 0.5^\circ$C, strong if 0.5°C $<$ IOD $< 2^\circ$C, extreme if IOD $\geq 2^\circ$C) (Flores-Larsen et al., 2022). They further developed ambient warmness degree (AWD) and overheating escalation factor (α_{IOD}) by comparing indoor and outdoor conditions to assess a building's sensitivity to external heat stress. Similarly, Homaei and Hamdy (2021) proposed a Weighted Unmet Thermal

Performance metric, which partitions the resilience curve into three threshold-based phases and assigns varying penalty scores (phase, hazard, and exposure-time penalties) to each segment's temperature-time integral. While this method offers a more comprehensive representation of resilience-curve complexity, its penalty framework lacks robust justification.

Only the study of Nik and Moazami (2021) and Al-Assaad et al. (2025) incorporated slope-based metrics, whether instantaneous or averaged, to illustrate how quickly a system absorbs a thermal shock and returns to safe conditions. Only Amaripadath et al. (2024b) have combined multiple metrics, such as IOD, H_e, WBGT, and HI, into a single resilience score to provide a more holistic view of overall thermal performance.

Bucking et al.(2022) advanced the approach by creating a dimensionless resilience curve representation (see Table 5). This approach is particularly suited to power outage scenarios because it incorporates both thermal and energy levels. They also included the maximum deviation and total area under disruption in the evaluation and extended to include cost considerations. By normalizing the curve, it may help mitigate discrepancies arising from different threshold definitions, and offer a more consistent basis for comparing resilience outcomes.

Meanwhile, Table 4 reveals that current metrics exhibit a high degree of complexity and inconsistency in naming conventions and threshold selections. Although they often measure the same underlying variable, their names and thresholds vary; sometimes the same term can even refer to different phenomena. Additionally, most metrics evaluate only single-zone or single-building performance. Aggregating results across multiple zones or buildings then poses further challenges (e.g., taking a simple mean, an area-weighted average, or the worst-case value).

Besides the indicators related to thermal conditions, other metrics are also incorporated into resilience evaluations to serve for assessment, comparison, and decision-making. Energy performance is a commonly considered category, and researchers aim to maintain robust thermal resilience without compromising energy efficiency. Metrics such as gas and electricity usage, energy use intensity are included for the basic energy performance (Almeida et al., 2023; Baniassadi et al., 2022b, 2019; Borghero et al., 2023; Elnagar et al., 2024; Hong et al., 2021; Lee et al., 2024; Liyanage et al., 2024; Ozkan et al., 2019; Pagliano et al., 2016; Park et al., 2024; Samuelson et al., 2020; Sun et al., 2021; Villa et al., 2024a, 2024b; Xu et al., 2022). In particular, energy consumption for cooling or HVAC systems is often examined (Krelling et al., 2023, 2024; Borghero et al., 2023; Guarino et al., 2022; Nik and Hosseini, 2023; Flores-Larsen and Filippín, 2021; Elnagar et al., 2024), as it reflects the energy required for active measures to remove heat from buildings during extreme events and also indicates the efficiency of related technical systems.

Some researchers have analysed peak energy demand (Almeida et al., 2023; Birge et al., 2025; Hong et al., 2021; Lee et al., 2024; Moazami et al., 2019; Park et al., 2024), and Yoon and Wu (2024) have further examined variations in peak load timing and magnitude, such as power peak shedding (PPS) and power peak hour shift (PPHS). These indicators help to understand the system ability to mitigate peak load pressure on the energy grid and reduce the occurrence of power outages during extreme weather events. This also reflects the energy flexibility of the building system. Some others have conducted in-depth analyses on it by utilizing energy management strategies to enhance the autonomy and agility of the system in responding to climate shocks. They have introduced the demand flexibility factor, self-consumption rate, and grid autonomy to evaluate how flexibly buildings can manage their energy demand under disruptions (Hosseini et al., 2024; Nik and Moazami, 2021).

A subset of studies goes further by converting operational energy consumption into greenhouse gas emissions to assess environmental impacts, e.g., (Elnagar et al., 2024; Lee et al., 2024; Samuelson et al., 2020; Williams et al., 2020). In addition, Samuelson et al (2020) have considered heat rejection to the urban environment of the buildings to expand the scope to include urban heat resiliency at a city scale.

Indicators related to cost and investment also represent an important dimension of resilience assessment. Cost-oriented evaluations can illuminate the value of investing in thermal resilience measures versus bearing the costs of inaction. For example, Bucking et al. (2022) analysed life-cycle costs over a 25-year period to assess building resilience during grid disruptions, accounting for lost load, repair expenses, and insurance; Sun et al. (2020) considered both material and labour costs for the financial feasibility of the intervention.

However, cost-based resilience assessment faces particular difficulties, as certain resilience benefits, such as occupants' well-being and life, are difficult or controversial to express in purely monetary terms (Sun et al., 2020). Moreover, the long-term cost projections involve substantial uncertainties, including energy price volatility, rapid technological advancements, and potential carbon market developments.

4. Discussions

4.1. Towards an integrated cross-scale resilience framework

Thermal resilience is addressed across a wide range of spatial and disciplinary scales, yet the conceptual paradigms used to define and assess it differ substantially. While this paper primarily examines technically quantifiable engineering performance in buildings and their interconnected built environment, it is also important to position these analyses within the broader landscape to reveal the linkages and disjunctions that arise across scales. To bridge these different dimensions, an integrated cross-scale framework is proposed for thermal resilience in the built environment (Fig. 8).

At the macro-urban climatic scale, resilience is conceptualized through climatological and land–atmosphere processes that operate

Table 5
The resilience metrics related to the quality function.

Metric	Definition	Equation	Literature
Performance quality function (Q(t))	A dimensionless variable that indicates the current functionality of a studied system normalized by the available functionality before the event	$Q(t) = \begin{cases} 0, & \text{if } T(t) \leq T_{\alpha,\text{icestorm}} \text{ OR } T(t) \geq T_{\alpha,\text{heatwave}} \\ 1, & \text{if } T(t) \geq T_{\gamma,\text{icestorm}} \text{ OR } T(t) \leq T_{\gamma,\text{heatwave}} \\ \lvert \frac{T(t) - T_\alpha}{T_\gamma - T_\alpha} \rvert, & \text{Otherwise} \end{cases}$ where $T_{\alpha,\text{icestorm}} = 0^\circ\text{C}$ and $T_{\alpha,\text{heatwave}} = 40^\circ\text{C}$ defines a failure as the zero limits, $T_{\gamma,\text{icestorm}} = 20^\circ\text{C}$ and $T_{\gamma,\text{heatwave}} = 25^\circ\text{C}$ define the ideal pre-event performance	(Bucking et al., 2022; Rostami et al., 2024; Rostami and Bucking, 2024)
Maximum loss of functionality (LoFMax)	The peak intensity of the consequences	$LoF_{\text{Max}} = 1 - Q(t)_{min}$, where $\text{Lo}F_{\text{Max}} \in [0, 1]$	(Rostami and Bucking, 2024)
Resilience (Res)	The accumulated performance deviations	$Res = 1 - \sum_{i=1}^{n} \frac{\int_{t_{1,i}}^{t_{2,i}} (1 - Q(t))dt}{t_{2,i} - t_{1,i}}$	(Rostami and Bucking, 2024)
Value of loss load (VoLL)	The product of the lost load energy difference at each timestep to the appropriate cost	$VoLL = \sum_{i=1}^{n} LossLoad(t_i) \times C(t_i)$	(Bucking et al., 2022; Rostami et al., 2024)

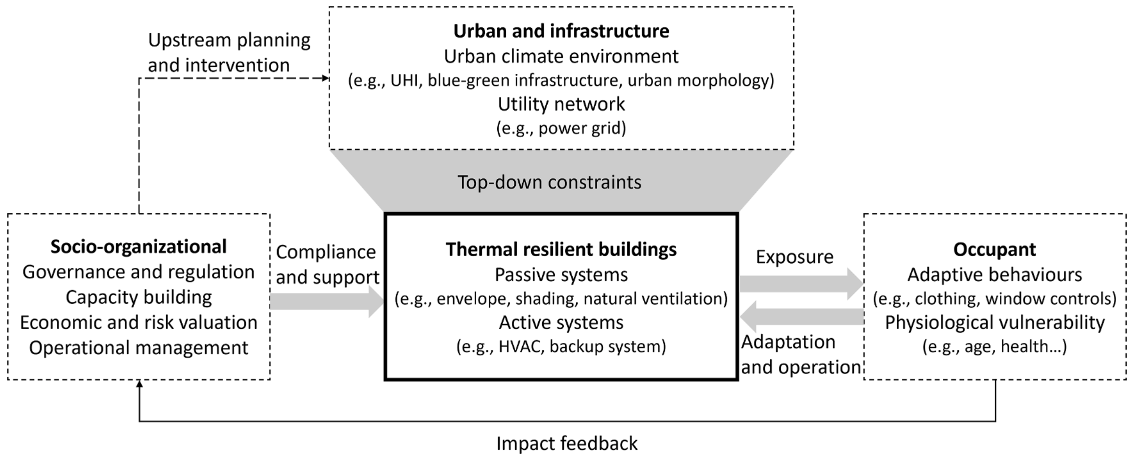

Fig. 8. An integrated cross-scale framework for thermal resilience in the built environment.

beyond buildings. Research on this domain typically relies on satellite remote sensing, urban climate models, and surface energy balance approaches to assess heat resilience under extreme temperatures or long-term climate change (Carvalho et al., 2017; Karimi et al., 2025). These studies typically adopt a heat vulnerability assessment framework, identifying high-risk areas by analysing exposure, sensitivity, and adaptive capacity (van Daalen et al., 2024). These macro-assessments emphasize static risk identification and hazard exposure rather than the dynamic resilience response. They primarily serve as environmental boundary conditions or external forcing inputs that inform building thermal resilience.

In a similar manner, at the infrastructure scale, the reliability and robustness of critical systems, particularly the power grid, fulfil the upstream role for the thermal resilience analysis of the built environment. Power grid resilience to extreme weather events has its own established assessment and quantification of the physical integrity of grid assets and the continuity of electrical supply (Jufri et al., 2019), rather than the downstream consequences on the built environment. It also acts as an external boundary condition for thermal resilience analysis, as the availability of electricity directly determines whether active building systems can function. When the grids fail, the building instantly degrades to a passive survivability mode, relying solely on its physical properties and occupancy-level adaptation.

These infrastructure conditions also influence how thermal resilience strategies are prioritized and implemented across different regions. For example, in the Global South and disadvantaged communities, where energy poverty is prevalent and power supply instability is often a normative condition rather than an exception, reliance on energy-intensive active cooling is often unfeasible. In these contexts, they tend to prioritize low-cost retrofits (e.g., cool roofs) and vernacular passive solutions (e.g., natural ventilation) to ensure passive survivability.

Thus, from a top-down perspective, the urban and infrastructural system can be seen as the "macro-constraint layer". On the one hand, macro-scale climatic and infrastructural factors define the magnitude and characteristics of the thermal shock to which buildings and occupants are exposed. On the other hand, heat vulnerability arising from urban form, infrastructure conditions, and underlying social inequalities creates spatially uneven risks. These macro-scale vulnerabilities propagate downstream, constraining and defining the baseline resilience capacity of specific neighbourhoods and buildings (Kim and Kim, 2024; Paneru et al., 2024; Xia and Hu, 2024). These vulnerability disparities also help identify priority areas where adaptive measures, targeted interventions, or policy support are most urgently needed.

Parallel to the physical and engineering dimensions, social-science research provides a complementary view of thermal resilience through "soft infrastructure". This socio-organizational layer does not directly interact with a building's thermodynamic processes but provides the necessary compliance directives and enabling support to ensure building functionality in extreme events. At the institutional level, governance structures and heat action plans set the regulatory standards, clarify responsibility allocations, and provide financial mechanisms to coordinate risk measures (Ulpiani et al., 2024; Birchall et al., 2023). Complementing these top-down measures, capacity building empowers communities by enhancing their knowledge and skills to anticipate heat stress (Virji et al., 2012). It is particularly critical in the Global South, where social adaptability often compensates for infrastructure limitations (Wieszczeczynska et al., 2024). This social support can serve as the ultimate buffer to mitigate acute thermal risks, for example, through neighbourhood mutual aid or evacuation to community cooling centres (Mosleh et al., 2024; Hamstead et al., 2020).

At the building scale, thermal resilience emerges through a bidirectional interaction between building systems and occupant dynamics. Building systems act as the primary modifiers of environmental exposure. Therefore, building thermal resilience is distinguished from general outdoor heat exposure or population-level health risk assessments. Occupant behaviour acts as a dynamic variable that actively modifies a building's physical performance under extreme thermal stress.

However, human responses under high thermal stress are neither uniform nor easily predictable. Alongside building thermal resilience research on technological components, such as building envelopes and HVAC systems, a growing body of literature has investigated occupants' adaptive behaviours via surveys, interviews, and monitoring (Lane et al., 2014; Huang et al., 2023; Bal-Fontaine et al., 2025). Besides human physiological thermal adaptation, residents can actively mitigate heat stress through clothing adjustments, spatial relocation, and the effective use of operable windows, shading and natural ventilation (Yang et al., 2024). Understanding the mechanisms underlying these protective responses is essential, as behavioural adaptation is shaped by a wide range of factors, such as physical capabilities, psychological perceptions, and socio-economic determinants (J. Li et al., 2024). Insights from these studies can contribute to the development of more realistic and context-sensitive occupant behaviour models and their integration with technological analyses.

4.2. *Trade-offs and synergies between thermal resilience and net-zero*

Under the context of climate change, the built environment needs to meet two parallel requirements: enhancing the resilience to withstand intensifying extreme events, while simultaneously achieving sustainability and net-zero targets to mitigate future climatic risks. These objectives rely on different evaluation methods, and prioritize different temporal performance horizons. Thermal resilience mainly focuses on dynamic behaviour under extreme conditions, while net-zero frameworks focus on steady-state or annual energy performance. Achieving short-term resilience often necessitates system redundancy, greater flexibility, and additional resource allocation. In contrast, pursuing long-term net-zero goals promotes strategies that minimize energy consumption and carbon emissions. As a result, strategies optimized for one objective may undermine the other. For instance, certain static improvement measures, such as external shading, can effectively mitigate summer overheating but simultaneously may increase heating demand during colder periods. While highly airtight buildings with mechanical ventilation with heat recovery (MVHR) reduce winter heat loss, they are prone to rapid overheating during heatwaves combined with power outages.

Researchers have been increasingly recognizing the potential trade-offs and synergies between current net-zero goals or energy efficiency and resilience (Alam et al., 2019; Gholami Rostam and Abbasi, 2021; Roostaie and Nawari, 2022). Existing research that considers both aspects typically follows two key trends. The first focuses on evaluating the thermal resilience performance of net-zero buildings, assessing their ability to withstand future extreme weather conditions (Amaripadath et al., 2023; Bucking et al., 2022; O' Donovan et al., 2021; Sengupta et al., 2023a; Amaripadath et al., 2024a; Rahif et al., 2023). For example, Amaripadath et al. (2023) have investigated the thermal resilience of near-zero energy homes during heatwaves, revealing that current building-level renovation strategies alone are insufficient to mitigate overheating risks. The second trend compares buildings' thermal resilience with their energy performance, analysing them as independent factors rather than in an integrated framework (Flores-Larsen and Filippín, 2021; Kesik et al., 2022; Krelling et al., 2024; Lee et al., 2024). Sun et al. (2020) studied the relationship between thermal resilience and energy efficiency in nursing homes, finding that passive measures may not save energy but can greatly improve thermal resilience, and active energy efficiency measures are not uniformly beneficial for resilience. Mehmood et al. (2022) evaluated different passive cooling solutions to understand the synergy and trade-offs between energy efficiency (energy consumption) and thermal resilience (passive survivability). In addition, research on phase change materials by Baniassadi et al. (2019) also identified mismatches between optimal melting temperatures for energy savings and those ideal for resilience enhancement during heatwaves.

These findings highlight the necessity for a balance between resilience and net-zero. However, this is highly context-dependent, varying significantly with local climatic conditions and no universal solution applies across all contexts. Moreover, some other potentially important interaction domains remain overlooked. For example, regarding life-cycle carbon, strategies that rely on increasing thermal mass or heavy insulation to enhance passive survivability may also lead to substantial embodied-carbon increases. Additionally, buildings with high passive survivability can apply this capacity to shed or shift peak loads under normal conditions to support grid stability and enhance renewable energy utilization. Currently, most analyses still treat net-zero and resilience as independent factors, lacking a quantitative assessment of their synergies and trade-offs within optimisation-based frameworks or multi-criteria decision analyses.

Beyond quantitative evaluations, qualitative studies across government, private, and civil sectors also point to a broad consensus: while these two goals are compatible, they have not yet been persistently or systematically coordinated (Nunes, 2023).

Ideally, the synergies between net-zero and resilience would be maximized through integrated design and coordinated planning. In reality, however, misaligned priorities among stakeholders, market mechanisms that favour short-term cost efficiency, and various operational constraints may create significant barriers to implementation in practice.

4.3. Translating thermal resilience into practice

Thermal resilience is not only an engineering challenge but a collective outcome shaped by multiple stakeholders. However, currently coordination across these actors remains limited, which may constrain the effective translation of theoretical resilience into practice.

Government authorities primarily shape resilience through regulatory and mandatory instruments. At present, most building regulations still focus primarily on reducing energy use and carbon emissions, but offer limited consideration of thermal resilience under extreme conditions or future climatic variability. However, some advanced practices have emerged. For example, the UK Building Regulation Approved Document O (HM Government, 2021) sets minimum overheating mitigation requirements for new residential buildings via simplified glazing and ventilation limits or dynamic modelling based on CIBSE TM59; New York City's Local Law 41 of 2021 requires city capital projects to assess risks using the Climate Resiliency Design Guidelines (NYC Mayor's Office of Climate and Environmental Justice, 2022), which includes assessing passive survivability duration during electric grid outages for critical facilities.

These regulatory advances are frequently underpinned by technical methodologies established by professional institutions. Furthermore, these institutions complement statutory mandates by developing voluntary, non-regulated frameworks and technical guidelines, such as ASHRAE Standard 55 (ASHRAE, 2023), CIBSE TM52 (CIBSE, 2013) and TM59 (CIBSE, 2017). Besides, there are also some building rating schemes, such as the Leadership in Energy and Environmental Design (LEED) system (U.S. Green Building Council, 2019a) and the Building Research Establishment Environmental Assessment Method (BREEAM) (BRE, 2025), which incentivize performance beyond statutory minimums by integrating these technical standards into their credit criteria.

However, these systems exhibit varying degrees of resilience integration. For instance, BREEAM evaluates overheating risk through CIBSE TM52 and TM59 criteria and the use of future weather files, whereas LEED addresses only current thermal-comfort performance based on ASHRAE Standard 55 and does not explicitly consider future heat stress. Moreover, most mainstream standards and rating schemes do not incorporate performance during power outages. Although emerging instruments such as the LEED Resilient Design pilot credits (U. S. Green Building Council, 2019b) and the European smart readiness indicator (SRI) (European Commission, 2020) have begun to address resilience during disruptions and grid interactivity, their market uptake remains limited, often serving as optional niche credits rather than fundamental design requirements.

The building supply chain (e.g., architects, engineers, developers, managers and insurance providers) translates resilience expectations into design decisions, system specifications and operational practices. Notably, the role of the insurance sector in building thermal resilience remains limited but is expected to grow: current coverage is typically limited to the maintenance fees or repair costs for physical damage and equipment failure caused during extreme heat events (Barrelas et al., 2021).

This review shows that current academic studies adopt dynamic, performance-based approaches to track the full temporal evolution under extreme events and use multiple metrics simultaneously. However, this does not imply that all stakeholders should, or can, adopt such complexity. To accommodate the diverse functional levels of stakeholders, this study proposes a recommended framework for approaches and metrics that stakeholders can adopt for building thermal resilience (Fig. 9).

Regulators and professional institutions can expand the current scope of energy efficiency and carbon emissions to include climate resilience as a fundamental requirement. Regulatory codes and technical standards tend to use simplified and often deterministic representations for extreme conditions, such as standard weather files for specific heatwave intensities, to ensure broad enforceability. These baselines

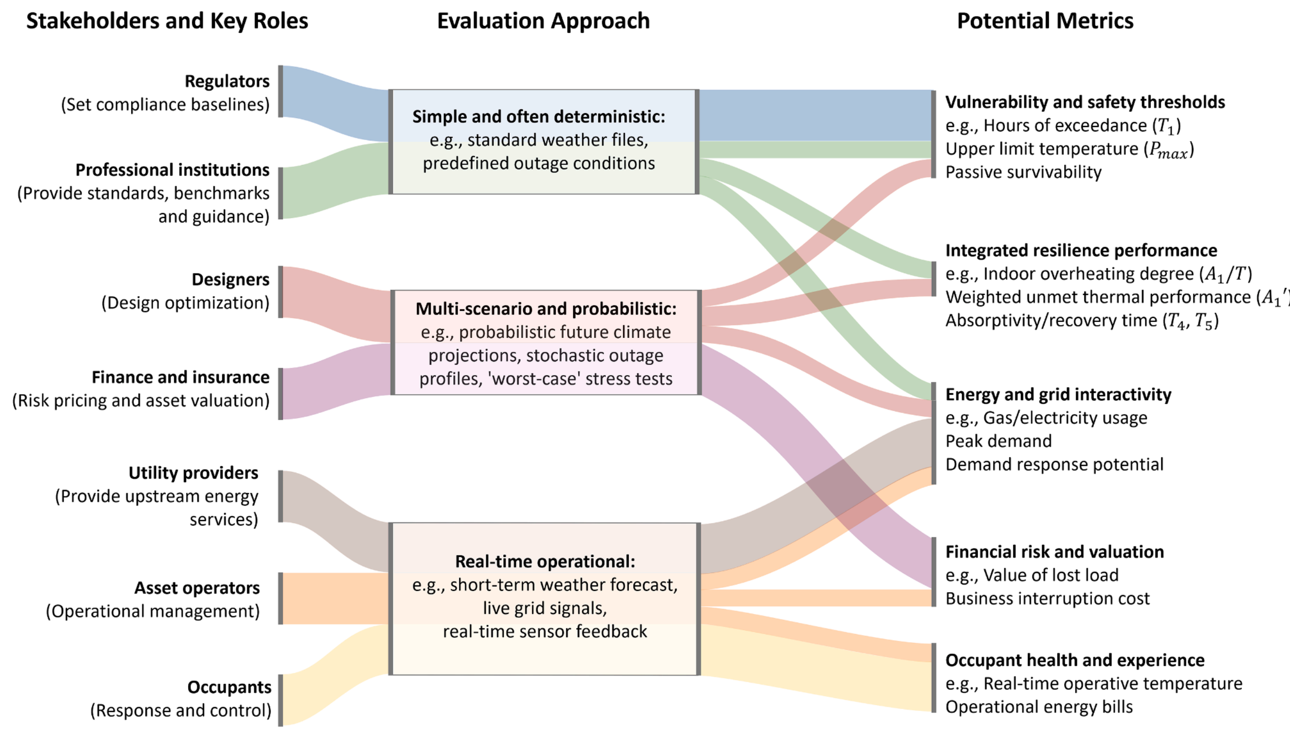

Fig. 9. Recommended framework for implementing thermal resilience across different stakeholders (note: the connectors have no quantitative meaning or weighting).

could also integrate grid-failure scenarios. In terms of metrics, regulatory codes can rely on simple indicators that quantify vulnerability, complemented by passive survivability criteria to ensure basic safety standards. They need to provide clear pass/fail thresholds for compliance purposes. Beyond regulatory baselines, professional institutions can further provide benchmarks with tiered classification labels to incentivize market differentiation and best practices. These standards and guidelines can incorporate detailed integrated resilience performance metrics that capture the full resilience dynamic. Furthermore, they can integrate metrics related to demand response and grid interaction, encouraging the transition towards grid-interactive efficient buildings that support both everyday load balancing and extreme-event response.

Designers (architects and engineers), acting on behalf of owners and investors, can go beyond minimum compliance and guidelines. They can adopt multi-scenario and probabilistic evaluations, which allow them to optimize performance across a wider range of conditions and inform their design options. In doing so, designers can look for opportunities to achieve synergies, such as the co-benefits of indoor environmental quality and energy performance during normal operations, as well as between thermal safety and system reliability during extreme events. This evaluation approach can also be tailored to specific project needs. For example, for critical facilities, prioritizing 'worst-case' scenarios can help guarantee high safety margins; whereas for long-term asset holders, scenarios extending 50 to 70 years into the future can help capture full lifecycle risks and prevent asset stranding.

Finance and insurance stakeholders may also use multi-scenario and probabilistic assessments to accurately estimate event likelihood and potential financial losses from cooling failures or uninhabitable conditions. By translating physical thermal risks into tangible economic signals, they can provide the necessary market incentives for thermal resilience investment that regulatory baselines alone cannot drive.

Asset operators, acting on behalf of the collective occupants, rely primarily on real-time monitoring and predictive control during the operational phase. Based on short-term weather forecasts, they can proactively initiate thermal pre-conditioning (e.g., pre-cooling or pre-heating), and ensure backup power readiness to maintain critical operations during thermal extremes. They need to adopt a holistic perspective that integrates technical, financial, and operational considerations.

Occupants, as the ultimate end-users, prioritize practical outcomes such as immediate thermal comfort, health safety, and energy affordability. It is important to support their transition from passive users to active participants. This can be achieved through structured training at building handover and broader awareness campaigns. In turn, their feedback (e.g., via surveys or post-occupancy evaluations) can help to shape the market expectations and indirectly influence policy evolution.

Finally, in the broader context of promoting building-level climate resilience and grid interactivity, **utility providers** should increasingly view buildings as flexible grid resources rather than passive loads. This shift allows utilities to consider how buildings can contribute to system stability during extreme weather by providing demand flexibility and participating in controlled load-shedding strategies.

5. Conclusions

This paper reviews over one hundred peer-reviewed articles to provide a comprehensive understanding of thermal resilience in the built environment. It covers the evolution of definitions, application domains, characterization of disruptive events, scenarios contextualization and performance evaluation methods, across scales from individual buildings to the interconnected urban environment.

The analysis reveals diversity and potential gaps in current studies. Evaluation approaches vary widely, using diverse definitions, metrics, and threshold criteria across studies; the interaction between thermal resilience and other performance dimensions, such as energy efficiency and grid reliability, remains an area for further integration; the interconnection between building scale, urban microclimates, and occupant-level adaptive behaviours remains insufficiently addressed and requires deeper investigation.

To address these challenges, this study proposes an integrated cross-scale framework that demonstrates the linkages among macro-scale urban and infrastructural systems, socio-organizational contexts, and building systems interacting with micro-scale occupant dynamics. It also advocates that future research should coordinate thermal resilience with net-zero goals, moving toward synergistic strategies that enhance robustness without compromising sustainability. Furthermore, it provides tailored recommendations for different stakeholders to effectively translate resilience concepts into practice.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used OpenAI's ChatGPT to enhance the clarity and grammar of the writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Yingyue Li: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Eirini Tsouknida:** Supervision, Funding acquisition, Conceptualization. **Tom Collins:** Supervision, Funding acquisition, Conceptualization. **Ashley Bateson:** Supervision, Funding acquisition, Conceptualization. **Rui Tang:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Esfandiar Burman:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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