Energy & Buildings 370 (2026) 118111

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Energy resilience in the built environment under disruptive events: hazard-, climate- and equity-informed systematic scoping review

Rakesh Ramesh [a,b,*], Hassam ur Rehman [a]

[a] VTT Technical Research Centre of Finland Ltd, PO Box 1000, 02044, Finland
[b] Department of Mechanical Engineering, Aalto University, Espoo, 02150, Finland

ARTICLE INFO

Keywords:
Energy resilience
Buildings
Passive survivability
Heatwaves
Cold climate
Equity

ABSTRACT

Buildings are primary sites where climate hazards translate into human crises, yet research on their ability to withstand and recover from energy disruptions remains conceptually fragmented and rarely integrates building physics with social science perspectives. Energy resilience is increasingly critical as climate extremes, grid instabilities, geopolitical shocks, and widening socioeconomic inequalities increasingly disrupt energy services.

This systematic scoping review synthesises evidence across the built environment to examine how energy resilience is defined, conceptualised, and measured across technical, climatic, and equity dimensions. Following PRISMA-ScR procedures, Web of Science and Scopus were searched for studies between 2000 and 2025, yielding 167 studies supplemented by 9 foundational resilience frameworks ($n = 176$).

The analysis reveals three structural challenges. Only 25% of studies (44 of 176) provide operational definitions, with most using resilience as a rhetorical construct. The field utilises twenty-nine distinct building-scale indicators, including several mathematically equivalent formulations that remain unrecognised across disciplines. Most studies rely on single-building, short-term, event-based metrics, with limited attention to multi-hazard trajectories, district-scale dynamics, or equity weighting. Empirical evidence is geographically skewed toward heat-related hazards in high-income regions, with fewer than 10% of studies addressing the Global South and limited coverage of cold-climate events. Passive envelope performance emerges as the most consistent determinant of resilience across climate contexts, while efficiency-resilience trade-offs remain underexplored.

This review identifies an inverse relationship between research density and climate exposure and highlights the absence of a cold-climate passive survivability standard as a critical gap. A six-step assessment framework is proposed, integrating hazard, climate, and equity dimensions to support harmonised metrics and policy development.

1. Introduction

Extreme temperature events constitute a major and growing source of climate-related mortality worldwide. Ongoing climate change is fundamentally reshaping patterns of thermal stress, as events that were once rare are now occurring with greater frequency and intensity, with large-scale fatalities observed during events such as the 2003 European heatwave [1,2] and recent extreme cold events in Texas and British Columbia in 2021 [3,4]. Simultaneously, the energy transition is introducing new systemic vulnerabilities, as centralised fossil fuel-based infrastructures are being rapidly replaced by distributed renewable generation characterised by different reliability profiles and distinct seasonal variability. Geopolitical incidents, including the continued targeting of Ukraine's energy infrastructure since 2022 [5], illustrate how quickly large-scale grid failures can translate into building-scale life safety risks, especially under prolonged winter conditions. These risks are further worsened by widening socioeconomic inequalities, which cause the impacts of energy disruptions to fall disproportionately on households with limited adaptive capacity, particularly low-income populations, elderly residents, and individuals with chronic health conditions. Against this confluence of climatic, infrastructural, and social stressors, energy resilience in buildings has emerged as a critical priority for both research and policy.

Energy resilience is conceptually distinct from the efficiency and reliability objectives that have influenced building policy over the past few decades. Efficiency optimisation seeks to minimise energy use under

* Corresponding author.
E-mail address: rakesh.ramesh@vtt.fi (R. Ramesh).

https://doi.org/10.1016/j.enbuild.2026.118111
Received 1 June 2026; Received in revised form 28 July 2026; Accepted 14 August 2026
Available online 16 August 2026

normal operating conditions, while reliability focuses on reducing the probability of system failure. Resilience, on the other hand, addresses performance when disruptions occur. From this perspective, the central questions concern the extent to which buildings can safeguard occupant health and safety during outages, and the speed with which essential functions can be restored. This reframing carries direct and sometimes counterintuitive implications for building practice. Highly insulated and airtight envelopes that minimise annual energy demand may, under prolonged heating outages in cold and temperate climates, or under cooling outages in hot climates where mechanical ventilation is the only air-exchange pathway, reduce passive survivability relative to less airtight construction, unless operable natural ventilation fallback is present [6–8]. This effect is not generalised across all high performance envelopes. When passive ventilation backup is preserved, higher levels of airtightness and insulation improve rather than reduce passive survivability. Distributed solar generation and battery storages can sustain critical loads during outages yet remain financially inaccessible to energy-poor households. Similarly, heat pumps that deliver high seasonal efficiency provide insufficient backup capacity during extreme cold events when ambient temperatures fall below their design range. These trade-offs between efficiency and resilience, and between technical performance and equitable access, underline the need for an integrated perspective and illustrate why building energy resilience cannot be fully addressed within either the energy efficiency paradigm or the disaster risk reduction paradigm that currently dominates the literature.

The existing review literature on building energy resilience has expanded considerably in the past five years, yet it remains bound by some limitations that prevent a comprehensive, multi-hazard, equity-informed synthesis. Fig. 1 provides a comparison of how key prior reviews and frameworks cover these dimensions. The detailed description supporting each classification (including scope constraints) is provided in

Table A1 (Appendix). Ahmed et al. [9] provide the most extensive treatment of passive cooling strategies and resilient cooling metrics, but their work is explicitly restricted to heat-driven overheating scenarios in warm climates, with cold-climate outages, compound events, and equity dimensions outside their stated scope. The IEA EBC Annex 80 programme developed an extensive framework for building-scale resilient cooling assessment, including metric guidance, but it is geographically and seasonally constrained. It does not address cold-climate outage scenarios, and its equity dimensions are acknowledged rather than systematically analysed [10].

The most recent and thematically closest precedent is Wei et al. [11], which reviews concepts, metrics, and strategies for energy resilience in the built environment and proposes a comprehensive definition. Their work makes a strong contribution to metric taxonomy and definitional clarity, and the present study builds explicitly on it. However, the review focuses primarily on technical dimensions of energy resilience, while allocating limited attention to equity, cold-climate and cold-outage scenarios relative to heat events. The present review integrates epidemiological and public health evidence linking indoor thermal conditions to health outcomes, a concept Wei et al. acknowledge but do not analyse, and which is necessary to derive health-based rather than engineering-based habitability thresholds. This work also operationalises equity as a structural dimension rather than treating it as a supplementary concern. In addition, the search strategy explicitly spans building physics, climate science, epidemiology, and social science databases within a single PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) procedure, whereas Wei et al. draw primarily from building energy and engineering literatures. Most recently, Zhang et al. [12] provide a critical review of building energy resilience for indoor thermal stability under extreme weather, examining both heat waves and cold waves within a vulnerability-robustness-tolerance-recoverability attribute structure and reviewing renewable energy-based enhancement measures. While their dual-season framing advances on earlier reviews, the review does not apply a formal systematic search procedure, does not integrate epidemiological evidence or equity dimensions, and does not map the geographic distribution of research effort relative to climate vulnerability, the three gaps that most directly motivate the present study.

Systematic reviews of energy poverty and thermal comfort in vulnerable households [13,14] centre equity but lack the building physics and hazard-specific knowledge needed to translate equity findings into design and code requirements. Public health studies documenting mortality and morbidity under thermal extremes [15,16]

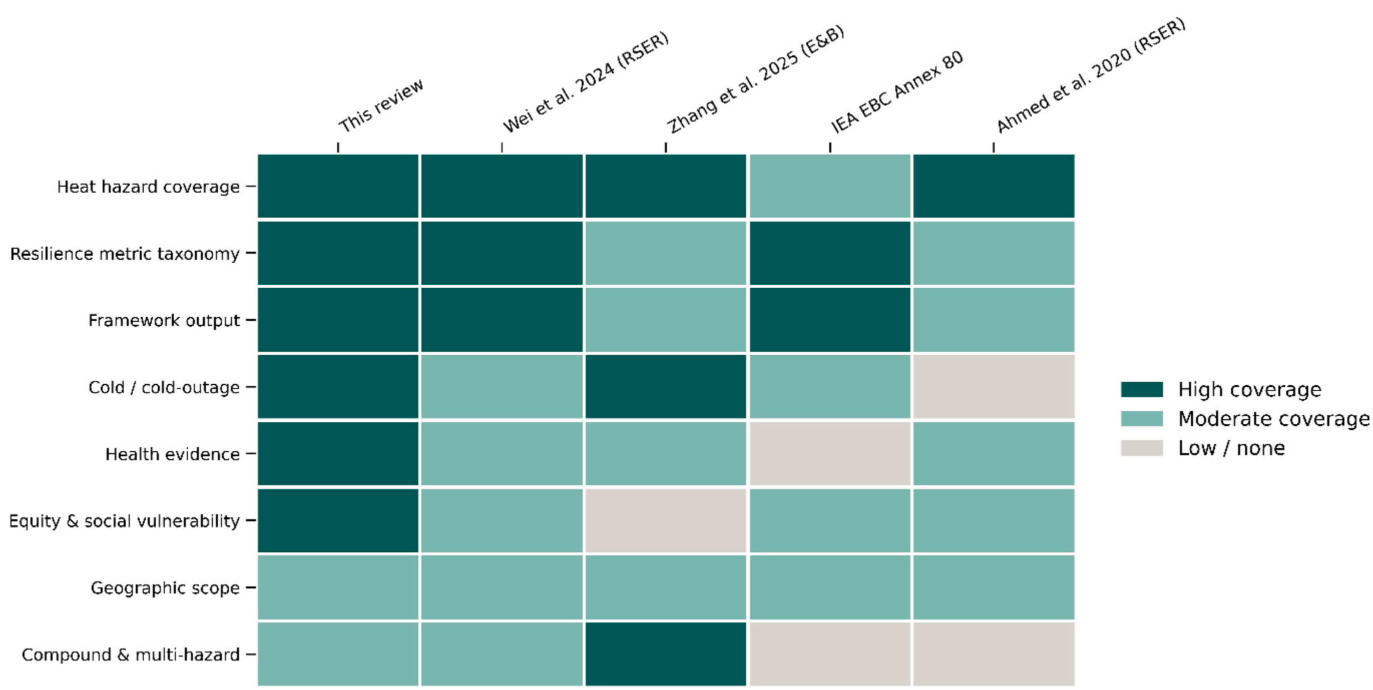

Fig. 1. Comparative coverage matrix of key review works and frameworks on building energy resilience.

establish the health burden with precision but do not examine building performance- or indoor thermal conditions as contributing factors.

A key knowledge gap in the existing literature is the lack of a synthesis that integrates hazard type, climate context, building level technical evidence, and socio-economic vulnerability within a single analytical framework, developed through a systematic, PRISMA-ScR guided review of multi-disciplinary sources. Such a synthesis would place equal emphasis on who is protected and on whether protection is technically achievable and would address cold-related hazards in proportion to their documented mortality rate rather than to their prevalence in the existing literature.

The present review addresses this gap through a systematic scoping review of 176 publications, applying hazard-, climate-, and equity-informed perspectives across the literature. The methodological contribution lies in this integration: while each of these dimensions has been examined independently in prior works, their integrated treatment within a single systematically assembled review has not previously been undertaken at this scale.

Four research questions structure this article: (1) how energy resilience in buildings is conceptualised and measured, and whether definitions are standardised; (2) which technical measures improve resilience, and under what climate conditions; (3) what socio-economic outcomes result from energy disruptions, and what equity implications arise; and (4) which critical research gaps and priorities emerge for future work. The review covers building and district-scale studies across all climate zones and hazard types, with particular attention to cold events that are underrepresented in previous review works. Fig. 2 illustrates the structure of this review and the three cross-cutting perspectives, hazard-, climate-, and equity-informed, that organise the synthesis that follows.

2. Search methods and study selection

A systematic scoping review was conducted to map how energy resilience in the built environment has been defined, operationalised and evaluated across diverse contexts and conditions. The review followed PRISMA-ScR guidance [17] to ensure transparency in study identification, screening and inclusion, and to support reproducibility of the work. The focus was on built environment research that analyses thermal performance, energy use or service continuity under disruptive events, including peer-reviewed journal articles and selected institutional reports with methodological or conceptual relevance.

2.1. Search strategy

A literature search was performed following the PRISMA-ScR framework to identify studies on energy and thermal resilience in the built environment. The search was performed in the Web of Science Core Collection, covering multiple indexed databases extending up to 2025. The search strategy was developed iteratively using topic-based queries (TS) and employing wildcard operators to capture variations in terminology. The first cluster targeted resilience-related concepts using truncated terms (e.g., *"energy resilien*," "thermal resilien*," "cooling resilien*," "heating resilien*")*, while the second captured disruption-related events (e.g., "power failure," "blackout," "disruptive event"). These were combined with built environment descriptors (e.g., "building," "built environment," "district") using Boolean operators (AND/OR) to ensure contextual relevance.

To further refine the scope toward human-centric and climatic dimensions, additional filters were applied by incorporating terms related to occupant impacts ("health," "indoor comfort," "user behavi*") and climatic context ("cold climate," "hot climate"), again using wildcard truncation where appropriate. The final search string, representing the intersection of resilience, disruptive events, built environment context, human factors, and climate conditions, was carried out on 23 October 2025, yielding 332 (Web of Science) and 164 (SCOPUS) records, respectively. After removal of 112 duplicate records, a total of 384 unique records were retained for screening. No geographic or language restrictions were applied during the initial database search.

A methodological distinction was applied to separate energy resilience from climate adaptation, concepts that are used interchangeably in the literature reviewed in this work. For screening and coding purposes, energy resilience was defined as the ability of a building or building-scale energy system to maintain or rapidly recover critical energy-related functions during and after disruptive events. This definition is consistent with resilience literature that emphasises the capacity of systems to withstand disturbances, maintain essential functionality, and recover performance following disruption [18,19]. Climate adaptation was defined as longer-term adjustments to building characteristics, technologies, infrastructure, or operating practices in response to changing climatic conditions, with the objective of reducing future vulnerability and enhancing performance under evolving climate conditions [20]. Accordingly, studies were classified as energy resilience when their primary focus was maintaining, withstanding, adapting to, or restoring energy-related building performance under disruptive events (e.g., power outages, extreme weather events, infrastructure failures). Studies whose primary focus was the long-term adjustment of buildings

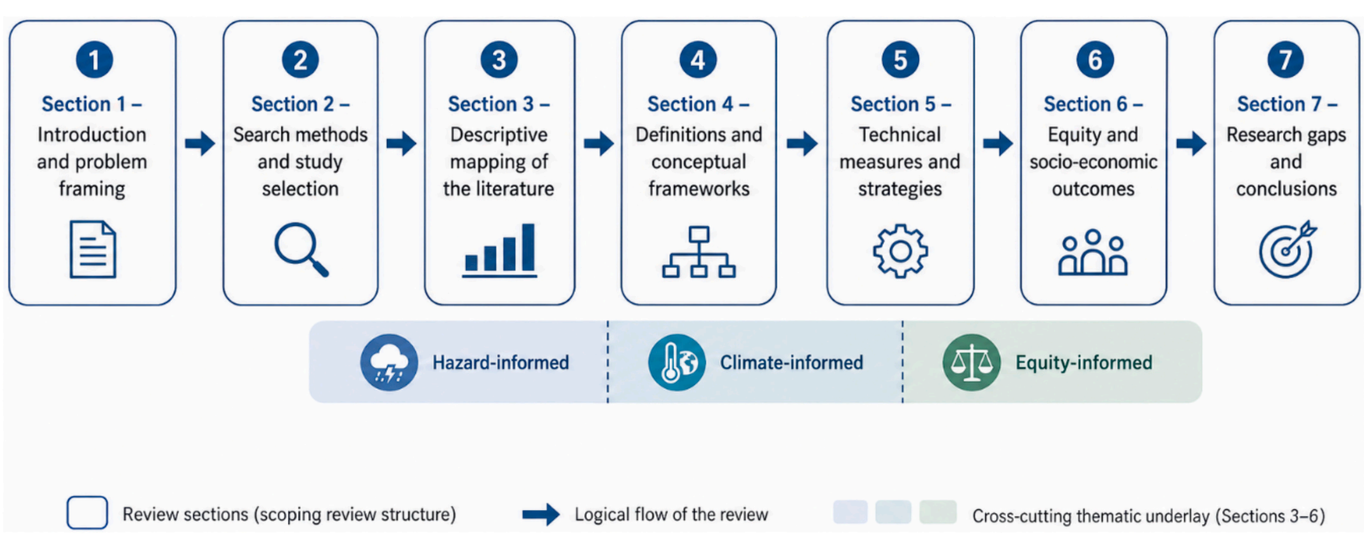

Fig. 2. Overview of the scoping review structure and analytical framework.

or their operation to changing climatic conditions were classified as climate adaptation. Studies addressing adaptation exclusively, without an event-based or disruption-focused performance dimension, were excluded during abstract screening. Studies addressing both dimensions (e.g., evaluating outage-event performance under a future climate projection) were considered relevant to both categories, and this was explicitly acknowledged and discussed in the relevant synthesis sections. (Sections 4, 6, and 10).

2.2. Supplementary searches, screening, and inclusion

Temporal and phase-based resilience concepts largely originate in infrastructure, disaster-management, and systems engineering literatures. The main database search was therefore complemented by a targeted supplementary search (SS1) for foundational theoretical frameworks on resilience dynamics. This search focused on five disciplinary domains not adequately covered by the primary keyword strategy: earthquake/infrastructure engineering, power systems resilience, disaster management, adaptive cycle & socio-ecological systems theory, and urban planning resilience frameworks. Citation tracking from key building-resilience papers and targeted keyword searches were used to identify contributions on *temporal phases, recovery trajectories* and *resilience dynamics* on the 25th of October 2025. This process yielded nine additional papers that provide the conceptual foundation for the temporal resilience framework adopted in this review. These foundational papers were screened against the same inclusion criteria as the main database search.

A second category of supplementary sources (SS2) was used to contextualise the technical measures in Section 6. Because many established passive and active resilience strategies draw on a broader building technology literature that predates and/or operates outside the 'resilience' terminology captured by the primary search, relevant technical papers were identified through citation tracking from papers and targeted keyword searches in building technology databases. This search was conducted on 30th October 2025 and identified 24 additional sources. These sources were screened against the same inclusion criteria as the primary search; peer-reviewed papers meeting the criteria are cited and established as technical context rather than as primary systematic evidence. Search terms used for this purpose included: *'passive survivability envelope,' 'microgrid islanding building,' 'PV battery outage,' 'cool roof solar reflectance,' 'evaporative cooling building,' 'double skin facade performance,' 'green roof thermal,' 'ground source heat pump efficiency,'* and *'thermal energy storage building.'* Statements regarding the distribution, frequency, and relative importance of strategies are based exclusively on evidence from the systematically screened corpus.

The 384 records were screened in two stages to ensure efficient and rigorous evaluation of relevance. In the first-stage screening, the literature was evaluated based on article titles, journal scope and subject classification to exclude studies clearly outside the built environment domain. Papers published in journals focused on biology, agriculture, food systems, genetics, aquatic ecosystems and other disciplines demonstrably unrelated to building energy performance or the built environment were excluded at this stage, reducing the literature database to 274 records. This initial filter removed studies where the terms "resilience" or "energy" appeared in contexts irrelevant to buildings, such as crop resilience to drought, marine ecosystem energy flows or genetic resilience mechanisms.

In the second-stage screening, the remaining 274 abstracts were independently reviewed to assess relevance against predefined inclusion and exclusion criteria. Studies lacking explicit connection to building or district scale energy resilience, thermal performance during disruptions or occupant outcomes during extreme events were excluded. Following the abstract review, 167 papers met all eligibility criteria and were retained for full-text analysis and metadata coding. The nine papers identified through the supplementary search (SS1) were assessed using the same criteria and all were included, resulting in a final corpus of 176 publications. The selection process is summarised in the PRISMA-ScR flow diagram (Fig. 3). The diagram outlines the sequential stages of identification, screening, and inclusion of studies retrieved from databases and registers, showing how records were filtered and refined to arrive at the final set of studies included in the review.

For each included study, metadata was extracted on publication year, geographic region, climate context, hazard type, methodological approach, resilience definitions, metrics and indicators, technical measures and socio-economic or health outcomes. These data form the basis for the descriptive mapping of the literature and the subsequent analysis.

3. Descriptive mapping of the literature

This section provides a descriptive overview of the included studies, examining how energy resilience is conceptualised, the hazards and methodological approaches selected, and the geographic and climatic distribution of research efforts. These patterns form the empirical basis for the subsequent conceptual, technical, and equity-focused analyses.

Publication activity on building energy resilience remained sparse before 2018, with less than five papers per year in the included literature collection. Activity then accelerated noticeably from 2019 onwards, with 17 papers in 2022, 24 in 2023, and approximately 37 in 2024 (Fig. 4), which means the majority of this field's evidence base is less than three years old at the time of writing, which is an important qualification. The post-2021 acceleration is consistent with the catalysing effect of the British Columbia heat dome, the Texas winter storm, and the onset of attacks on Ukraine's energy infrastructure, all of which created urgent demand for building-scale compound-event and passive survivability research that had not previously existed at scale.

Resilience conceptualization: Each paper was evaluated for how explicitly it defined energy resilience or related concepts, based on the coding undertaken for this review. Only approximately 25% of included papers, around 44 of them, provided a formal, operational definition of energy or thermal resilience, typically defined either as the ability to maintain energy service continuity or, at the building scale, to maintain indoor thermal conditions, or to limit the magnitude and duration of performance degradation through indicators such as hours of safety, survivability time, or thermal autonomy [13,14,22–24]. A further 22% addressed resilience dimensions (recovery time, survivability, overheating thresholds, or load flexibility) without consolidating them under an explicit definition [6,9,25–29]. The remaining studies used 'resilience' instrumentally, either as a framing term without definitional grounding, which is in line with the umbrella-use of resilience documented in infrastructure and urban planning research [30–32]. Collectively, this reveals significant conceptual diversity: most building-scale energy studies treat resilience as an implicit rather than explicitly justified construct.

Applying this boundary retrospectively across the literature, the majority of included studies evaluate short-term, event-based resilience responses, typically outage or extreme-weather scenarios assessed against historical or design-basis conditions. A smaller subset of studies additionally adopted an adaptation perspective by evaluating resilience performance under future climate projections rather than historical climate conditions. This dual-framed subset is differentiated from event-based studies throughout the technical measures discussion (Section 6) and the research gaps synthesis (Section 10), where the resilience versus adaptation orientation of each measure or gap is noted.

Hazard Type: Papers were classified by the primary disruptive events they addressed, noting that some studies considered multiple hazards, and some were independent of the type of hazard. Heat-related threats dominated, appearing in 118 papers, reflecting strong emphasis on overheating, resilient cooling and heat-health interactions (e.g. [6,26,33–35]). Power disruptions (blackouts, grid failures, supply interruptions) were discussed in 26 papers, including work on blackouts during heatwaves and cold spells, energy security and outage case

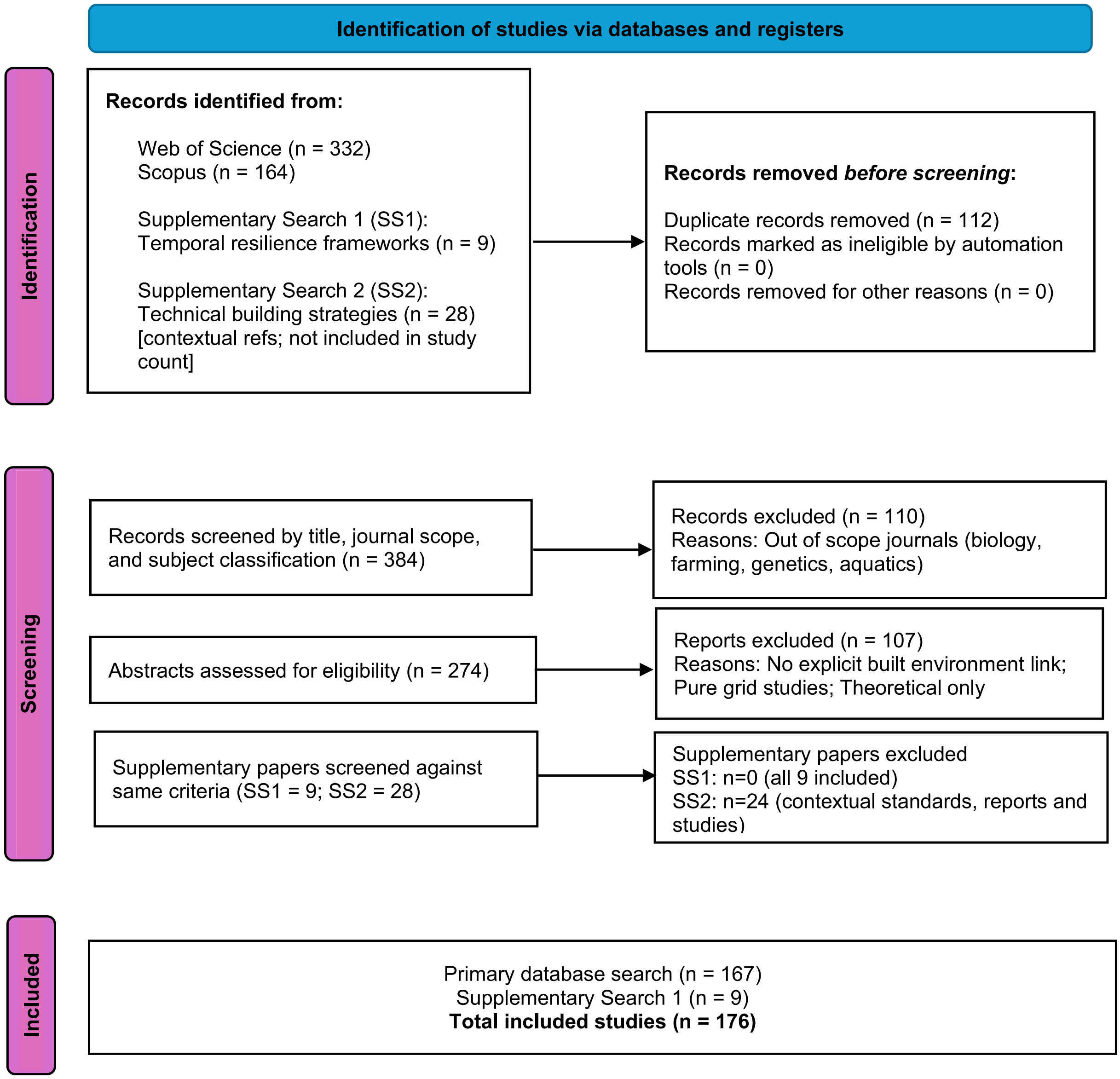

Fig. 3. PRISMA flow diagram illustrating the study selection process. Adapted from [21].

studies, and analyses of building-scale autonomy and microgrid performance (e.g., [36–41]). Cold-related hazards (cold snaps, extreme winter, heating demands) were addressed explicitly in only around 24 papers, typically in the context of cold-climate or Indigenous-housing performance, passive survivability under cold outages, or cold-related health burdens (e.g., [7,42–47]). Compound or cascading hazards, where multiple disruptions occur simultaneously or sequentially (e.g. heatwave & blackout, storm-induced flooding plus distribution failure, conflict-driven supply disruptions), appeared in just 18 papers, despite growing evidence that multi-hazard contexts strongly shape health, equity and infrastructure outcomes (e.g., [14,48–50]). Because several studies addressed more than one hazard, category counts exceed the total number of included papers. As shown in Fig. 5, the distribution of publications is strongly skewed toward heat-related events, with relatively limited attention given to cold-related hazards.

Methodological Approach: The literature establishes a strong preference for computational and conceptual approaches. Simulation and modelling studies (building energy models, thermal dynamics simulations, parametric sensitivity analyses, and coupled building-grid models) accounted for approximately 26 papers (~15%), spanning single-dwelling, multi-family, office, and district-energy scales (e.g., [6,26–28,36,37,51–55]). Mixed-methods approaches combining simulation with empirical monitoring, surveys or qualitative analysis represented around 30% of the reviewed papers (e.g., [33,43,56–60]). Conceptual and analytical approaches (theoretical frameworks, resilience metric proposals, and policy analyses without primary data collection) formed the largest single category at 65 papers (~37%) (e.g., [30,31,61,62]). Epidemiological and statistical studies, including mortality analyses and hospital admission data, contributed 35 papers (~20%) (e.g., [4,57,58]). Empirical qualitative and survey-based studies accounted for 15 papers (8%), and experimental or field-monitored studies for 12 papers (7%) (e.g., [30,40,57,58,63]). This distribution highlights a critical methodological gap: resilience strategies are predominantly evaluated through computational frameworks rather than validated through experimental studies or large-scale empirical assessments, reiterating calls in the resilient-cooling and thermal resilience literature for more field-based evidence. An interesting finding is that very few literatures bridge building-physics methods and health or equity outcomes within the same study, highlighting what the discussion section describes as the equity-technical disconnect.

Geographic and Climatic Context: Papers were mapped by

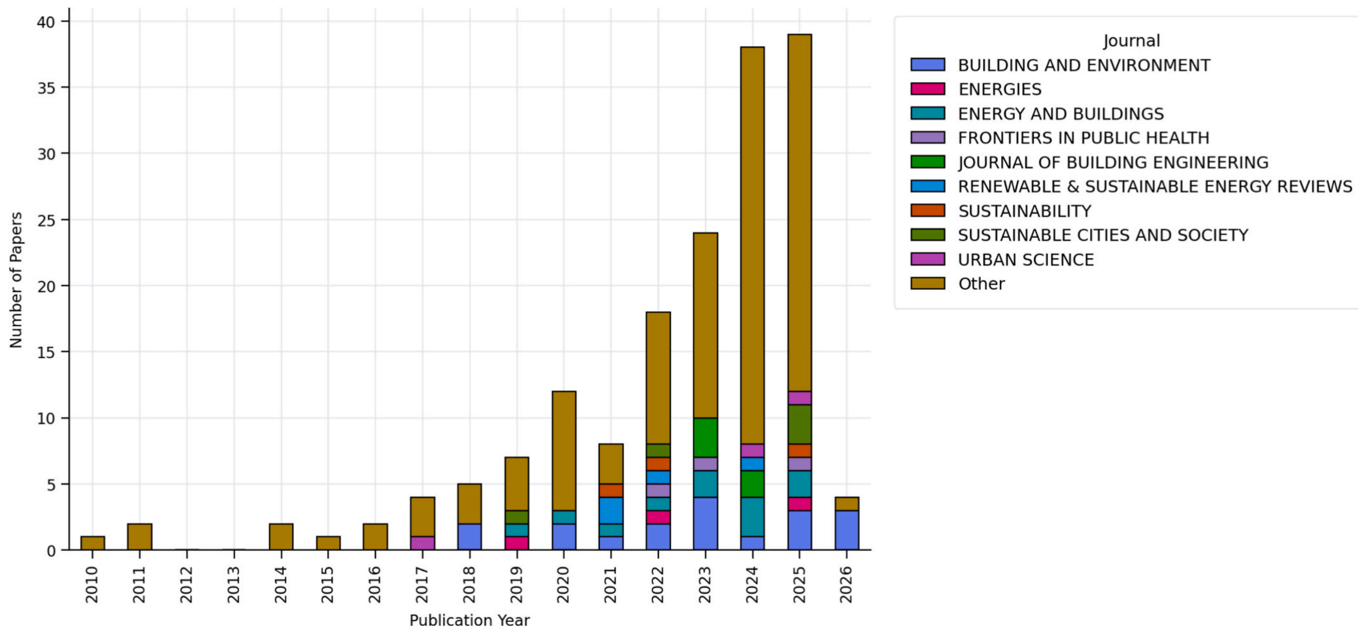

Fig. 4. Number of publications per year by journal (≥3 papers shown individually; <3 grouped as Other).

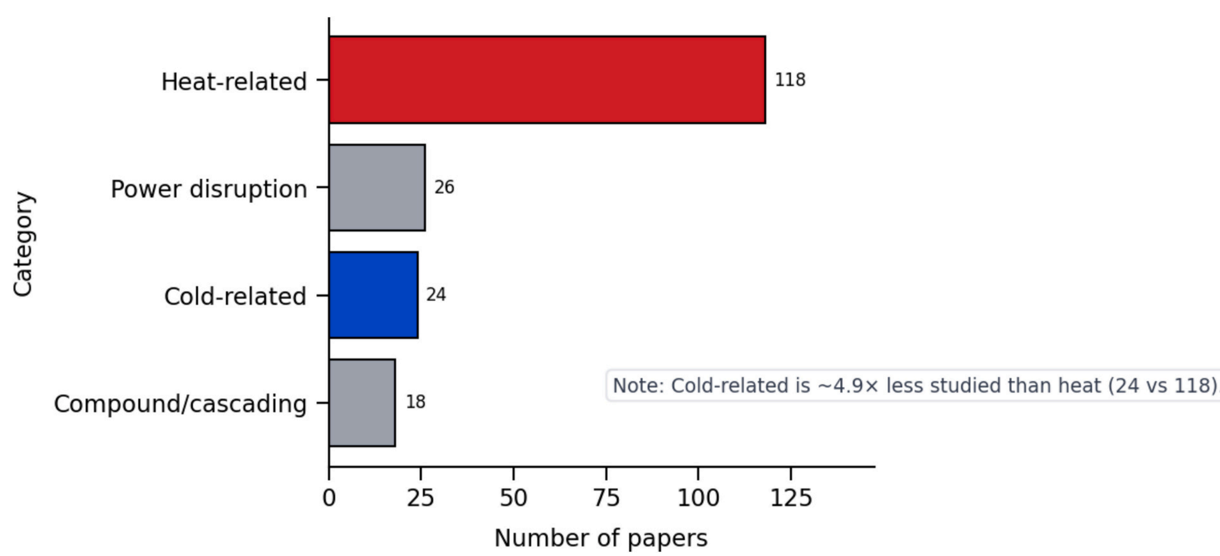

Fig. 5. Distribution of publications across hazard categories, highlighting a strong concentration of research on heat-related events ($n = 118$) compared to cold-related events ($n = 24$). Power disruptions ($n = 26$) and compound/cascading events ($n = 18$) remain comparatively less explored.

geographic scope and climate focus (Fig. 6). USA and Canada (27 papers, 15%) and Europe (26 papers, 15%) together dominate, followed by China (13 papers, 7%) and Australia (9 papers, 5%). Africa, South and Southeast Asia, and Latin America together contributed 14 papers, approximately 8% of the corpus, despite these regions containing the majority of the world's most climate-exposed and energy-insecure populations. The Middle East appeared in only 2 papers. Twenty-one papers were classified as global or multi-country in scope. A further 64 papers could not be assigned to a specific geography, typically conceptual or framework studies. This concentration means that the evidence base is shaped almost entirely by the priorities, climates, building technologies, and institutional capacities of wealthy nations, a finding with direct implications for the transferability of the benchmarks, strategies, and metrics this corpus treats as standard.

One pattern emerging from the descriptive mapping that warrants closer analytical attention is that only a quarter of the 176 included papers provide an operational definition of energy resilience. As a result, the literature base is built on an inconsistently defined construct, raising fundamental questions about comparability, interpretation, and the validity of cross-study synthesis. This issue motivates a closer examination of how energy resilience is defined and conceptualised across the field.

4. Definitions and conceptual frameworks

4.1. *Definition of energy resilience in built environment*

Energy resilience in the built environment lacks a universally accepted definition, with consensus divided across disciplinary boundaries, spatial scales, and temporal frameworks. This arises partly from resilience's multi-disciplinary origins: engineering perspectives emphasise “bounce-back” to equilibrium states [64], psychology focuses on

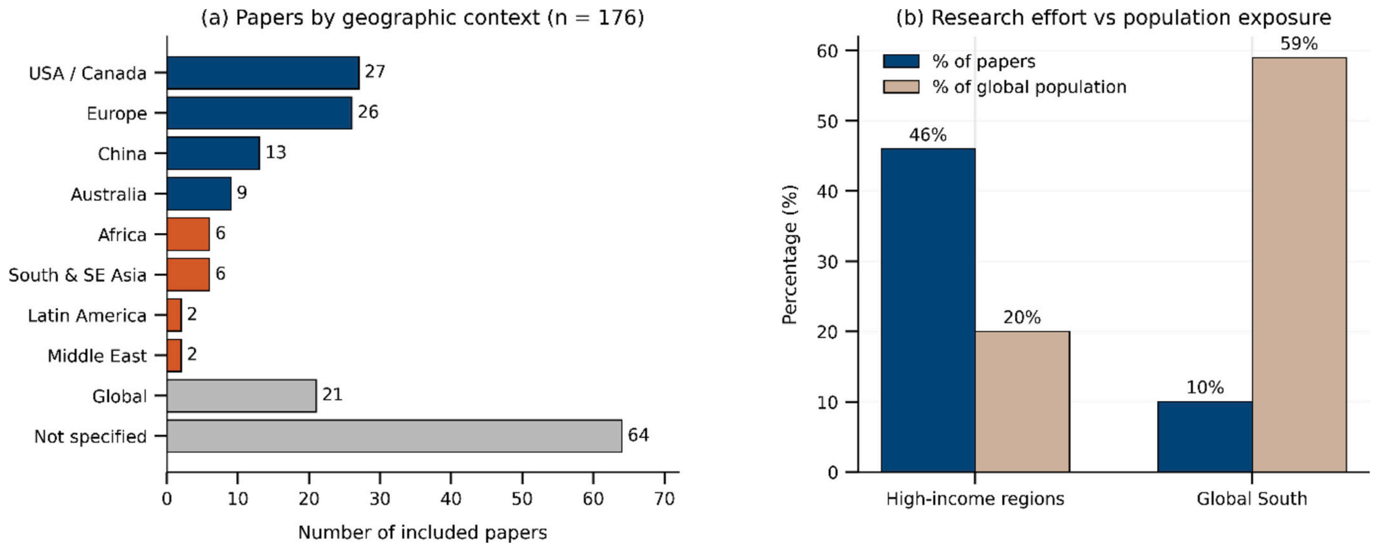

Fig. 6. Geographic distribution of included studies ($n = 176$) and disparity with population exposure; (a) Distribution of studies by geographic context (b) Comparison between research effort (% of papers) and global population exposure across high-income regions and the Global South.

individual adaptive capacity [65], and socio-ecological systems theory stresses transformation and learning [66], each importing different assumptions into energy contexts.

At the building scale, many studies implicitly adopt a “passive survivability” viewpoint, in which resilience is considered as the ability to maintain habitable indoor conditions without external power for a defined duration, while others define it through indicators such as hours of safety, thermal autonomy, or maximum indoor temperature during outages [22,33,36,37,56]. Recent work on thermally resilient communities and resilient cooling explicitly links these building-level definitions to socio-technical measures, emphasising that resilience depends not only on building envelopes and energy systems but also on institutions and community practices [14,22,56]. As a result, even when similar terminology is used, operationalisations differ in threshold choices, time horizons, occupant types, and performance dimensions.

System-level definitions also reveal similar divides. The International Energy Agency (IEA) defines energy resilience emphasising its “capacity to cope with hazardous events, respond while maintaining functions, and transform for long-term adaptation” [67], yet this definition competes with narrower definitions focusing solely on recovery speed, or broader frameworks integrating energy security. This lack of consensus has been attributed to studies often adopting distinct interpretations shaped by disciplinary perspectives, problem complexity, or application specific objectives. At the district level, resilience definitions range from technical load-balancing and islanding capability to socio-technical framings incorporating community governance and decision-making participation, with limited integration across these perspectives [14,34].

Climate-context definitions further this challenge. In cold and Arctic climates, resilience definitions often prioritise maintaining indoor temperatures above minimally acceptable thresholds (typically 15–18 °C) for specified durations during extended blackouts, focussing on life safety and infrastructure protection concerns [37,43]. In hot climates, definitions shift toward limiting overheating, ensuring equitable access to cooling, and avoiding heat-related mortality and morbidity [14,22,56]. Very few frameworks explicitly bridge these cold and hot climate perspectives in a unified way.

Equity integration in resilience definitions remains inconsistent and contested. While some recent frameworks explicitly centre vulnerable populations and just-transition principles, most mainstream technical frameworks do not, treating equity as a downstream concern rather than an important aspect of the definition itself [68,69]. This inconsistency has practical consequences: a resilience measure designed without an equity framework can meet its technical targets while deepening inequality, protecting well-resourced buildings while leaving energy-poor households exposed to the same hazards.

In summary, the literature reveals no unified understanding of energy resilience in the built environment. Definitions differ across scales, climatic contexts, and analytical framings, ranging from purely technical performance to explicitly equity-oriented interpretations. This lack of a unified definition documented here has consequences for the field: (i) unharmonised metrics, because metrics are built on definitional foundations that do not communicate across disciplines; (ii) inequitable investment allocation, because frameworks without explicit equity definitions produce unjust outcomes by default; and (iii) misalignment between research outputs and policy requirements, because policymakers cannot process evidence produced under incomparable definitional assumptions.

4.2. Related concepts and distinctions

Understanding why definitions have divided requires examining the building blocks that different communities have used to operationalise resilience. Several terms appear consistently across the literature, but they function as partial definitions rather than synonyms: each captures a different phase or dimension of the resilience cycle and their misconception with resilience itself is a primary driver of the terminological confusion mentioned above [9,25]. Their relevance varies across the disruption timeline: reliability, redundancy, and stability are primarily associated with pre-crisis preparedness; robustness and flexibility govern system performance during disturbances; recoverability becomes critical in the post-crisis phase; while transformability and antifragility capture longer-term adaptive and evolutionary capacities [70]. Table 1 and Fig. 7 therefore organise these concepts into a structured taxonomy, clarifying both their relevance and their relationship to resilience in the built environment.

Reliability refers to the probability that a system performs its intended function under normal or expected operating conditions, and is typically strengthened through maintenance, component quality, and conservative operational margins [23,26]. Robustness focuses on the capacity of a system to withstand disturbances without significant degradation in performance, often through structural hardening or passive design strategies [6,71]. Fig. 7 illustrates the temporal distribution of these concepts across disruption phases, highlighting how

Table 1
Key system properties commonly associated with resilience, including their definitions, temporal relevance (pre-, during, and post-crisis), and their roles in supporting or extending resilience.

Term	Definition / Description / Timeline	Relationship to Resilience
Reliability	Probability that a system performs its intended function under expected operating conditions; primarily pre-crisis	Forms the baseline of resilience by reducing likelihood of failure; does not account for extreme disruptions
Redundancy	Duplication or diversification of critical components (e.g., backup systems, storage, microgrids); pre- and during crisis	Enhances resilience by avoiding single points of failure and enabling continued operation under component failure
Stability	Ability of a system to maintain or return to equilibrium, especially in coupled systems; pre- and during crisis	Supports resilience by preventing cascading failures, but often prioritises returning to original state rather than adaptation
Robustness	Capacity to withstand disturbances without significant performance degradation; during crisis	Core resilience attribute enabling passive survivability and maintaining minimum functionality under stress
Flexibility	Ability to adapt operation dynamically (e.g., HVAC control, load shifting, storage use); during crisis	Extends resilience by enabling adaptive responses under constrained conditions; includes socio-technical dimensions and equity considerations
Recoverability	Capacity to restore acceptable performance within a given timeframe after disruption; post-crisis	Critical for resilience evaluation; links infrastructure recovery with human exposure and health outcomes
Transformability	Ability to fundamentally reconfigure systems when existing structures become inadequate; long-term	Extends resilience beyond recovery toward systemic change aligned with future risks and climate conditions
Antifragility	Capacity to improve and reduce vulnerability as a result of disturbances; long-term	Represents an advanced resilience outcome where systems benefit from shocks and become stronger over time

different resilience attributes dominate before, during, and after extreme events.

When disturbances exceed design expectations and partial or complete system failures occur, redundancy and stability become central attributes. Redundancy involves the duplication or diversification of critical components or pathways to prevent single points of failure, such as emergency generators, distributed energy resources, storages, and islanded microgrids [72]. Stability, particularly within coupled electricity-thermal systems, concerns the ability to maintain or rapidly return to operational equilibrium and to prevent cascading failures [73]. While essential for system continuity, stability-oriented approaches often prioritise returning to pre-event operating states, whereas resilience frameworks explicitly accommodate controlled degradation and reconfiguration to prioritise critical functions.

Energy flexibility has emerged as a complementary concept with particular relevance for resilience in buildings and districts under disruptive events. In addition to its traditional role in demand response and grid interaction, flexibility is increasingly conceptualised as an adaptive capacity under constrained conditions [74–76]. Resilience-oriented flexibility must be evaluated through an explicit equity lens, accounting for differential exposure, sensitivity, and adaptive capacity during disruptive events [77–79].

Recoverability addresses the post-event phase. Following a disruption, recoverability, referring to the capacity of system components and users to restore acceptable performance levels within a given timeframe, becomes a main concern. In the built environment, recoverability includes not just physical repair and recommissioning, but also the restoration of safe indoor conditions and access to essential services [80,81].

It has been argued in recent research that under accelerating climate change and increasing frequency of extreme events, returning to pre-disturbance state neither be sufficient nor desirable. Transformability refers to the capacity to reconfigure or redesign energy systems when existing structures become non-ideal, for example through decentralisation, electrification coupled with storage, climate-resilient retrofits, or community-scale energy systems [40,82]. In this context, the closely related concept of antifragility highlights whether post-event adaptation leads to systematically reduced vulnerability in subsequent disruptions [83]. Together, these concepts emphasise that energy resilience in the built environment is fundamentally phase dependent.

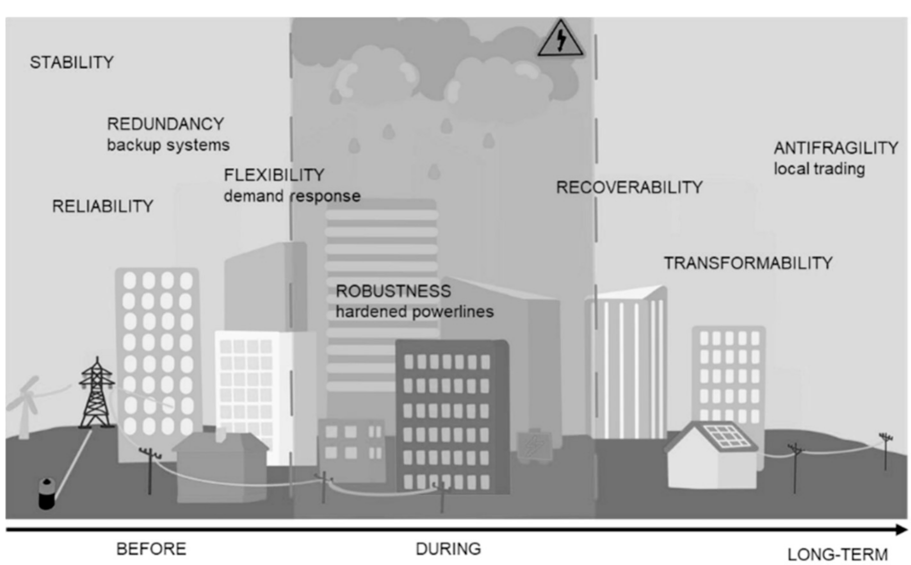

Fig. 7. Temporal relevance of resilience-related concepts across disruption phases. Reliability, stability and redundancy are most relevant pre-event; robustness and flexibility are responsible for system performance during disturbances; recoverability is critical in the post-event phase; while transformability and antifragility represent longer-term adaptive capacity and system evolution [70].

4.3. Phases and temporal dimensions

Resilience in the built environment is increasingly conceptualised as a dynamic, time-dependent process rather than as a static attribute. Across disciplines, resilience frameworks agree on a shared temporal logic in which systems anticipate and prepare for disturbances, absorb and withstand impacts, maintain degraded but functional performance, and subsequently recover, adapt, or transform. This timeline has become the guiding perspective for evaluating the performance of buildings, energy systems, and communities under disruptive conditions. Fig. 8 maps the degree to which key frameworks in the literature explicitly address each temporal stage. Particularly, anticipation and learning phases are consistently under-addressed relative to the in-event absorption and recovery phases, even in frameworks that claim to cover the full resilience cycle.

This temporal framework thinking has roots in structural and infrastructure engineering: Bruneau et al. first developed the link between performance loss and recovery trajectories, a concept subsequently interpreted into measurable indicators applicable to energy and power systems [64,84]. International policy frameworks formalised the stagewise preparation-absorption-recovery-adaptation cycle [85], while systems-oriented perspectives based on adaptive cycle theory introduced a further point that recovery involves structural reorganisation rather than just restoration to prior states; meaning resilience must accommodate transformation, not only bounce-back [86–88].

Building-focused research has translated these frameworks into domain specific fields spanning pre-event operation, disruption onset, deliberate stabilisation under degraded conditions, recovery, and redefinition of acceptable performance [53,81,89]. The common consensus across these works was that assessing resilience requires capturing both the magnitude and duration of performance loss. This includes not only whether a building eventually recovers, but also how far conditions deviate from the optimum and how long occupants are exposed before recovery occurs. Recent studies advocate therefore for integrated frameworks spanning pre-event preparedness, in-event degradation, exposure duration, recovery speed, and longer-term adaptation, particularly under climate change and conditions of unequal vulnerability [43,69].

5. Climate hazards, disruptive events, and building-scale energy resilience

5.1. Overview and Hazard taxonomy

Climate change is increasing the frequency, duration, and severity of climate extremes, exposing buildings and energy systems to growing stress. The literature identifies various climate stressors, but building-level analyses predominantly focus on overheating during heatwaves, with relatively fewer studies on cold spells, floods, or compound events, leading to a research bias toward heat-related hazards. These hazards increasingly occur simultaneously or have a cascading effect, for example, heatwave coinciding with blackout, or storm damage to buildings and grid followed by cold-weather outages, thereby generating compound risks that exceed the design assumptions present in codes, standards, and conventional building performance models [74,90]. From an energy-resilience perspective, climate hazards act through three pathways: demand amplification, supply disruption, and habitable conditions degradation, with the third pathway most directly threatening occupant health and life safety [87].

5.2. Heat-related events

5.2.1. Hazard characterisation and modelling practice

Heatwaves are the most extensively studied climate hazard in building-scale resilience research, reflecting their increasing frequency, intensity, and duration and their strong influence on peak energy demand [9,25,53]. In built environment studies, heatwaves are implemented through various modelling approaches: typical meteorological years with synthetic heatwave episodes, design heatwave files created for stress testing, and future climate projections (e.g., through weather

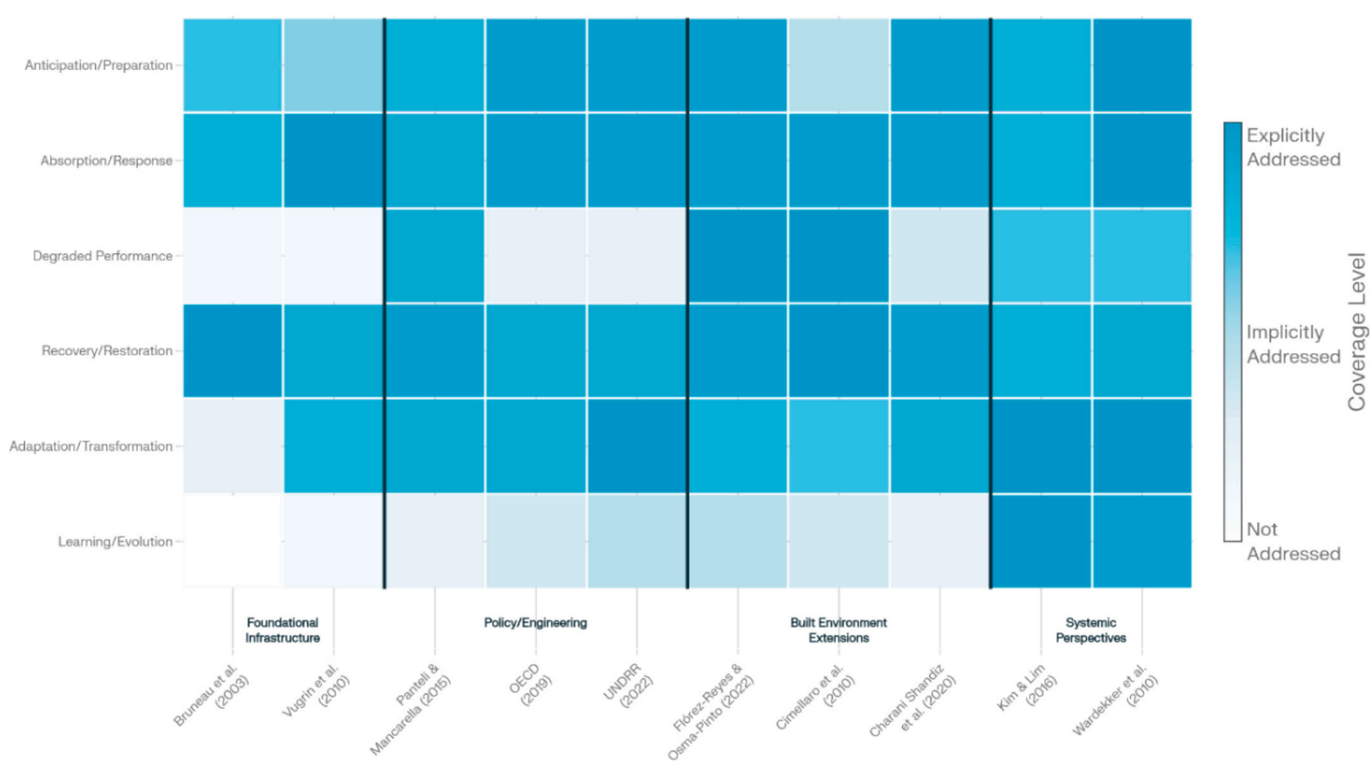

Fig. 8. Conceptual alignment of multi-stage resilience frameworks. Colour intensity indicates the degree to which each framework explicitly addresses each temporal stage, from anticipation through learning and evolution.

morphing methods) to assess the robustness of building envelope and cooling strategies under altered conditions [28,87,91].

Rather than relying on annual average metrics, recent studies evaluate building performance under discrete heatwave events, an approach grounded in the concepts of thermal resilience and resilient cooling and associated with IEA EBC Annex 80 and other international programmes [10,24,74]. These studies emphasise that resilience assessment must consider the time-based structure of heatwaves (their duration, sequencing, and intensity) together with humidity and solar conditions, and their interaction with system-level stressors.

5.2.2. Impact pathways, vulnerabilities and adaptive strategies

Heat-related events affect buildings through direct thermal loads and indirect system level interactions. High outdoor temperatures and solar gains raise indoor operative temperatures and cooling loads, extending periods above comfort or safety thresholds particularly in poorly shaded, or inadequately ventilated dwellings [92–94]. At the envelope level, low insulation, low thermal mass, and high solar exposure, especially from west and south-west facing glazing, or low-albedo roofs, result in rapid indoor heating during prolonged heatwaves [36]. Top floor and attics, small apartments with high internal gain-to-volume ratios, and highly glazed modern designs exhibit greater susceptibility [95,96]. Night-time heat retention prevents buildings from releasing accumulated internal gains, fast tracking cumulative overheating during multiday heatwaves, especially in densely built urban areas, lightweight structures and in rooms where cross-ventilation is constrained [94,97,98]. In addition, high ambient temperatures deteriorate transformers, reduce thermal plant efficiency, and can decrease PV output through module heating, thereby simultaneously increasing the demand while reducing the capacity to serve it [99].

At system level, simultaneous operation of air-conditioning (AC), mechanical ventilation, and fan during heatwaves produces sharp cooling demand peaks that stress distribution networks and increase the likelihood of grid overload or outages [100]. Operational vulnerabilities include strong reliance on active cooling, undersized or inefficient AC units, limited nighttime ventilation opportunities, and single point mechanical failures such as centralised cooling. Socially, elderly residents, chronically ill occupants, low-income and energy-insecure households, and populations in UHI intense districts are disproportionately vulnerable, and often already operate under cost-constrained comfort rationing that restricts their capacity to respond during emergencies [101–103].

Adaptive responses include passive strategies (e.g., shading, thermal mass, natural ventilation) and active measures such as efficient cooling, thermal storage, and PV systems with islanding capability. This is explained in more detail in Section 6. Studies in social housing contexts demonstrate that adaptive mixed-mode ventilation and targeted envelope retrofits can simultaneously reduce energy poverty indicators and improve summer thermal comfort, though poorly designed measures risk shifting costs onto already constrained tenants [27,104]. The equity constraints on access are addressed in Section 7.

5.2.3. Landmark events and lessons

Recent extreme heat events demonstrate how heatwaves simultaneously threaten life, decrease economic output, and expose weaknesses in buildings and energy systems. The 2003 European heatwave remains a historic case, causing more than 70,000 excess deaths across the continent and generating economic losses estimated around tens of billions of euros, including severe impacts on agriculture, health, transport, and energy systems [2]. An analysis of extreme temperature related catastrophic events in Europe over a thirty-year period (1988–2019), drawing on the Emergency Events Database (EM-DAT), found that heatwaves accounted for the vast majority of deaths from temperature-related disasters during that period. This pattern is consistent with the non-linear relationships between temperature deviation and excess mortality [1,79]. Continent level modelling across 1368 European regions projects that temperature-related mortality will increase substantially under continued warming, with the sharpest increases likely in southern and eastern regions where adaptive infrastructure is weakest [1].

In Western Canada, the 2021 heat dome over British Columbia led to a large spike in emergency department visits and hospital admissions concentrated among older adults and residents of socially disadvantaged areas, with investigations highlighting the vulnerability of housing stock in a region historically unaccustomed to such extremes [105]. Likewise, even in cold Nordic climates such as Helsinki, heatwaves have been linked to increase in respiratory morbidity among older adults [106]. Recent multi-year heat events in North America and Europe have demonstrated the same underlying pattern: buildings heavily reliant on active cooling, combined with grids operating near capacity, are susceptible to cascading failures under extreme heat.

5.3. Cold-related events

5.3.1. Hazard characterisation

Cold spells and extreme cold events are relatively underrepresented in the building energy resilience literature, yet they pose equally severe, and often acute risks to indoor thermal safety, particularly in cold and Arctic climates and in regions with high electrification rates. Cold-related hazards in building studies are typically defined as multi-day periods with outdoor temperatures below design minima or specified critical thresholds [8,42,107]. Guidance developed under programmes such as IEA EBC Annex 73, Annex 93 and related efforts on thermal energy system resilience in cold climates emphasises that design and assessment must explicitly account for emergency or degraded operation scenarios during extreme cold, in addition to normal comfort criteria. This includes the definition of acceptable indoor temperature ranges under emergency conditions, envelope and system performance targets to avoid freezing damage, and the specification of system redundancy to maintain basic functionality under design cold conditions [107,108].

In modelling practice, cold events are implemented using historical extreme winters and design-day sequences, synthetic cold-spell files inserted into typical meteorological years, and future climate projections that account for shifting extremes, with explicit outage scenarios to evaluate performance [8,103,109].

5.3.2. Impact pathways, vulnerabilities and adaptive strategies

Cold events stress buildings through two related pathways: increased heating demand when energy is available, and rapid under-heating when supply is interrupted. Synchronised winter peak demand strains electric networks and gas or district-heating systems, creating risk of cascading supply failure [8,42]. More critically for life safety, indoor temperature decay can be rapid during outages, driving indoor conditions below habitable thresholds within hours to a day under severe cold, as documented in older residential buildings in continental and Arctic climates [54,98,110].

Vulnerability during cold extremes is influenced by envelope performance, building typology, mechanical and control strategies, infrastructure exposure and social conditions. At the envelope level, low thermal resistance, air leakage and thermal bridges accelerate temperature decay and create condensation and freezing risks [41,44]. Lightweight constructions with minimal thermal mass exhibit the fastest decay once heating is lost, whereas higher thermal mass and ground coupling can buffer short-term fluctuations but lengthen recovery times without sufficient heating [54,98]. Top floor units, poorly insulated basements, unheated crawlspaces and geometries with high surface-area-to-volume ratios are more susceptible [111]. On the system side, single fuel dependence and lack of redundancy in heat sources, controls and circulation pumps increase risk; cold temperature derating of batteries and inverters reduces on-site backup effectiveness during exactly those conditions when it is most needed [112]. Freezing of domestic water pipes, fire sprinklers and hydronic loops introduces additional risks of infrastructure damage [113]. Socially, low-income households, renters in poorly maintained buildings, remote communities with long restoration times and medically vulnerable occupants face disproportionate risk; energy poverty and prepayment meter disconnections can trigger under-heating even in the absence of system outages [14,42].

Across cold-climate contexts, the building envelope (thermal resistance, airtightness, and thermal bridge control) consistently emerges as the dominant driver of passive survivability, with high-performance assemblies extending the period above critical habitability thresholds by hours to days. Redundant heat sources and backup strategies for active systems compound these envelope gains. The technical evidence on both passive and active cold-climate strategies, including the specific vulnerabilities of heat pumps and battery systems at low temperatures, is examined in full in Section 6.

5.3.3. Landmark events and lessons

Cold wave disasters remain significant in a warming climate and have direct relevance for building level energy resilience. Analysis of extreme temperature-related catastrophic events in Europe from 1988 to 2019 identifies cold events, alongside heatwaves, as repeated drivers of large mortalities, with the health impacts disproportionately concentrated among elderly populations and in housing stock with inadequate insulation or heating redundancy [1]. Grigorieva et.al.'s study on Alaska documents that extreme cold climates intersect acutely with social vulnerability, limited housing quality, and constrained energy access, creating conditions in which outages during cold events can threaten life safety within hours [42].

Cold events combined with energy system failures provide important lessons. The February 2021 "Great Texas Freeze" is one of the most extensively studied recent case. It led to widespread outages in electricity and gas supply, left millions of residents without power or heating for prolonged periods, and caused multi-billion dollar losses across energy, housing, and industrial sectors [4]. Analyses of it consistently highlight the lack of preparedness of infrastructure for cold winters, limited redundancy in heating systems, and building envelopes with relatively poor insulation or airtightness, all of which accelerated the indoor temperature decay once power supply was lost. More recent events, including sustained attacks on Ukraine's energy infrastructure since 2022, which reportedly disabled large fractions of the country's generation and heating capacity over multiple consecutive winters [5], and electricity shortages in Ecuador that have threatened continuity of health and critical social services [114], demonstrate the vulnerability of populations and buildings when centralised heating and power supply are disrupted for extended durations under cold conditions. These instances collectively reinforce the case for robust envelopes, local backup heating options, and district and building level thermal storages as essential components of cold climate energy resilience.

5.4. Hydrometeorological Hazards and other events

While thermal hazards, whether from extreme heat, extreme cold, or conflict-driven supply disruption, constitute the primary focus of building energy resilience research, hydrometeorological events interact with building systems through a distinct mechanism. Floods, storms, high winds, icing and wildfires also affect building energy resilience by acting as triggers of supply disruption and causing structural damage rather than through direct indoor thermal effects.

Building level flood studies characterise hazards through inundation depth, duration, and flow characteristics to estimate heating, cooling, and electrical system downtime, with the location of the equipment being the key design variable. Storms and wildfires feature more commonly in infrastructure level assessments, but they represent important boundary conditions for building energy resilience. For instance, facade and roof damage compromises airtightness and insulation, while distribution network failures cause outages that then interact with thermal stresses as described in sub-sections 5.2 and 5.3 [90,115]. Compound weather extremes that combine hydrometeorological & thermal stressors can exceed what is anticipated from either hazard in isolation and remain less represented in building level resilience frameworks. Existing literature suggests these hazards should be treated primarily as triggers of energy disruptions and constraints on recovery and to be combined with temperature related resilience analyses in multi-hazard scenarios.

Conceptual frameworks for resilient buildings and utilities stress that resilience must be defined against multi-hazard trajectories. There is also a lack of empirical and modelling research that specifically measures building performance in these situations; the majority of this research focuses on heatwave-blackout combinations, while cold outage scenarios are only now starting to get equivalent attention. [24,54,116]. Potential future work could include flood-induced displacement followed by heatwaves, wildfire smoke interactions with building ventilation strategies, and the compounding of cold extremes with long-duration grid failures.

The lack of compound hazard studies reflects several methodological barriers rather than a single cause. Standard building performance workflows are usually driven by Typical Meteorological Year (TMY) data or single-design extreme events, whereas compound hazards require temporally coherent sequences linking weather extremes with infrastructure failure, outage duration, and recovery. Such inputs are not readily available as standard datasets. In addition, building simulation tools commonly used in the field can represent indoor thermal response under altered weather and reduced HVAC availability, but cascading failures in electricity, gas, district heating, water, or communication systems often require ad-hoc coupling with infrastructure or power system models. Also, critical boundary conditions, such as outage onset, restoration sequence, partial service availability, occupant behaviour, and emergency ventilation choices, are rarely observed in detail during real events, limiting model validation. Compound hazards also often involve interacting thresholds (e.g., heat stress combined with loss of ventilation, or cold exposure combined with pipe freezing risk), making single-metric assessment inadequate. These challenges explain why compound event modelling remains limited despite its recognised importance.

Hydrological and meteorological hazards account for the majority of recorded weather and climate-related financial losses in most regions, including the EU, while extreme temperatures contribute a relatively smaller share of economic loss but a disproportionately large share of weather-related mortality [1,79,117]. This asymmetry points to thermal resilience as a critical life safety objective and supports the integration of hazard-informed planning of buildings and energy infrastructure.

6. Technical resilience measures

The reviewed literature consistently distinguishes building-scale technical resilience approaches into active and passive strategies. Passive strategies, whereby the building regulates indoor conditions through its envelope and material properties, are considered the first line of defence regardless of climate. Active measures, including on-site PV, wind turbines, hybrid microgrids, heat pumps, and electrical and thermal storage, provide a second line of defence focused on adaptive operation during outages and recovery following grid disturbances.

This two-tier paradigm applies equally to cold and hot climates, although the specific strategies differ substantially. In cold climates, the passive first line prioritises slowing heat loss and preventing freeze damage during heating outages, while the active second line focuses on backup heating capacity, heat pump winterisation, and thermal storage. In contrast, in hot climates, passive strategies emphasise limiting heat gains and improving natural ventilation, while active measures focus on resilient cooling systems, backup power for air conditioning, and thermal storage to maintain indoor comfort during outages. Together, these measures improve habitability and survivability during extreme weather events by reducing dependence on the grid and maintaining tolerable indoor conditions during power outages. Frequency data in this section are derived from the literature base of 176 papers. Specific technology performance data are contextualised using supplementary technical literature identified through citation tracking (Section 2.2).

6.1. Passive strategies

Across the reviewed articles, passive approaches such as building design and retrofitting account for a significant share of identified strategies (19.9% and 30.8% respectively), while renewable generation (11.8%) and storage (7.2%) are also widely integrated. The remaining studies emphasise policy, behavioural and system-level measures. Fig. 9 summarises the distribution of resilience enhancement strategies across studies, indicating the prevalence of passive envelope measures and the comparatively minor share of active renewable and storage solutions. This is consistent with existing guidelines that couple passive survivability at the building level with grid-interactive active systems.

In the built environment, orientation and bioclimatic design are widely recognised as foundational passive measures for resilience. Suitable orientation can maximise solar gains and daylight in cold climates while enabling structures that minimise heat gain in hot climates through compact form and mutual shading, thereby reducing heating and cooling loads and improving energy resilience [118,119]. Envelope design variables have been studied in simulation studies to evaluate their impact on both energy use and resilience under extreme climate scenarios, with parametric analyses demonstrating how they influence energy flexibility and resilience metrics [120,121]. Beyond new construction, envelope retrofitting of external walls, windows, and ventilation systems is shown to improve indoor thermal stability during blackouts, reduce space heating and cooling demand, and enhance resilience under extreme weather. Measures such as expanded polystyrene insulation have been found to lower energy use while moderating indoor temperature fluctuations [122].

Several envelope technologies further reinforce this first line role by directly targeting solar and environmental loads. Cool envelope materials, roofing and wall products with high solar reflectance and thermal emittance, such as white membranes, cool-coloured tiles and reflective coatings, reduce radiative heat gains, lower roof and wall surface temperatures, and decrease cooling demand [123,124]. Advanced glazing technologies including static high performance glazing, smart dynamic systems, and PV-integrated glazing further regulate solar heat gains and daylight; standards and experimental studies emphasise the importance

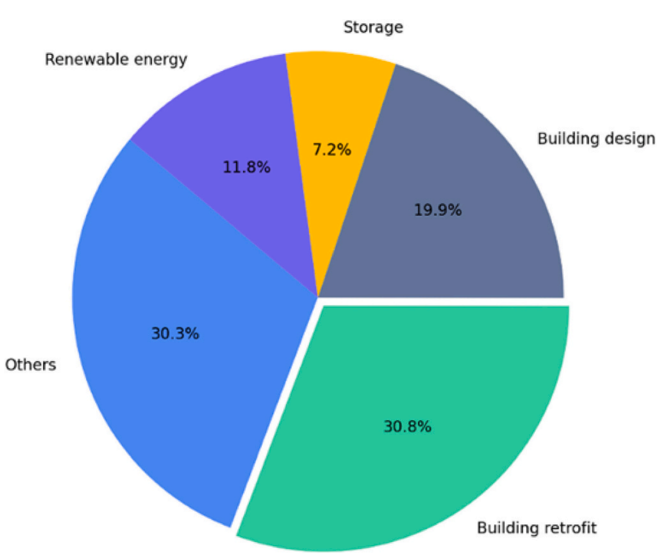

Fig. 9. Distribution of resilience enhancement strategies across the reviewed studies (frequency-weighted).

of climate, orientation, shading interactions, and occupant behaviour in assessing their contribution to resilience [125–127]. Double-skin or ventilated facades have proven to continue providing cooling during heatwaves even in the absence of grid power [128,129].

Nature-based and low energy cooling strategies complement these envelope measures. Green roofs and facades reduce roof and wall temperatures, mitigate UHI effect, regulate stormwater, and maintain cooler building surfaces during heatwaves and droughts [130,131]. Evaporative cooling utilises the latent heat of water vaporisation to provide low energy cooling that is particularly effective in hot, dry conditions, and can be coupled with PV or battery systems to remain operable during outages, thereby offering resilience to extreme heat and electricity interruptions [132]. Ventilative cooling strategies are also highlighted as robust, low energy options for reducing cooling loads and maintaining comfort. Natural night ventilation, in particular, is recognised as an energy free and outage resilient mechanism for discharging stored heat in buildings [133].

In cold climates, the passive strategy order shifts substantially. Thermal resistance, airtightness, and thermal bridging control are influential, as they directly regulate the rate of indoor temperature decay during heating outages. Traditional and vernacular building forms in cold regions demonstrate this logic architecturally. An evaluation of Zhuangke dwellings in China's severe cold zone, shows that thick masonry walls, south-facing orientation for passive solar gain, and compact form collectively reduce heating demand while extending passive survivability during supply interruptions [41]. Field surveys similarly confirm that locally adapted construction practices, including heavy thermal mass, small window-to-wall ratios on north-facing facades, and draught-proofing strategies, improve indoor thermal conditions and reduce occupant health risk during cold snaps [134]. A comparative simulation study of single-family housing under both extreme heat and extreme cold conditions shows that the envelope measures that most extend passive survivability differ between seasons. Insulation level dominates cold-season outcomes, while solar shading and thermal mass together dominate hot-season outcomes, meaning that designs optimised for a single season underperform on the other [7]. This seasonal asymmetry is confirmed by studies of passive and low-energy strategies for bedroom thermal comfort during both heatwaves and cold snaps [98]. Existing retrofit programmes almost exclusively target winter heating efficiency, systematically overlooking the summer overheating risk that climate change is introducing, creating a potential future conflict between cold-climate resilience and hot-season survivability that current standards do not yet address [8].

Taken together, these passive measures build a resilient envelope and design "backbone" that reduces demand, enhances passive survivability, and provides the conditions under which active systems can operate more effectively.

6.2. Active strategies

Complementing this passive backbone, active measures are framed as mechanisms for adaptive operation under constrained conditions and for accelerating recovery after disruptive events. Microgrids are widely proposed to improve reliability and resilience of buildings and communities [135,136]. In the context of resilience, they are configured to prioritise critical loads and allow reconfiguration according to load priorities and sectoral needs. For example, hospital microgrids are designed with redundancy and recovery objectives to maintain essential medical equipment during blackouts, whereas residential microgrids emphasise cost optimisation and flexibility [137,138]. Microgrids are therefore understood as combinations of renewable generation and storage capable of off-grid operation to supply essential energy services during outages.

On-site renewable generation, particularly PV, acts as an important resource in such microgrids. Building-scale studies indicate that PV can provide uninterrupted energy to meet critical building demands during extreme weather and blackouts, thereby sustaining habitability. Homaei et al. report that PV-based heating improved resilience by 50 degree-hours in cold conditions, although their analysis excluded appliance loads [139]. Gupta et al. analyse PV-battery systems in Oxford, United Kingdom, showing that PV can meet daily household demands in summer, while community-level battery sharing improves self-consumption and economic performance [140]. Survey-based work by Kotani et al. in Japan highlights user knowledge as a major barrier to realising PV benefits in standalone mode during blackouts, underscoring the need for education and training [141]. At larger scales, Lagrange et al. demonstrate that a renewable-based hospital microgrid can extend minimum outage resilience by over 34 h while delivering substantial life-cycle cost savings [142]. Yet the resilience potential of building-integrated PV (BIPV) in standalone or islanded applications remains underexplored, suggesting a need for future work in this field.

Cold climate contexts introduce specific requirements for active resilience measures that are largely absent from the hot climate literature. The core challenge is that the active systems most relevant to cold-climate resilience are themselves vulnerable to the conditions they are deployed to address: air-source heat pump output decreases at very low temperatures, battery and inverter performance is derated in cold conditions, and district heating networks can experience supply temperature drift and pump or substation failures during extended cold events [8,19]. This creates a conundrum: the buildings most exposed to cold-outage risk are often those where the active backup systems are also least reliable. Simulation studies of residential building stock under winter outage scenarios show that hybrid heating configurations (combining a primary heat pump with a secondary non-electric heat source) substantially extend the period above critical habitability thresholds [143]. At the system level, NREL's analysis of the US residential building stock demonstrates that the combination of envelope upgrades and on-site storage provides the greatest cold-season resilience co-benefit, with thermally massive well-insulated envelopes reducing the active heating power required to bridge an outage and therefore extending the duration that a given battery capacity can sustain habitable conditions [143]. These findings reinforce the conclusion that cold-climate active resilience cannot be designed as a simple extension of the hot-climate active resilience toolkit. It requires consideration of heating source redundancy, low-temperature system performance, and the interaction between storage capacity and envelope thermal inertia.

Other renewable and hybrid energy systems diversify the active resilience measures. Wind turbines can serve as complementary generation source at district or campus scale. Sepúlveda-Mora and Hegedus show that hybrid microgrids combining PV, wind, batteries and generators can raise resilience indices by up to 40% in commercial buildings and enable survival of multi-day outages [144]. Azerefegn et al. report that integrating PV/wind into unreliable grid-diesel systems for Ethiopian industrial parks yields cost-effective configurations and up to 45% CO_2 reductions while improving power reliability during outages [145]. Ground-source heat pumps (GSHPs) and geothermal systems utilise stable ground temperatures to provide efficient heating and cooling, reduce peak electricity demand, and improve grid resilience [146,147]. Hybrid concepts that couple geothermal heat dissipation with PCM 'cool batteries' in ceilings have shown substantial reductions in discomfort hours during power cuts in extremely hot climates [148].

Finally, energy storage emerges as a central technology for active resilience. Storage is used to buffer mismatches between supply and demand, charging during normal operation and discharging during outages to maintain habitable indoor conditions [149]. Stationary electrical storage supports both grid flexibility and building-level resilience due to high efficiency, fast response and high energy density. Studies of integrated energy systems show that adding storage can maintain critical loads and reduce service losses across electricity, heating and cooling in failure scenarios [150,151].

6.3. Resilience-specific technical mechanisms

The strategies discussed in Sections 6.1& 6.2 are frequently described in the literature in general design terms (e.g., "adding insulation," "installing PV") without specifying the mechanism by which it functions differently under resilience conditions than under normal conditions. Nevertheless, several studies reveal resilience specific mechanisms that are distinct from their efficiency-focused counterparts.

Thermal mass and envelope sizing under outage conditions: Unlike conventional envelope design, which is primarily evaluated in terms of annual heating and cooling demand reduction, resilience-oriented design is evaluated by the ability of the building to maintain acceptable indoor temperatures during service disruptions. Studies show that this distinction often creates a design trade-off rather than a uniformly positive effect. Increased airtightness improves passive survivability during cold-weather outages by slowing heat loss but can worsen hot-weather outage outcomes by trapping internal and solar heat gains once mechanical cooling is unavailable. Consequently, cold- and hot-hazard resilience cannot always be optimised through a single envelope specification [54]. This trade-off is hazard-specific: airtightness improvements are consistently beneficial under cold-dominated conditions, whereas locations exposed to both cold and heat hazards require explicit joint evaluation of both outage scenarios rather than reliance on a single airtightness target.

Distributed generation and storage sizing/control logic: Unlike conventional sizing approaches that optimise economic performance (e.g., levelised energy cost or self-consumption), resilience-oriented PV-battery and microgrid design prioritises autonomy duration and the continuity of critical loads during islanded operation. Studies report autonomy durations ranging from several hours to more than 34 h, depending on system size, load definition (critical-only versus whole-building supply), and dispatch strategy. Load-shedding hierarchies, critical-circuit prioritisation, and controllable backup loads emerge as important resilience-specific design variables that differ from conventional demand-response control approaches. Improving building efficiency can substantially reduce the backup power capacity required to achieve a given resilience target. [140–142]. One study reported a 19% reduction in required backup power capacity during a three day cold-snap scenario when efficiency measures were combined with the building's baseline energy system [54]. This finding suggests that resilience-oriented sizing is best treated as a joint building design problem rather than solely as an exercise in adding storage or generation capacity. Reported autonomy durations are also strongly dependent on local solar resource availability and seasonal insolation and consequently, identical PV-battery configurations provide different outage coverage in a high-latitude winter outage than in lower-latitude regions with greater solar availability, although sensitivity to this factor is rarely examined explicitly in literature.

Natural and mixed-mode ventilation as a resilience-specific pathway: During a power outage, natural ventilation represents one of the few cooling strategies capable of functioning without reliance on external energy supply. Its resilience value therefore extends beyond its conventional role as a cooling-energy reduction measure during normal operation. Natural ventilation has been identified as an effective strategy for limiting indoor overheating during summer outage conditions by promoting passive heat removal when mechanical cooling is unavailable [54]. These findings reinforce the broader efficiency vs resilience trade-off identified in this work. Envelope airtightness requirements associated with current NZEB standards are optimised primarily for normal-operation energy performance and inadvertently constrain this outage-specific cooling pathway. The effectiveness of natural ventilation is strongly dependent on climatic and environmental conditions. Its benefits are greatest when outdoor conditions permit effective heat rejection, particularly during cooler nighttime periods. Where outdoor temperatures remain persistently high throughout an outage event, the potential of natural ventilation to mitigate indoor overheating is correspondingly reduced. As a result, natural ventilation cannot be assumed to constitute a universally effective resilience measure and requires climate-specific evaluation within outage resilience assessments.

Across all three mechanisms, resilience-specific performance is disproportionately reported through simulation rather than field validation and evaluated against a single reference occupant or building configuration in the majority of cases (Section 7). The mechanisms described above should therefore be read as simulation-derived and context-specific rather than as generalisable performance guarantees. This methodological limitation is examined in more detail below and later in Limitations (Section 11).

6.4. Methodological approaches to resilience evaluation

The technical measures discussed above are evaluated using different methodological approaches, which vary in both their ability to generalise findings and their degree of proximity to field validation. Building performance simulation using physics-based tools (e.g., EnergyPlus, TRNSYS, IES-VE, and comparable whole-building energy models) remains the most common approach for quantifying passive survivability and technical resilience performance, accounting for the majority of the 26 simulation-based studies identified in this review (Section 4). These tools represent heat transfer, infiltration, and system operation explicitly, enabling comparisons of design variants under identical disruptive events, but rarely incorporate stochastic or probabilistic weather generation, and are validated against measured field data in only a minority of cases.

Unlike physics-based simulation studies, a smaller subset of the literature applies data-driven or machine-learning methods to predict occupant risk, vulnerability, or demand-response patterns from empirical datasets (e.g., [46] applying machine learning to predict household cold-wave risk). These approaches represent the methodological frontier of the field. They are the most recently emerging and the least represented in the current corpus, but they trade physical interpretability for pattern-recognition capacity and are currently applied almost exclusively to risk prediction rather than resilience-strategy evaluation itself. This suggests a disconnect between the field's predictive and design-evaluation methodologies that receives little explicit attention in the literature.

Field-monitored and experimental studies are the least represented methodological category in the reviewed literature. Consequently, many of the performance estimates discussed in Sections 6.1 and 6.2, including PV-battery autonomy duration and envelope retrofit benefits, are derived primarily from simulation rather than observation under real disruptive events. This highlights a continuing need for field validation alongside increasingly sophisticated modelling approaches.

Across the simulation and experimental studies summarised in Table A2, both passive envelope and active measures function by extending the duration over which buildings maintain acceptable indoor conditions during outages. Passive measures primarily delay the onset of unsafe conditions, while active systems sustain operation beyond the passive survivability limit. This merging in mechanism is observed across climates, building types, and hazard conditions, indicating that extension of the survivability duration is the unifying functional outcome of resilience-enhancing interventions.

The technical evidence discussed above establishes that the engineering solutions for building energy resilience are available, scalable, and commercially mature. However, it does not address the distributional dimension of their benefits. Measures such as passive envelope upgrades, PV + BESS systems, and community microgrids require capital investment, building ownership or long-term tenure, and access to physical infrastructure, all of which are unevenly distributed across populations. The following section therefore examines whether the buildings and occupants with the greatest resilience needs are also those for whom these technically established solutions are most accessible.

7. Equity constraints on technical resilience performance

7.1. Thermal Exposure and Health

Energy resilience outcomes are unequally distributed, with low-income households, elderly populations, chronically ill occupants, and marginalised communities experiencing disproportionate exposure to thermal stress, service disruptions, and recovery burdens during power outages and climate-related hazards. Recent research increasingly reframes energy resilience not only as a technical system property, but as a socio-technical and justice relevant concept, intersecting with energy poverty, adaptive capacity, and long-lasting spatial inequities in housing quality and infrastructure investment [68,69,152]. In England, Rizmie et al. show that extreme hot and cold days substantially increase emergency hospital admissions, with the steepest risk among older adults and residents of the most deprived neighbourhoods, emphasising how socio-economic deprivation amplifies temperature related health burdens [57]. Similar patterns emerge in Australia, where Li et al. find that the probability of energy hardship rises sharply during both extreme heat and cold events, particularly for renters and low-income households [153].

An underlying theme in health and building performance research is the strong coupling between indoor thermal conditions during disruptions and adverse health outcomes. Epidemiological evidence shows that a 1 °C increase above local historical temperature baselines is associated with a 1–4% rise in all-cause mortality, while elderly individuals and those with cardiovascular, respiratory, or metabolic conditions experience risk multipliers of approximately 2-10× [15,16]. Cold exposure below 15 °C is independently associated with higher rates of cardiovascular events, respiratory infections, and excess winter mortality, particularly where outages coincide with inadequate insulation and heating system failure [154–156]. High-burden neighbourhoods often experience systematically warmer indoor and outdoor conditions, by approximately 0.5–2 °C, due to UHI effects, envelope inefficiencies, and constrained adaptive behaviours [97,101,157].

Within cities, sharp spatial gradients in heat risk are closely linked to housing stock and urban form. In London, Cole et al. demonstrate systemic inequalities in heat risk, where hotter microclimates, older inefficient housing, and higher concentrations of socially vulnerable residents overlap in specific districts [158]. A district-scale analysis in Milan by Zendeli et al. similarly shows that cardiovascular and respiratory emergency calls during heat events cluster in high-density and socioeconomically disadvantaged neighbourhoods [159]. Empirical studies from southern Finland demonstrate that extreme heat can translate into adverse health outcomes even in cold climates, especially for older age groups, with respiratory impacts observed and cardiovascular effects reported [106].

7.2. Cascading impacts beyond thermal exposure

Beyond direct thermal exposure, disruptions trigger cascading health impacts that extend well beyond comfort metrics. Loss of refrigeration and cooking capacity compromises food safety; water and sanitation interruptions result in increased infectious disease risks; and power-dependent medical devices, including dialysis equipment and ventilators, become unreliable or unusable during prolonged outages. Simulation studies of assisted living facilities confirm that compound events push indoor temperatures beyond safe thresholds within hours, with recovery times extending well beyond the duration of the outage itself [54]. Large-scale events repeatedly illustrate these dynamics: the 2003 European heatwave (>70,000 excess deaths), the 2021 Texas winter storm (>180 direct and indirect fatalities), and the 2021 British Columbia heatwave, during which Clark et al. report large spikes in emergency department visits concentrated among older adults and socially disadvantaged residents [2,4,105]. In the Caribbean, Méndez Lázaro et al. quantify how compound heat-humidity events in Puerto

Rico between 2015 and 2020 were associated with increased mortality, particularly in coastal and urban regions with constrained access to cooling and healthcare [160]. Resilience assessment frameworks rarely integrate such health-linked thresholds explicitly, despite evidence that risk escalates non-linearly with outage duration and temperature deviation.

7.3. Barriers to resilience upgrading

Equity considerations act as a constant barrier to effective resilience upgrading. Low-income households face restrictions preventing investment in PV, battery storage, envelope retrofits, or backup systems, while simultaneously bearing the highest relative economic and health costs of outages. Modelling of residential energy burdens in the United States projects that climate-driven increases in heating and cooling demand will widen this gap further, with low-income and minority households facing the sharpest absolute increases in energy expenditure relative to income [161]. Resilience policies that rely on voluntary adoption or market-driven incentives (such as rebates, tax credits, green mortgages) have consistently been shown to reinforce rather than reduce these disparities, as uptake concentrates in households with the financial headroom and ownership status to act [162]. This risk is compounded by demographic trajectories. Projections across global cities show that the intersection of population ageing and rising heatwave frequency will produce rapidly expanding clusters of compound vulnerability, concentrated in neighbourhoods already lacking sufficient resilience investment [163].

Studies on overheating, climate justice and health consistently show that disadvantaged groups live in poorer quality housing and have fewer resources to adapt, resulting in higher exposure to heat and cold and limited access to effective retrofit measures [15]. Work on natural ventilation in warm climates highlights that many building stocks still depend on passive or low-cost strategies whose performance can be inadequate during heatwaves, especially where energy poverty constrains the use of mechanical cooling. These economic and social stressors directly condition both the ability to implement resilient building measures and the level of vulnerability to energy-related disruptions.

Building-level adaptation can yield substantial health and equity co-benefits when designed with vulnerable occupants in mind. Williams et al. show that envelope upgrades, shading, and efficient mechanical systems can simultaneously reduce indoor heat stress, mortality risk, and greenhouse gas emissions, with the largest relative benefits for low-income households in thermally poor housing, but only when interventions are designed with those households as the explicit target [22]. In social housing in Spain, Bienvenido-Huertas et al. [164] and Alba Rodríguez et al. [165] demonstrate that adaptive mixed-mode ventilation and targeted retrofits can reduce energy poverty indicators while improving summer comfort, though poorly designed retrofits or tariff structures risk shifting costs onto already constrained tenants through rent increases or maintenance obligations.

7.4. Behavioural constraints and limits of adaptive capacity

Occupant behaviour under disruption is a critical but underrepresented dimension of resilience assessment. This has been acknowledged in social science papers, but rarely in simulation studies. Households adapt by reducing thermostat setpoints, changing window and shading practices, shifting appliance use, or clustering occupancy within limited heated or cooled zones when outages are anticipated. However, many low-income households already operate at the threshold of affordable thermal comfort due to financial constraints, a concept identified in the literature as 'comfort rationing', whereby heating or cooling is curtailed to mitigate energy expenditures [166]. There is little to no residual adaptive capacity during emergencies.

Qualitative work in Hong Kong by Lai et al. similarly finds that many low-income older adults already undercool their homes for cost reasons [167]. In Accra, Boafo et al. document how residents of informal dwellings and crowded tenements recognise intensifying heat yet report severely constrained action, with limited access to effective cooling and disconnected knowledge of institutional support [168]. Social cohesion and community networks are repeatedly identified as informal resilience assets facilitating resource sharing and mutual aid, while social isolation worsens vulnerability, particularly among elderly residents and single-occupant households [114,169]. The most severe impacts often fall on those already at the margins of the housing system. Gabbe et al. show that unsheltered people experiencing homelessness face extreme heat exposure with very limited access to shade, water, and indoor cooling, and that existing plans and building-based interventions rarely address this [170].

7.5. Mental health, social cohesion and long-term consequences

The health consequences of energy disruptions extend beyond the acute physiological impacts of thermal exposure documented in the preceding section, extending into psychological wellbeing, social functioning, and long-term economic trajectories that standard building performance metrics do not capture. Psychological impacts, including stress, anxiety, and post-traumatic stress symptoms linked to evacuation, prolonged displacement, or repeated exposure, are documented across public health and social science journals but are rarely integrated into engineering-oriented resilience metrics [171–173]. An observational study in China finds that older adults exposed to extreme weather events report worsened mental health, particularly where social support and indoor environmental quality are poor [38]. Other clinical works link higher temperatures and heatwaves with increased risk of anxiety, depression, and aggravation of severe mental illness [174,175]. Sector-specific examples, including disruption of childhood immunisation coverage during heatwaves in Pakistan [176] and threats to health system continuity from electricity shortages in Ecuador [114], further demonstrate how extreme temperatures and outages jointly undermine core social services. Indirect economic losses encompassing reduced productivity, supply chain disruptions, healthcare expenditures, temporary relocation, and long-term mental health costs are substantial but remain inconsistently quantified.

7.6. Pathways linking climate, building physics, and equity

The preceding sections report climate hazard characteristics, technical resilience measures, and equity-differentiated outcomes largely as parallel findings. However, these dimensions interact systematically rather than independently. Examining these interactions explicitly clarifies how climate context and building physics jointly shape resilience risks across population groups and consequently influence the relevance of different metrics and resilience strategies.

In cold climate outages, the primary physical mechanism is indoor temperature decay following heating system failure, whose rate is determined by envelope thermal resistance and airtightness (Section 6.1). Because older and lower-income housing stock disproportionately exhibits poor insulation and limited heating system redundancy (Section 7.1, 7.3), this population experiences faster and more severe temperature decay under an otherwise identical outage event. This mechanism has a direct metric implication: indicators that capture indoor temperature decay (e.g., Robustness Threshold Duration and Hours of Safety) are particularly relevant for assessing vulnerability because the rate of decay is the key factor differentiating resilient and non-resilient housing stock (Section 8).

In heat-related outages, the governing mechanism instead runs through mechanical dependency. Highly airtight, mechanically cooled buildings lose the capacity to leak heat once power is interrupted, a vulnerability largely absent in buildings retaining natural or mixed-mode ventilation pathways. Because renters and low-income owner-occupiers are constrained from installing either backup cooling or ventilation retrofits (Section 7.3), this translates into increased risk for this population. This mechanism motivates the solution-packaging guidance in Step 6 (Section 9): natural ventilation retention should be prioritised specifically for building stock occupied by populations least able to afford active-system backup, since the technical intervention and the associated equity gap are intrinsically linked rather than independently determined.

Compound hazards illustrate a third, distinct mechanism: interaction rather than simple co-occurrence. When thermal exposure and equipment or power failures occur simultaneously, risks to medically power-dependent and socially isolated occupants increase disproportionately because thermal deterioration reduces the available response window, while the absence of nearby support independently delays detection and intervention (Section 7.5). Neither factor alone fully accounts for the elevated risk observed in these populations. Instead, the elevated risk emerges from the interaction between these factors. This helps explain why the lack of compound hazard studies identified in Section 5.4 represents more than a gap in hazard coverage. It limits the evidence available to assess equity outcomes under the conditions where vulnerability be greatest. It also motivates the recommendation in Step 5 of the six-step framework (Section 9) to report resilience indicators for both standard and vulnerable occupant profiles. Similarly, design strategy prioritisation cannot be equity-neutral, since retrofit prioritisation based solely on energy savings fail to identify housing stock occupied by the populations most vulnerable to disruption-related harms.

Across the building-focused literature, socio-economic and health determinants of thermal risk are widely acknowledged but inconsistently operationalised in quantitative resilience models. Occupant behaviour is represented almost universally as a binary or archetypal schedule rather than as a spectrum shaped by economy and culture that empirical evidence describes. Health risk is quantified through heterogeneous indicators, clinical indoor temperature limits, comfort indices, and proxy outcomes such as hospital admissions, without standardised thresholds or systematic control. Formal survivability metrics appear in only a small subset of the literature, while vulnerable groups are typically modelled as static demographic categories rather than as people with differing physiological baselines, care access, and behavioural constraints. Physical performance metrics must therefore be complemented by social vulnerability indicators, if resilience assessment is to reflect the unequal lived experience of disruptions that this review documents. These limitations point to the importance of how resilience is defined and measured in practice. The following section therefore examines the range of metrics and performance indicators used across the literature.

8. Metrics and performance indicators

The review identified 29 distinct metrics in use across the included literature for quantifying building-scale energy resilience (Table A3, Appendix). Unlike conventional building performance assessment, which operates from a compact set of standardised indicators such as annual energy use intensity or peak demand, resilience assessment draws from five disciplinary traditions: structural engineering (robustness and performance-curve indices), building physics (degree-hour metrics, thermal autonomy), systems engineering (self-sustainment duration, energy deficit), epidemiology (Heat Index dangerous hours, Wet-Bulb Globe Temperature thresholds), and financial risk theory (Conditional Value at Risk). The absence of a singular framework results in a fragmented metric landscape, reflecting the definitional division identified in Section 4.

The 29 metrics are organised into six functional categories, summarised in Table 2: (i) thermal survivability metrics, which quantify the duration and magnitude of indoor temperature deviation below or above habitability thresholds during outages (e.g. Passive Habitability Duration/Hours of Safety, PHD/HoS; Unmet Degree-Hours, UDH; Indoor Overheating Degree-Hours, IOD); (ii) resilience performance-curve indices, which integrate the area under the performance-loss trajectory across the disruption timeline (e.g. Thermal Resilience Index, TRI; event-based resilience ratio, R_event); (iii) decay and robustness metrics, which characterise the rate and onset of performance degradation (e.g. Robustness Threshold Duration, RT; Collapse Speed, CS); (iv) thermal comfort and exposure metrics, calibrated against physiological thresholds rather than fixed temperature limits (e.g. Standard Effective Temperature Degree-Hours, SET-DH; Wet-Bulb Globe Temperature, WBGT; Heat Index Dangerous Hours, HI-DH); (v) energy autonomy metrics, which quantify the electrical self-sufficiency of buildings or districts under constrained supply (e.g. Self-Sustainment Duration, SSD; Energy Deficit, E_def; critical-load coverage ratio); and (vi) composite or multi-phase metrics, which attempt to integrate across phases, hazard levels, or spatial zones (e.g. Weighted Unmet Thermal Performance, WUMTP; Thermal Autonomy, TA; Building Climate Vulnerability Factor, BCVF/aIOD). It is important to note that not all catalogued indicators measure energy-service continuity directly. Thermal comfort and exposure metrics (category iv) quantify the physiological consequences of thermal stress during a disruption rather than the performance of the building or energy system itself. They are included because the literature frequently uses these outcomes to evaluate the effectiveness of resilience interventions.

These metrics differ not only in terminology but also in the aspect of resilience they capture. Time-to-threshold indicators (e.g., PHD, HoS, RT) quantify the duration of protection before a predefined habitability or performance threshold is exceeded. Degree-hour metrics (e.g., IOD, UDH, SET-DH) capture both the intensity and duration of thermal stress and are therefore sensitive to prolonged exposure. Performance-curve

Table 2
Summary of six categories of indicators used in the literature to assess building energy resilience and its physiological consequences, including both energy-service-continuity metrics and thermal comfort/health-risk outcome indicators used as resilience proxies. Metric definitions, formulas, interpretation are provided in Table A3.

Category	Representative metrics	Resilience phase coverage	Applicable hazard types	Key limitation
Thermal survivability	PHD / HoS; UDH; IOD	Absorption; Degradation; Recovery *(Anticipation/adaptation not covered)*	Heat; Cold; Power outage	Single-building; fixed occupant profile; no equity weighting; cold-climate variants less standardised
Performance-curve indices	TRI; R_event; RI	Absorption; Degradation; Recovery *(Anticipation/adaptation not covered)*	Heat; Cold; Power outage; Compound	Requires full trajectory data; TRI / R_event equivalence unrecognised
Decay and robustness	RT; CS; PHD	Absorption; Degradation only	Cold; Power outage	Cold-focused; no recovery dynamics; limited applicability to heat contexts
Comfort and exposure	WBGT; HI-DH; HoE; CvaR; SET-DH	Degradation; Absorption only	Heat; Compound	Heat-dominated; climate-dependent calibration; limited cold-climate use
Energy autonomy	SSD; E_def; CLCov; IAT; FR	Absorption; Recovery	Power outage; Compound	Electrical-only; must be combined with thermal metrics; no affordability dimension
Composite / multi-phase	WUMTP; TA; BCVF / aIOD	Absorption; Degradation; Recovery; Adaptation *(no anticipation)*	Heat; Cold; Power outage; Compound	No standard weighting; equivalence unrecognised; no equity weighting

metrics (e.g., TRI, R_event) characterise the degradation and recovery trajectory over the disruption period, while energy-autonomy metrics (e.g., SSD, E_def) evaluate the capacity to maintain critical services under constrained energy supply. These metric groups are complementary rather than interchangeable, and metric selection should reflect the hazard under study, the building and occupant characteristics, and the intended assessment objective, whether life safety, thermal comfort, system autonomy, or recovery performance.

A methodologically important finding from the metric catalogue is that several indicators used under different labels are, in practice, the same calculation applied to the same underlying time series, but with different names and sometimes slightly different boundary assumptions. Performance-curve indices such as the Thermal Resilience Index (TRI) and the event-based resilience ratio (R_event) both represent the time-averaged area under a normalised performance curve over a defined disruption window and are therefore functionally identical when they use the same performance definition and event duration (see Appendix below for a formal derivation and the boundary conditions under which this equivalence holds). Similarly, the adjusted Indoor Overheating Degree metric (aIOD) and the Building Climate Vulnerability Factor (BCVF) both express the ratio between indoor overheating and outdoor heat exposure and reduce to the same quantity when computed over matching hours, thresholds, and climate periods. Under shared input definitions, the climate-sensitivity metric CT describes the same underlying relationship, framed explicitly as a response to outdoor warming.

These unrecognised equivalences mean that studies labelled with different metric names can be generating numerically comparable outputs, while nominally similar assessments, such as LEED IPpc100 versus IOD/BCVF-based approaches, are not directly comparable due to differences in integration windows, thermal indices and threshold definitions. This redundancy reduces the effective diversity of the metric landscape and increases the apparent methodological diversity reported in the literature. Mapping these categories against the temporal resilience phases discussed in Section 4 reveals a systematic gap: absorption-phase and degradation-phase metrics are well represented, while no validated metric exists for the anticipation or learning phases. This asymmetry mirrors the gap identified in Fig. 7 that characterises the literature as a whole.

Three operationally grounded metric combinations emerge from the taxonomy. For cold-climate outage resilience, the combination of RT, PHD/HoS, CS, and UDH jointly characterises how long the safety margin persists, how fast conditions deteriorate, and how far indoor temperatures fall below critical thresholds. For heatwave resilience and chronic climate-change sensitivity, IOD, aIOD/BCVF, Hours of Exceedance, and HI-DH constitute the most widely applied set, with WBGT recommended as the physiologically rigorous complement in high-humidity contexts where dry-bulb temperature alone understates heat strain. For buildings with distributed generation and storage, SSD and E_def provide the energy-side counterparts to thermal survivability metrics, together defining the autonomous operation envelope.

These combinations differ in their underlying mechanisms rather than simply in nomenclature. RT and PHD/HoS quantify how long passive protection persists before robustness and habitability thresholds are crossed, whereas UDH captures cumulative severity, expressed as degree-hours outside the acceptable range, and is therefore sensitive to outage duration but less sensitive to the rate of onset. CS directly captures the rate of indoor thermal deterioration and is therefore more informative where early warning, shelter-in-place, or evacuation windows are the design concern. PHD/HoS is particularly useful for safety or code-oriented interpretation, but comparative ranking is strengthened when it is reported alongside degradation rate and cumulative-severity indicators.

In an analysis of Nordic single-family houses, Rehman et al. show that an old, low-insulation building without PV or batteries crosses the robustness threshold after 1 h and the habitability threshold after 9 h, whereas a new, low-infiltration building without on-site renewables remains habitable for the full 30-h outage and only crosses the robustness threshold after 8 h. Integrating rooftop PV and batteries extends robustness and habitability to 30 h in both buildings: for the new building this reduces CS and DoD to zero, while for the old building CS and DoD are substantially but not fully reduced (to 0.231 °C/h and 0.15, respectively, from 0.381 °C/h and 0.372) [177]. This illustrates that RT and DoD distinguish clearly between envelope and storage configurations even though they do not, on their own, capture the shape of the degradation curve that CS is designed to detect. Reporting only one metric type therefore risks obscuring part of the picture. In an assisted living facility in Houston, Sheng et al. report that HoS during the three-day 2021 cold snap increases from 9 h for the baseline envelope to 16 h when infiltration is reduced, while SET degree-hours below 12.2 °C remain zero, indicating that survival time is controlled by envelope design rather than SET thresholds in this cold event context [54]. A similar pattern appears in heat-related outages. In a three-day summer outage case study of a Florida nursing home, Sun et al. report that Danger+ Heat Index conditions are reduced from 32.3% under baseline operation to 1.2% with cross-ventilation and 6.5% when lighting and miscellaneous electric loads are reduced, while safe-time fractions reach approximately 100% under full backup power and exceed 90% with 50% backup power or 24-h thermal storage [53]. These cases suggest that survival time and safe duration assessment, in both cold and hot outages, are best answered by threshold crossing or time-fraction metrics (RT, HoS), while degree-hour and rate-based metrics (UDH, DoD, CS) remain the more informative choice for characterising how severely, and how quickly, conditions deteriorate once safe limits are breached.

A notable absence across all 29 metrics is any explicit equity weighting. No metric in the catalogue differentiates performance by occupant vulnerability profile, housing tenure, or income-constrained adaptive capacity. The consequence is that a building can satisfy passive survivability criteria under a standard occupancy assumption while providing materially inadequate protection for elderly, medically dependent, or economically constrained occupants, a gap that connects directly to the equity findings in Section 7.

WUMTP represents the closest existing attempt at a composite metric integrating all phases and zones, but its sensitivity to implementation means that results are not comparable across studies without standardised weighting schemes, currently constrains its policy utility. An important standardisation gap is a cold-climate passive survivability standard comparable to the LEED IPpc100 criterion (cumulative SET degree-hours not exceeding a threshold over a defined outage period): no equivalent cold-hazard standard exists.

9. Synthesis framework

The six-step structure presented here reflects a logic common to resilience assessment frameworks, including those developed in infrastructure engineering, socio-technical resilience, and building science. Frameworks proposed by Bruneau et al. [64], Hamstead et al. [14], and Hong et al. [74] similarly organise analysis around system boundaries, hazards, performance attributes, and recovery processes. However, the contribution of the present framework does not lie in redefining this, but rather in operationalising it for building-scale energy resilience under disruptive events by explicitly integrating three elements that are treated separately in prior works: hazard-specific performance pathways based on building physics, health-based thresholds derived from epidemiological evidence, and equity constraints that affect both achievable performance and its interpretation. In this sense, the framework is not a new concept, but a domain-specific synthesis that connects previously disconnected layers into a single operational procedure.

Fig. A1 (Appendix) illustrates these relationships in a Sankey-based representation of the framework, linking its six components: stakeholders, boundaries, disruptive events, resilience attributes, indicators, and solutions. The diagram illustrates generalised connections across the reviewed studies, with link thickness indicating the relative frequency of observed changes.

Step 1: Identification of stakeholders and beneficiaries. This step specifies the stakeholders whose resilience is being assessed, including building occupants, owners, facility managers, local communities, policy makers, and network operators. Defining these actors determines which dimensions of resilience are prioritised and which trade-offs are considered acceptable. This variability underlines that resilience is not an intrinsic system property alone but is dependent on whose outcomes are prioritised. Stakeholders should be explicitly differentiated by vulnerability profiles (e.g., age, health status, tenure), as these determine acceptable risk thresholds and evaluation criteria. This differentiation addresses a disconnect identified in this review (Section 7): equity-focused studies and simulation-based building physics studies show minimal methodological overlap within the studied literature, such that the populations most exposed to disruption-related health risk are frequently absent from the quantitative models used to evaluate resilience. Identifying vulnerable stakeholder groups explicitly at this step is intended to prevent that disconnect from recurring. Consequently, frameworks developed for assisted living facilities, social housing systems, or grid operators reflect different performance criteria and priorities.

Step 2: Definition of the system boundary. The spatial and organisational boundary determines whether the assessment focuses on asset-level performance, neighbourhood energy exchanges, or interactions with wider infrastructure systems. This review defines three boundary tiers: Single Building (one building and its internal energy system, e.g., a residential building, office, school, or hospital); Multiple Buildings (a group of interconnected buildings or a district, e.g., a building block, campus, housing estate, or district energy system, where energy sharing and collective resilience measures are assessed); and Grid (the wider electricity or energy network, e.g., a municipal or regional system, encompassing interactions between buildings and external infrastructure). Explicit definition of the boundary reduces ambiguity and inconsistencies in reported metrics and findings, particularly where building-scale and district-scale performances are implicitly confused. Throughout this review, the terms urban and city refer to climate/physical exposure context and case-study geography, respectively, rather than to additional boundary-scale categories, and are therefore distinct from the three tiers defined here. This step is therefore a prerequisite for comparability and methodological coherence.

Step 3: Characterisation of disruptive events. The selection and definition of disruptive events represent a central element of resilience analysis. Reviewed studies consider a wide range of hazards, often differing in type, frequency, duration, and intensity, with limited standardisation in how these are operationalised. This is a substantive rather than a terminological gap. Compound-hazard studies account for only 18 of the 176 studies included in this review, and heat-related disruptive events dominate the literature disproportionately relative to documented cold climate mortality, meaning the hazard taxonomy itself reflects an uneven evidence base rather than a fully populated reference set. The choice of reference event therefore determines not only which indicators (Step 5) are relevant, but whether the evidence base can support the assessment at all. Event characterisation should consider not only physical severity but exposure duration relative to vulnerable occupant thresholds. Importantly, the choice of reference event directly determines the relevance of performance indicators and limits the applicability of technical and operational strategies.

Step 4: Selection of resilience attributes. Resilience is operationalised through a set of attributes (including preparedness, absorption, response, adaptation, recovery, and mitigation), although their selection and interpretation vary across studies. The literature indicates that these attributes serve as an intermediate layer linking system contexts ('who' and 'where') to measurable performance aspects ('how'). This step implicitly defines the scope of both evaluation and intervention, determining which aspects of system performance are considered or neglected. Consistent with Fig. 8, this review identifies that anticipation and learning phases are relatively under-addressed even in frameworks involving full cycle coverage. This step therefore requires explicit statement of which attributes are not assessed in a given study, rather than allowing preparedness and recovery to be omitted. The relevance and prioritisation of resilience attributes differ across occupant profiles, with vulnerable groups exhibiting greater sensitivity to absorption and degradation phases.

Step 5: Specification of resilience indicators. Appropriate indicators are selected from the metric set summarised in Table A3 (Appendix), informed by hazard type (Section 5), building characteristics and occupant profiles, and policy context. Notably, equity-oriented studies extend beyond physical performance metrics to incorporate social vulnerability dimensions, such as deprivation indices, housing tenure, and dependence on critical medical equipment, highlighting that resilience outcomes are jointly determined by technical performance and socio-economic conditions. Resilience indicators should be reported for: (i) a standard reference occupant profile and (ii) at least one vulnerable occupant profile. Differences between profiles should be explicitly reported and interpreted as equity-relevant performance gaps.

Translating social vulnerability into building-physics boundary conditions requires mapping social vulnerability sub-domains onto established physiological and behavioural parameter adjustments used in the thermal comfort and heat stress modelling literature, in the absence of case specific survey data. Equity relevant boundary conditions enter building physics models through two distinct channels: physiological occupant parameters (metabolic rate, clothing insulation, thermoregulatory thresholds) and pre-event behavioural/economic boundary conditions (heating setpoint, heating duration, and the starting indoor temperature at the onset of a disruptive event).

For occupants whose vulnerability is primarily physiological, the standard reference values used in comfort modelling, a near-sedentary metabolic rate of 1.0–1.3 met and clothing insulation of 0.5–0.7 clo, on the basis of the ASHRAE 55 SET method [178], are not themselves age-adjusted, and applying them uniformly to elderly occupants risks understating risk. Rather than an ad-hoc offset to these values, purpose-built elderly thermoregulation models are recommended, since these incorporate measured age-related reductions in metabolic rate, cardiac output, and shivering response directly rather than through a uniform metabolic-rate shift: Novieto [179] and Ma, Xiong & Lian [180] adapt young-adult thermoregulation models to older populations by incorporating age-related changes in body characteristics and thermoregulatory response, providing a more defensible basis for modelling elderly occupants than uniform parameter shifts. For threshold reporting, the statutory adequate warmth standard used in UK fuel poverty policy is adopted; 23 °C in the main living area and 18 °C in other rooms for elderly/infirm households, versus 21 °C/18 °C for the general population [181,182] in place of an unvalidated uniform threshold shift. By contrast, an equally well-established heat-side threshold specific to vulnerable populations was not identified in the studies reviewed; this should therefore be treated as an evidence gap rather than as a settled parameter.

Energy-poor households are better represented through the second channel than the first: rather than modifying occupant physiology, simulations should adjust the pre-event indoor temperature and heating schedule to reflect documented under-heating behaviour. Recent UK survey evidence during the 2022–23 cost-of-living crisis found mean heating thermostat settings fell by 1.1 °C (20.3 °C to 19.2 °C), with the households making the largest energy reductions also reducing daily heating hours, not only setpoint [183]. Initiating the outage simulation from an indoor temperature 2–4 °C below the code-assumed comfort baseline, and/or with a reduced daily heating duration, is therefore recommended. This distinction carries a direct methodological consequence for the performance-curve indices discussed in Section 8: because these indices are normalised against a pre-event baseline Q_0

(Section 8, Appendix A), applying a uniform code-assumed baseline to energy-poor households will systematically overstate their resilience margin relative to their actual lived starting conditions.

Beyond these two channels, several additional occupant categories require parameterisation logic that is neither purely physiological nor purely economic. As summarised in Table 3, these categories modify physiological assumptions, behavioural response assumptions, pre-event boundary conditions, health-risk interpretation, or solution feasibility. These mechanisms should therefore not be treated as interchangeable modelling adjustments. Simulation studies should explicitly specify which vulnerability category, or combination of categories, is being represented and through which boundary condition channel, rather than treating "vulnerable occupant" as a single homogeneous category. Where no locally validated parameter set exists, the ranges in Table 3 are recommended as a minimum standardised default, pending the development of population-specific parameter sets through coordinated physiological and survey data collection.

Step 6: Identification and packaging of solutions. Resilience enhancement strategies are described in the literature as combinations of passive, active, and hybrid technical measures, complemented by behavioural, policy, and system-level interventions. Rather than being universally applicable, these solutions depend on earlier decisions, such as how and what stakeholders are prioritised, how system boundaries are defined, and how hazards are characterised. Tenure status is treated in Step 5 as a structural constraint on occupant vulnerability rather than an occupant parameter; here, it directly constrains solution feasibility, since renters and low-income owner-occupiers are systematically less able to install PV-battery systems, envelope retrofits, or backup heating regardless of the technical merit of these measures. Equity considerations therefore emerge as a cross-cutting constraint, especially in terms of access, affordability, and the distribution of benefits and risks. Among the technical measures mentioned in Section 6, one policy-relevant aspect deserves explicit guidance: where outdoor conditions, air quality, security, and operable openings permit, natural and mixed-mode ventilation pathways can provide passive heat discharge capacity during outages in highly airtight, mechanically cooled buildings. This function is not necessarily captured by current NZEB compliance pathways and should therefore be considered explicitly in solution packages for buildings otherwise reliant on active cooling. Solutions should be evaluated not only by technical effectiveness but also by their ability to reduce identified equity gaps between occupant profiles. The literature emphasises that, without explicit consideration of these factors, potential solutions inadvertently reinforce existing vulnerabilities rather than mitigate them.

To illustrate the analytical value of the proposed framework, a representative case from the reviewed literature is interpreted through its six components. The study by Ach-Chakhar et al. [187] examines the 2003 European heatwave as a reference event, quantifying its implications for occupant thermal comfort and cooling demand in a residential building in Nantes. The 2003 heatwave, which resulted in thousands of heat related fatalities in France, provides a well-documented epidemiological context against which building-scale simulation results can be evaluated.

Within the framework, the primary stakeholders (Step 1) correspond to building occupants, whose thermal comfort and health risks are directly affected, while secondary stakeholders include designers, urban planners, and policy makers concerned with overheating in both existing and future building stocks. The system boundary (Step 2) is defined at the apartment and building level, with explicit consideration of the surrounding urban microclimate, thereby linking indoor performance to local outdoor conditions. The disruptive event (Step 3) is characterised as an extreme heat episode, represented by the 2003 heatwave, with a focus on its impacts on indoor environmental conditions and energy demand. The study primarily addresses mitigation and adaptation attributes (Step 4), by quantifying overheating risks, assessing the influence of UHI intensity, and evaluating design responses to reduce thermal

Table 3
Vulnerable-occupant categories and their corresponding boundary-condition channel for Step 5 implementation.

Vulnerability type	Boundary-condition channel	What differs from standard occupant	Recommended default parameter/ adjustment
Elderly occupants (65+)	Physiological	Lower resting metabolic rate and slower thermoregulatory response to cold or heat exposure	Use elderly-specific body-heat models [179,180] rather than a uniform metabolic rate adjustment; report cold-side thresholds using 23 °C in the living area and 18 °C in other rooms [181,182]
Mobility-limited occupants	Behavioural / delayed response	Reduced capacity to relocate, access resources, or undertake protective actions during unsafe conditions	Extend response-time assumptions and model reduced probability of relocation or adaptive behaviour
Infants/young children	Physiological; No validated model yet	Higher surface area to mass ratio; immature thermoregulation; unable to adjust clothing or location independently	No adult-derived default is appropriate; identified as a gap for future parameter development
Chronic illness (particularly cardiovascular/ respiratory conditions)	Health-risk interpretation	Elevated health sensitivity to thermal exposure, which not be captured by standard comfort or temperature-decay metrics alone	Report exposure outputs separately for this group and interpret them using epidemiological risk functions where available. Apply the mortality-risk evidence already cited in Section 7.1 (approximately 1–4% increase in mortality per 1 °C above baseline; elevated cardiovascular risk below 15 °C)
Income/tenure-constrained (energy-poor households)	Behavioural/ economic starting conditions	Physiologically capable of adaptation, but heating or cooling use is limited to reduce cost ("comfort rationing")	Simulate a pre-event indoor temperature 2–4 °C below the standard comfort baseline; assume reduced daily heating duration [183]
Medically power-dependent occupants (dialysis, ventilators, refrigerated medication)	Power supply, not temperature	Vulnerability arises from loss of power supply rather than temperature exposure alone	Specify a minimum backup power duration; assess using power-continuity metrics (SSD, E_def) rather than temperature decay metrics alone
Cognitive impairment/ dementia	Behavioural	Reduced capacity to recognise risk, operate controls, open windows, or undertake self-protective action	Model a low probability of adaptive behaviour (e.g., window opening, thermostat

(*continued on next page*)

Table 3 (*continued*)

Vulnerability type	Boundary-condition channel	What differs from standard occupant	Recommended default parameter/ adjustment
			adjustment, use of cooling strategies, or relocation), in contrast to the standard occupant
Socially isolated occupants, including single-occupant elderly households	Delayed detection/ response	Absence of nearby support delay recognition of unsafe conditions and reduce access to help	Extend response and recovery time assumptions; reduced mobility and living alone were both associated with elevated mortality risk during the 2003 heatwave [184,185], and social isolation independently elevates risk [186]
Renters/insecure tenure	Structural feasibility constraint (Step 6)	Limited authority or incentive to modify the envelope, install PV-battery systems, add backup heating/ cooling, or alter ventilation systems	Do not treat as a Step 5 occupant parameter; instead, use it to constrain which Step 6 solutions are feasible for this occupant group

stress. On the other hand, preparedness, short-term response, and post-event recovery dimensions are not explicitly addressed. With respect to indicators (Step 5), the analysis deals with occupant-centric and energy-related metrics, including overheating indices, duration of thermal exceedance, temperature rises attributable to UHI effects, and cooling energy demand. These correspond to the occupant and hybrid indicator categories identified in this review. In terms of solutions (Step 6), the study highlights the importance of integrating climatic considerations into building design and cooling system sizing and encourages the use of resilience-oriented simulation metrics to support retrofit and design decisions. The proposed measures emphasise passive and design-oriented strategies, such as orientation, layout optimisation, and material selection, to mitigate overheating and reduce cooling demand under extreme heat conditions.

For example, the assisted living facility study by Sheng et al. [54] evaluates passive survivability under heat and cold outages. Under dual-profile resilience reporting, the same simulation outputs would be evaluated against at least two occupant types: a standard healthy adult and an elderly resident with cardiovascular vulnerability. A lower tolerable SET or Heat Index threshold for the latter (e.g., shifting the 'safe' range down by 1–2 degrees) would convert a subset of hours previously counted as 'safe' into 'unsafe', thereby reducing effective Hours of Safety and increasing dangerous SET degree-hours This illustrates that resilience metrics derived under standard conditions overestimate protection for vulnerable populations, supporting the need for dual-profile reporting.

In the Sankey-based synthesis, this case aligns with a pathway linking occupant focused stakeholders, building-scale boundaries, and heatwave hazards to adaptation-oriented attributes, occupant-centric indicators, and predominantly passive design strategies. This mapping demonstrates how the framework enables systematic classification and comparison of diverse studies. More broadly, it illustrates that the range of approaches observed in the literature can be structured within a common outline, while still preserving context-specific detail.

These further highlight that state-of-the-art studies tend to pay attention to specific sections of the resilience spectrum, often focussing more on adaptation and mitigation stages over preparedness and recovery, thereby strengthening the need for more integrated assessment approaches. The following Discussion section examines the implications of this and considers the extent to which greater standardisation could improve comparability and cumulative knowledge development within the field.

10. Discussion

This review is best understood as a field-diagnostic systematic scoping study rather than a conceptual theory paper or a purely descriptive overview. Its primary contribution is a verified taxonomy of 29 building-scale energy and thermal resilience metrics, including several unrecognised equivalence groups that explain why nominally different indicators can produce identical outputs under shared assumptions yet diverge under mismatched integration windows and thresholds. On this basis, the review identifies two structural gaps that must be closed for the field to consolidate: the absence of a cold-climate passive survivability standard comparable to LEED IPpc100, and the lack of equity-weighted resilience metrics that reflect the conditions of populations most exposed to disruption-related health risks. Returning to the four research questions that structure this review, three cross-cutting findings shape the answers, and each has a different relationship to existing information. The first confirms what literature had never systematically documented at this scale: that passive envelope performance is the most consistent and climate-agnostic determinant of building energy resilience. The second reveals a blind spot in the literature: that the hazard, geographic, and methodological composition of the research corpus is misaligned with the distribution of climate risk. The third reframes what the field has mischaracterised: that energy efficiency and market-driven resilience policy are not acceptable proxies for thermal resilience and equitable protection, respectively. These form the basis for the interpretation that follows.

10.1. Answering the research questions

Conceptualisation and measurement. Definitional heterogeneity is not merely a terminological issue in building energy resilience research. It constitutes a barrier for cross-study synthesis, code integration, and policy translation. Only a quarter of the included studies operationalise energy or thermal resilience through a formal, reproducible definition, while approximately half deploy the term as rhetorical framing without specifying either measurement criteria or the reference population. This pattern is consistent with the umbrella use of resilience documented across infrastructure and urban planning literatures and indicates that the concept has diffused into building science more rapidly than consensus on its meaning has emerged. A unified definition must not only be grounded in vulnerability, resistance, robustness, and recoverability, but also explicitly differentiate by hazard type and occupant profile as integral elements rather than being context specific.

Technical measures. The evidence on passive envelope strategies represents the most consistent finding across the literature corpus. High thermal resistance, continuous airtight assemblies with minimal thermal bridging, and appropriate solar management extend passive survivability by hours to days as compared to code-minimum construction. This effect is robust across climate zones, building types, and hazard conditions, and is consistently reproduced across independent simulation studies using different modelling tools and boundary assumptions [7,8,143]. Distributed PV-BESS systems similarly extend autonomous operation, by ~6–34+ hours depending on system sizing, load definition, and dispatch strategy, with variation driven primarily by the difference between critical-load and full-load operation rather than absolute battery capacity. Individually, these findings are well established. However, their replication across this literature collection, which spans cold and hot climates, residential and non-residential building types, and European, North American, and Asian contexts, provides a level of convergence that single climate studies cannot achieve. Another important and recurring finding is the efficiency vs. resilience trade-off in buildings. Where mechanical ventilation constitutes the only air exchange pathway and no operable window backup is provided, passive survivability during power outages be reduced. This effect, first identified by Baniassadi and Sailor [6], has since been replicated across multiple studies and climate contexts. Its continued absence from national building energy codes, despite several years of empirical evidence and the increasing adoption of electrification and net zero energy buildings, constitutes an actionable regulatory gap identified in this review. The required distinction is not between efficient and inefficient buildings, but between airtightness strategies that incorporate operable natural ventilation fallback and those that prevent it.

Socio-economic outcomes and equity. The epidemiological evidence linking indoor thermal conditions to adverse health outcomes during disruptions is well established and extensively replicated, with studies reporting a 1–4% increase in mortality per 1 °C above historical temperature baselines and risk multipliers of 2-10× for elderly individuals and those with pre-existing cardiovascular, respiratory, or metabolic conditions. This review does not extend the underlying epidemiological evidence; rather, it positions it within a building performance framework that the health literature rarely engages with.

The more consequential finding is structural. Equity-focused studies and simulation-based building physics studies display minimal methodological overlap within the corpus. As a result, the populations most exposed to disruption-related health risks, including low-income households, elderly residents, medically dependent occupants, and renters in under-maintained housing, are largely absent from the quantitative models used to assess building resilience performance. This divergence cannot be attributed to sampling imbalance alone, nor resolved by increasing the representation of social science studies within reviews. Rather, it reflects a disciplinary separation in which tools for informing protective interventions are developed and evaluated without explicitly considering the populations at highest risk. This drawback limits the ability of current modelling approaches to inform equitable resilience strategies and represents a critical constraint on the translation of building-level performance analysis into public health protection outcomes.

Economic value of resilience investments. The economic evidence represents the weakest aspect of the literature, and this limitation is itself a substantive finding. Most building-scale resilience studies do not assume cost-benefit analysis of resilience measures as different from energy efficiency investments. The subset of studies that do include economic assessment suggests that the co-benefits of high-performance envelope upgrades in cold climates, including avoided costs from pipe-freeze damage, post-event displacement, and healthcare expenditure, justify investment independently of energy savings [144]. Similarly, PV–BESS configurations can achieve cost-neutral or cost-positive resilience outcomes in contexts characterised by frequent grid outages. However, these findings are derived from a limited number of case-specific analyses and cannot be readily generalised. The more fundamental limitation is methodological. Building energy resilience and energy efficiency are typically evaluated within separate frameworks, passive survivability metrics on one hand and life cycle cost analysis on the other, with no established method for integrating the two. As a result, resilience-specific outcomes, such as avoided mortality, reduced healthcare burden during disruptions, or the value of maintaining thermal safety for medically dependent occupants, remain largely unquantified in economic terms. Developing a standardised valuation framework for these outcomes, analogous to the role of the social cost of carbon in climate policy, represents a research priority yet to be systematically addressed within either building physics or health domains.

These findings indicate that developing energy resilience in the built environment requires not only improved technical solutions, but a reconfiguration of how resilience is defined, measured, and governed across disciplines and scales. Without such alignment, the field risks continued fragmentation between evidence gathering and practical implementation.

10.2. Research gaps and priorities: Cross-cutting findings

Addressing the fourth research question, this subsection identifies cross-cutting research gaps and future priorities that arise from the collective interpretation of findings across the descriptive mapping, revealing issues that are not evident within the individual sections alone.

Hot Climate Bias. The observed ratio of heat-to-cold studies does not reflect proportional differences in mortality burden, infrastructure risk, or policy relevance. Cold-related mortality is globally comparable to heat-related mortality [154], and recent climate and geopolitical events have demonstrated the population-scale consequences of cold vulnerability. This imbalance instead reflects the geographic composition of the research community. Southern European, United States and Australian contexts, where overheating dominates building design, account for a disproportionate share of studies. Prior works of resilient cooling reflect and reinforce this bias. Although a post-2021 increase in cold-climate and compound-event studies is observable, this shift appears driven primarily by disaster-triggered research activity rather than anticipatory research planning, indicating a reactive pattern that has implications for research governance.

Metric fragmentation. The twenty-nine building-scale resilience metrics identified in Table A3 include multiple instances of mathematical equivalence that remain unrecognised across the disciplinary communities utilising them. This is not a minor issue of terminology. Assessments conducted under the LEED IPpc100 criterion (SET degree-hours over a 7-day outage) are not directly comparable with Nordic passive survivability approaches (e.g., hours above 15 °C), nor with IOD/BCVF-based formulations developed within the building physics literature. Partial standardisation efforts exist, including LEED IPpc100, EN 16798–1, and work under IEA EBC Annexes, but these are climate-specific, non-interoperable, and do not capture the full resilience cycle. Addressing this requires a coordinated effort extending across hazard types, climate zones, and occupancy contexts to establish a unified, internationally validated metric set.

Global South Gap. There is an inverse relationship between research density and climate vulnerability exposure. Fewer than 10% of empirical studies in this corpus address contexts in the Global South, despite these regions being home to the majority of the world's most climate-exposed and energy-insecure populations. As a result, the benchmarks, design strategies, and performance metrics treated as standard in the field are derived predominantly from engineered building stock, grid-reliable systems, and institutional conditions not representative of all environments. This review quantifies this disparity explicitly across a multi-disciplinary literature collection. More importantly, the issue extends beyond general underrepresentation: resilience metrics, thresholds, and intervention strategies are being defined in contexts fundamentally distinct from those in which disruption impacts are most severe.

Compound Hazard Scarcity. Only 18 of 176 reviewed papers addressed compound or cascading hazards. As discussed in Section 5.4, this gap arises from two compounding constraints rather than one: a data constraint, since standard weather files are not built to co-occur with independently modelled outage or infrastructure failure schedules; and a modelling tool constraint, since mainstream building simulation engines accept single hazard weather-driven inputs rather than natively coupled multi-hazard inputs. Advancing this research area will likely require either standardised compound event datasets or simulation tools that accept compounding multi-hazard boundary conditions, rather than continued reliance on study-specific manual workarounds.

Occupant representation. Across simulation studies, occupant behaviour during disruptions is typically represented through fixed schedules, binary window operation, and standardised occupancy profiles. This simplification is particularly consequential for resilience assessment, where passive survivability depends on assumptions regarding occupant responses during system failure, such as ventilation behaviour, adaptive clothing, spatial relocation, or reliance on external support. While stochastic occupant modelling approaches capable of capturing such variability are well established in the building simulation literature [188], their application to resilience modelling remains limited. Consequently, performance estimates derived under standard occupant assumptions overestimate protection levels for vulnerable populations, including elderly or medically dependent occupants. Although social science studies in the corpus in this work document this behavioural variability, it has not been integrated into building physics models, reflecting a disciplinary divide rather than a lack of available tools.

Climate Scenario Gap. A further limitation relates to the temporal validity of resilience assessments. The majority of simulation studies rely on historical weather data or present-day typical meteorological years to define design hazards, rather than future climate projections. As a result, buildings designed to perform under historical conditions be inadequate over their lifetime. This is particularly important for envelope-based strategies, whose performance characteristics are fixed at construction and cannot be readily modified. Although a small but growing subset of studies applies future climate projections, using weather-morphing techniques or ensemble scenarios, this remains a minority practice. The incorporation of probabilistic future climate conditions into resilience assessment represents an important methodological boundary that remains largely unexplored.

10.3. Implications for practice and policy

Passive Survivability. Evidence showing that envelope performance governs passive survivability across climate zones and hazard types points to an actionable code implication: the introduction of a minimum passive survivability tier (alongside existing energy performance requirements). This tier would specify minimum PHD/HoS thresholds, differentiated by building type, climate zone, and occupant vulnerability profiles. The LEED IPpc100 criterion demonstrates that explicit pass/fail thresholds for passive survivability are both technically feasible and implementable within existing certification frameworks. Its limitations are primarily geographic: the SET-based metric, the 7-day outage assumption, and the use of Fahrenheit units reflect US building practice and do not translate directly to European, Nordic, or Global South contexts. An equivalent cold-climate standard is currently absent and represents an immediate standardisation gap identified in this review. Any such provision must explicitly address the efficiency-resilience trade-off. Certification should require demonstration of minimum survivability performance under defined outage conditions as an integral component of airtightness compliance, ensuring that highly airtight envelopes do not become thermal risk amplifiers when active systems fail.

Equity targeted policy. The literature constantly indicates that resilience policies based on voluntary adoption or market-driven incentives, such as rebates, tax credits, and green financing instruments, tend to concentrate benefits among households with the financial capacity and tenancy security to act. These groups systematically differ from those most exposed to thermal disruption risks. While this imbalance is well established within the energy justice literature, this review establishes it explicitly within the domain of building resilience. The populations most vulnerable to disruption-related health impacts are also those least effectively reached by market-based mechanisms. In this context, required minimum standards in social housing, care facilities, and other high-vulnerability settings are likely to provide both more equitable and more cost-effective protection than incentive-based programmes. The administrative infrastructure required for such targeting (deprivation indices, energy poverty metrics, housing tenure data, and medical dependency registers) already exists in a lot of high-income countries and could be utilised without the need for new data collection systems.

Vulnerable occupant profiles. An actionable implication of the occupant representation gap identified in this review is procedural rather than methodological. Existing resilience assessment frameworks typically treat occupants as standardised recipients of indoor conditions, rather than as agents whose physiological characteristics, economic constraints, and behavioural capacity shape risk exposure. A minimal but consequential procedural change would be to require the specification and reporting of resilience performance for at least one vulnerable occupant profile alongside the standard reference case. Where a building satisfies passive survivability criteria for the standard profile but fails for an elderly or medically dependent occupant, this performance gap should be explicitly disclosed. In occupancy types characterised by high vulnerability, such as social housing or old-age housing, design compliance should require proof that such gaps are mitigated rather than accepted. This recommendation aligns with emerging health-equity principles in building standards, requires no new metric development, and would shift the implicit reference population used in resilience assessment toward those most at risk.

Research investment alignment. The inverse relationship between research density and vulnerability exposure identified in this review reflects characteristics of the global research system rather than individual research choices. Institutions with the capacity to conduct advanced building simulations and longitudinal studies are usually located in high-income countries, leading to a concentration of evidence in relatively low-vulnerability contexts. This imbalance contributes to a self-reinforcing standardisation dynamic, in which the metrics, thresholds, and benchmarks embedded in international guidance frameworks are derived from the contexts most represented in the literature. As a result, these standards not be transferable to regions characterised by informal housing, limited grid reliability, or constrained institutional capacity. International programmes such as IEA EBC Annexes, Horizon Europe partnerships, and other development finance institution initiatives are well positioned to support research with institutions in climate-vulnerable regions. Expanding such efforts is not only an equity imperative but also a methodological necessity. A resilience field built on geographically narrow evidence cannot credibly claim global applicability.

The policy implications outlined above should be interpreted considering the methodological constraints of the underlying evidence. Several identified gaps, particularly the limited representation of Global South contexts and the lack of systematic economic evaluation, are shaped in part by the review's scope and search strategy and therefore define priorities for future research as much as current policy limitations.

11. Limitations

This review is subject to some methodological constraints inherent to its scope and design. The literature search was conducted using Scopus and Web of Science, which provide comprehensive coverage of peer-reviewed research but do not fully capture grey literature from governmental, institutional, and practitioner sources. Consequently, applied resilience guidance be underrepresented relative to academic studies. In addition, the search strategy relied partly on resilience-related terminology. Given that relevant studies are also published under adjacent framings, such as thermal comfort during outages, and energy security, some studies not have been captured through the primary database search.

The review also reflects the interpretive characteristics of a scoping methodology. Classification of studies by hazard type, methodology, geographic context, and building typology involved human decision-making, although consistency was maintained through structured discussion and consensus within the research team. In line with PRISMA-ScR guidance, no formal quality appraisal was conducted. The synthesis therefore spans studies with varying designs and strengths of evidence. Conclusions based on smaller subsets of simulation or case-study evidence should be interpreted more cautiously than those consistently replicated across the corpus. The literature base reflects what was indexed up until October 2025 and given the rapid acceleration of publication activity in this field, relevant papers published in late 2025 and 2026 be underrepresented.

A further limitation relates to the geographic distribution of the available evidence. Studies addressing vulnerability, lived experience, and equity are disproportionately concentrated in high-income country contexts, restricting the extent to which the review captures the conditions typical of settings where energy-disruption risks are most acute.

A further methodological constraint concerns language scope. Although no formal language filter was applied during screening, the search strategy was constructed using search terms in English and executed within Web of Science and Scopus, both of which disproportionately index journals in English. Given that a substantial share of Global South research, particularly from Latin America and North Africa, is published in Spanish, Portuguese, French or Arabic, this language-driven database skew is a plausible contributing factor to the Global South underrepresentation identified in this review, alongside the funding concentration and publication incentive factors discussed above. Future reviews should incorporate regional databases (e.g., SciELO, Redalyc) and non-English search terms to distinguish an evidence gap from a discoverability gap.

These limitations qualify the scope of this work but do not alter its central findings. The main patterns, including definitional fragmentation, unharmonised metrics, geographic concentration, and limited attention to equity, appear across several diverse types of studies. This makes it unlikely that they are the result of the search strategy or classification methods.

12. Conclusion

Over the past decade, energy resilience in the built environment has evolved from a niche intersection of building physics and emergency management into a rapidly expanding cross-disciplinary field. More than 60% of the literature in this field has been published in the three years preceding this review, indicating that it is scaling faster than it is consolidating, and making its structural weaknesses more, not less, urgent.

This study contributes (i) a consolidated taxonomy of 29 resilience metrics including equivalence groups, (ii) an integrated hazard-climate-equity analysis across 176 studies, and (iii) a six-step operational assessment framework for building resilience.

The literature reviewed here indicates that technical knowledge for improving building resilience is largely established. High-performance envelopes extend passive survivability by hours to days, while PV-battery systems enable 6–34 h of autonomous operation. These findings are consistent across climates and building types. The primary constraints are therefore not technical, but structural: conceptual standardisation, geographic representation, and equity integration. Only 25% of the studies provide operational definitions of resilience; fewer than 10% of empirical studies address the Global South; and populations most exposed to disruption-related health risks remain underrepresented in quantitative models.

Each of these gaps has a clear and actionable corrective. A cold-climate passive survivability standard (the direct counterpart to LEED IPpc100) addresses an immediate standardisation need and requires no new technology. Likewise, NZEB and other airtightness mandating standards should incorporate a mandatory operable natural-ventilation fallback, independent of mechanical system availability, as a condition of compliance. Across the studies reviewed in this work, highly airtight buildings without operable natural ventilation fallback consistently exhibit reduced passive survivability during outages, exposing a significant gap in standards that still treat airtightness and ventilation as independent rather than interacting design parameters. Requiring resilience assessments to report results for a vulnerable occupant profile alongside standard assumptions would directly improve equity integration. Redirecting a portion of IEA EBC, Horizon Europe, or development-bank funding toward co-produced research with institutions in climate-vulnerable regions would strengthen geographic representation. The six-step assessment framework proposed in Section 9 provides an operational structure linking these actions to practice through stakeholder definition, system boundaries, hazard characterisation, indicators, and solutions.

Buildings can protect people during energy disruptions, and the technologies required to do so are already mature and widely available. The remaining gaps relate less to engineering capability than to standardisation, equitable implementation, and alignment of research with the populations most at risk. Closing the gap between existing knowledge and the populations most at risk remains the central challenge for future research and policy.

CRediT authorship contribution statement

Rakesh Ramesh: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hassam ur Rehman:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Microsoft CoPilot to improve the gramar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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.

Acknowledgements

The authors acknowledge financial support from the Research Council of Finland through the project Addressing the Challenges of Achieving Energy Resilience in Buildings During Power Outages in Finland: A Human-Centric Approach Integrating Technical, Social and Economic Dimensions 2025–2029 (REBUILD-Fin) [Decision No. 367935]. This work was also supported by the Driving Urban Transitions Partnership, co-funded by the European Union, through the RES-PED project (Enabling Energy Resilience through New Energy-Flexible and Affordable Positive Energy District Concepts; Grant No. 101069506). The authors additionally acknowledge IEA EBC Annex 93 - Energy Resilience of Buildings in Remote Cold Regions. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A. Appendix

Table A1
Comparative review of key studies on building energy resilience.

Dimension	This review	Wei et al. (2025, RSER)	Zhang et al. (2025, E&B)	Ahmed et al. (2021, RSER)	IEA EBC Annex 80
Review type & method	Systematic scoping (PRISMA-ScR)	Structured review; no PRISMA reporting	Critical review: corpus not formally defined	Narrative review	Annex outputs
Heat hazard coverage	All climates; heatwaves, UHI, heat + blackout	Primary focus; structured disruption taxonomy	Heat + cold treated jointly	Strong focus; passive cooling synthesis	Defined within Annex scope
Cold outage coverage	Co-primary: cold spells, winter outages	Included but heat-dominant	Explicitly included	Out of scope (warm climate)	Addressed in other Annexes
Compound hazards	Gaps identified: heat + blackout, cold + blackout etc.	Cascading disruptions noted	Central framing (extreme weather + outage)	Single-hazard framing	Single-hazard framing
Health evidence	Integrated (epidemiological studies; mortality thresholds)	Acknowledged; not synthesised	Wellbeing discussed; not integrated with building evidence	Referenced; not systematically reviewed	Outside scope
Equity & vulnerability	Analytical dimension (energy poverty, adaptive capacity, vulnerable groups)	Framed but not embedded	Not addressed	Brief mention	Partially acknowledged
Resilience metrics	29 metrics; formulas, equivalence, climate suitability	Most comprehensive prior taxonomy	Qualitative + quantitative approaches	Comfort/overheating indicators only	Strong operational guidance
Geographic scope	Global; Global South share quantified	Global; no regional analysis	Global; no regional breakdown	Some Global South; not systematic	Mostly high-income countries

Table A2
Simulation and experimental studies evaluating resilience interventions under disruptive events.

Method	Disruptive event	Event duration	Location	Mitigation action	Performance metrics	Survivability extension outcome	Reference
EnergyPlus whole-building simulation	Power outage / HVAC power loss during extreme heat	3 days	Florida, San Francisco & Chicago	Natural ventilation; Load reduction; Envelope insulation; Window improvement; Shading; PV; Thermal storage	Energy efficiency, costs, Heat index	Delays onset of dangerous indoor heat conditions, extending the period before critical thresholds are reached; active backup required beyond passive limit in some cases	[53]
EnergyPlus simulation	Power outage + extreme hot and cold events	Heat wave 6 days; Cold snap 3 days	Greater Houston area	Envelope upgrades; Natural ventilation; Airtightness adjustment; Efficiency package	SET degree-hours, Heat Index, Hours of Safety; ~19% reduction in backup capacity	Extends duration over which safe indoor conditions are maintained, reducing required backup duration; reveals trade-offs affecting survivability span across seasons	[54]
Experiment (Net-zero residential building)	Summer power outage	3 days	Shizuoka, Japan	PV + battery; Load shedding; Circuit prioritisation	PMV, WBGT, duration of supplied loads	Maintains acceptable indoor conditions and essential services across the full outage duration, effectively sustaining survivability span through active support	[189]
Simulation (Energy Plus)	Heatwave + power outage	~6 days	Brussels, Belgium	Natural ventilation; Cool roof; Solar shading	Indoor overheating degree (0.59 → 0.19 °C); exceedance hours; SET; Heat index	Reduces rate and magnitude of indoor overheating, prolonging the time before thermal thresholds are exceeded	[190]
Whole building simulation (Energy Plus)	Power outage + Heat wave	3 day outage +3 day heat wave	All U.S. climate zones	Code-driven efficiency upgrades	Heat stress metric; discomfort index	Indicates that efficiency measures can extend or, in some cases, shorten survivability duration depending on climate and design assumptions	[116]
Coupled climate + building model	Heat wave + Blackout	5 day outage within 8 day heat wave	Phoenix, Arizona	Cool roof; Street trees	Heat exposure risk indicator	Lowers indoor heat exposure rates, passively extending the survivable period during prolonged outages	[191]
Building stock models	Power outage + Heat wave	5 days	Phoenix, Arizona	High thermal mass; Basement refuge	Qualitative thermal performance	Slows indoor temperature rise, extending time before unsafe heat levels occur; provides localised zones with longer survivability	[192]
Modelica model + experiment	Heatwave shock	Variable	Ghent, Belgium	Shading; Night ventilation; Thermal mass; Airtightness	Degree of Shock	Reduces combined severity duration of thermal stress, effectively extending acceptable indoor condition duration	[89]
Simulation (HOMER)	Power outage	2 h	Iraq	PV + Battery	Energy, cost, emissions	Maintains power availability during short outages, preserving	[193]

(continued on next page)

Table A2 (*continued*)

Method	Disruptive event	Event duration	Location	Mitigation action	Performance metrics	Survivability extension outcome	Reference
						operational conditions throughout the disruption	
Simulation (HOMER)	Power outage	Variable	Tanzania	PV + Battery + Generator	Cost of energy; savings	Extends survivability duration under longer outages with battery systems; generators more effective only for short-duration events	[194]
Simulation (MATLAB)	Extreme weather	7 days	N/A	PV + battery	Resilience metric; SoC	Improves system-level resilience capacity, increasing the duration over which building operation can be sustained under disruption	[195]

Table A3
Consolidated set of KPIs for building energy and thermal resilience, including explicit calculation bases or definitions as reported in the literature. References indicate studies in which the metric is explicitly defined, formulated, or applied in building resilience assessment.

#	Metric (abbreviation)	Full name	What it measures (building-scale meaning)	Formula	Implication for resilience	Reference
			Passive Thermal Survival Metrics *These metrics quantify how long a building can passively maintain habitable or safe indoor conditions without active HVAC, during or after a supply disruption.*			
1	**PSI**	Passive Survivability Index	Total duration (h) over which a building passively maintains indoor temperature within habitable bounds during a loss of power/cooling/heating event; aggregated across hot-season and cold-season scenarios.	PSI = PS_summer + PS_winter where PS_summer = hours indoor T stays ≤ upper habitability limit (e.g. 30 °C) without cooling, and PS_winter = hours indoor T stays ≥ lower habitability limit (e.g. 15 °C) without heating, both evaluated over a defined outage window.	Higher is better. A higher PSI means the building can protect occupants for longer under both heat and cold outages, a composite measure of all-season passive resilience.	[151]
2	**PHD / HoS**	Passive Habitability Duration / Hours of Safety	Time (h or days) from outage start until indoor conditions first cross a defined habitability threshold - the upper safety temperature limit in a heat event, or the lower limit in a cold event.	PHD = t_H − t_0 where t_0 = outage start; t_H = first time T_indoor(t) crosses the habitability limit T_H (e.g. 15 °C for cold events; SET 86 °F / 30 °C for heat events).	Higher is better. Longer PHD / HoS means occupants can safely remain in the building without active systems for a greater duration; directly linked to life-safety outcomes during compound heatwave-blackout or cold-outage events.	[74]
3	**TA**	Thermal Autonomy	Fraction (%) of occupied hours over a reference period during which the building passively maintains indoor conditions within an acceptable comfort band without any active heating or cooling.	TA (%) = (N_comfort_passive / N_occupied) × 100 where N_comfort_passive = occupied hours the free-running indoor operative temperature lies within the defined comfort band; N_occupied = total occupied hours in the reference period.	Higher is better. TA represents the baseline passive robustness of the building. High TA buildings require less active energy and are inherently more resilient to supply disruptions. Complements PHD/HoS for chronic vs. acute resilience assessment.	[139]
4	**T_CT**	Time to Comfort Threshold Exceedance	Elapsed time (h) from the onset of a disruption until indoor operative temperature first exits the defined comfort band. A 'time-to-failure' metric that captures how quickly comfort is lost once active systems are removed.	T_CT = t_CT − t_0 where t_0 = disruption start; t_CT = first time T_op(t) exits comfort band (e.g. [20,26] °C). T_CT ≤ RT (robustness threshold duration) since comfort thresholds are stricter than robustness thresholds.	Higher is better. Longer T_CT indicates the envelope and passive systems delay comfort failure; useful for comparing design alternatives and sizing backup systems.	[10]
5	**SET-DH / DoS**	SET Degree Hours Outside Livable Range / Days of Safety	Cumulative Standard Effective Temperature (SET) deviation outside the defined 'livable' band (54–86 °F / 12–30 °C) during an outage. Days of Safety (DoS) is derived as the time until cumulative SET-DH exceeds a pass/fail limit	SET-DH = Σ [max(SET_i − 86, 0) + max(54 − SET_i, 0)] × Δt [°F·h] DoS = (t_L − t_0) / 24 [days] where t_L = first time cumulative SET-DH(t) ≥ limit L (e.g. L = 216 °F·h per LEED IPpc100 over a 7-day design outage).	SET-DH: lower is better. DoS: higher is better. A building passes the LEED IPpc100 survivability criterion when cumulative SET-DH ≤ 216 °F·h over the 7-day design outage window.	[196]
			Thermal Failure & Degradation Metrics *These metrics characterise how, how fast, and how severely indoor thermal conditions degrade after a supply disruption*			
6	**RT**	Robustness Threshold Duration	Duration (h) from outage start until indoor temperature first crosses the defined robustness threshold (e.g. 18 °C in cold events; building-specific upper limit in heat events).	RT = t_rob − t_0 where t_0 = outage start; t_rob = min{t > t_0 | T_indoor(t) crosses T_rob}.	Higher is better. Longer RT means the envelope resists thermal degradation longer before entering the 'vulnerable' zone. Together with T_CT and PHD, RT characterises the 3-	[177]

(continued on next page)

Table A3 (*continued*)

#	Metric (abbreviation)	Full name	What it measures (building-scale meaning)	Formula	Implication for resilience	Reference
					stage degradation sequence: comfort → robustness → safety.	
7	**IoF**	Impact of Failure	Magnitude of the total indoor temperature drop during an outage; the thermal 'shock' experienced by occupants. Split into two stages: setpoint-to-robustness-threshold and robustness-threshold-to-minimum, capturing the full degradation path.	IoF = (P_ST − P_RT) + (P_RT − P_min) = P_ST − P_min [°C] where P_ST = design setpoint, P_RT = robustness threshold, P_min = minimum indoor temperature reached during outage. IoF uses the design setpoint as the starting reference.	Lower is better. Higher IoF means a more severe thermal disturbance and therefore poorer resilience. The 2-step split allows diagnosis of which degradation stage is most critical.	[177]
8	**AoE**	Amplitude of Event	Similar to IoF but uses the measured or simulated indoor temperature the moment the disruption begins (T_actual,start) rather than the design setpoint. Captures the true amplitude of thermal swing experienced during the event.	AoE = T_actual,start − P_min [°C] where T_actual,start = measured/ simulated indoor temperature at outage start t_0; P_min = minimum indoor temperature reached during the outage.	Lower is better. AoE be larger or smaller than IoF depending on whether the building was pre-conditioned above or below setpoint at outage start.	[139]
9	**CS**	Collapse Speed	Rate of indoor temperature decline from the pre-event setpoint (or actual start temperature) to the minimum indoor temperature reached during the outage. Characterises how fast the building 'collapses' thermally once supply is lost.	CS = (P_ST − P_min) / (t_min − t_0) [°C/h] where t_0 = outage start; t_min = time at which P_min is first reached. For cooling failure (summer), the same applies in the overheating direction (positive values indicate heating rate).	Lower CS (magnitude) is better. A building that cools or heats slowly gives occupants more time to respond. High CS indicates poor thermal inertia or high envelope conductivity.	[177]
10	**DoD**	Degree of Disruption	Normalised, dimensionless severity index combining both the magnitude and duration of performance degradation over a defined reference window. Can be computed for any performance parameter (indoor temperature, PMV, energy, etc.).	DoD = [(P_disruption − P_reference) / P_reference] × (t_disruption / t_reference) where P_disruption = performance during disruption; P_reference = reference (undisturbed) performance; t_disruption = duration of disruption; t_reference = reference duration	Higher DoD indicates a larger and/or longer disturbance ≥ worse resilience. Being dimensionless, DoD enables cross-building and cross-parameter comparison.	[19]
11	**TRI / R_event**	Thermal Resilience Index / Event Resilience Ratio	Integral resilience index adapted to indoor thermal performance: the area under the normalised thermal performance curve during an event window, divided by the ideal (maximum) performance area. Quantifies what fraction of ideal performance is preserved.	TRI = R_event = [1/(t1 − t0)] × ∫[t0 → t1] Q(t) dt where Q(t) = normalised thermal performance function (e.g. 1 when within comfort/safety band, 0 when completely outside); [t0, t1] = event window. TRI_rel = TRI_design / TRI_reference (for comparison to a reference building).	Higher is better (TRI/R_event → 1 means conditions were maintained throughout the event). Captures both duration and severity of exceedance in a single number.	[196]
			Thermal Stress & Comfort Metrics			
			These metrics quantify the cumulative or instantaneous severity of indoor thermal conditions relative to comfort thresholds, primarily during normal occupancy or chronic overheating rather than acute events.			
12	**IOD**	Indoor Overheating Degree	Time-integrated indicator of indoor overheating severity normalised by occupied hours. Accounts for both how much and how long indoor operative temperature exceeds a comfort preference, giving a single number representing the combined frequency and intensity of overheating.	IOD = (1/N_occ) × Σ max(T_op,i − T_pref,i, 0) [°C] where N_occ = total occupied hours; T_op,i = indoor operative temperature at hour i; T_pref,i = preferred/comfort temperature at hour i	Lower is better. IOD = 0 means no overheating. Higher IOD reflects chronically overheated indoor environments. Increases with climate warming unless mitigated by envelope or shading upgrades.	[197]
13	**AWD**	Ambient Warmness Degree	Climate-side analogue of IOD: severity of outdoor warmness over occupied hours, integrating the intensity and duration of outdoor temperatures exceeding a defined base value.	AWD_Tb = (1/N_occ) × Σ max(T_a,i − T_b, 0) [°C] where T_a,i = outdoor air temperature at hour i; T_b = base outdoor temperature; N_occ = occupied hours.	AWD is a climate severity descriptor, not a building performance indicator on its own. It provides the denominator for aIOD/BCVF.	[10]

(*continued on next page*)

Table A3 (*continued*)

#	Metric (abbreviation)	Full name	What it measures (building-scale meaning)	Formula	Implication for resilience	Reference
					Higher AWD in a given climate year means more severe climate forcing, allowing building response to be normalised. Lower is better.	
14	**aIOD / OER**	Adjusted Indoor Overheating Degree (aIOD) / Overheating-to-Exposure Ratio	Sensitivity of indoor overheating to outdoor climate: the slope of the regression of IOD on AWD across multiple climate scenarios. Quantifies whether and how strongly a building amplifies outdoor warmness indoors.	aIOD = IOD / AWD_Tb or, when fitted across multiple climate scenarios: aIOD = d(IOD) / d(AWD) [dimensionless]	aIOD <1: building damps outdoor warming (thermally resilient). aIOD >1: building amplifies outdoor warmness, a direct indicator of climate vulnerability. aIOD = 1: building transmits climate forcing without attenuation. Lower is better.	[198]
15	**BCVF**	Building Climate Vulnerability Factor	Identical in form to aIOD but framed explicitly as a vulnerability indicator for policy and design assessment. Quantifies how strongly a building's overheating severity responds to climate-driven outdoor warming, enabling buildings to be labelled or ranked by climate vulnerability.	BCVF = IOD / AWD_Tb [dimensionless] Mathematically equivalent to aIOD. also be expressed as the regression slope when multiple climate scenarios are available: BCVF = d(IOD) / d(AWD)	BCVF <1: building reduces indoor overheating relative to outdoor warming (‘climate-resilient’). BCVF >1: building amplifies outdoor climate forcing (‘climate-vulnerable’). Used to classify or certify buildings in resilience labelling schemes.	[199]
16	**UDH**	Unmet Degree Hours	Time-integrated thermal discomfort metric; Cumulative temperature deviation (heating shortfall or cooling excess) from a comfort setpoint or threshold over occupied hours.	UDH_heat = Σ max(T_set,heat − T_op,i, 0) × Δt [°C·h] (cold unmet) UDH_cool = Σ max(T_op,i − T_set,cool, 0) × Δt [°C·h] (hot unmet) where T_set = comfort setpoint or threshold; T_op,i = indoor operative temperature.	Lower is better. UDH can be split into heating and cooling shortfalls and summed across zones. Less physiologically nuanced than SET-DH or IOD but widely understood.	[7]
17	**HoE / %HoE**	Hours of Exceedance / Percentage Exceedance	Number (or percentage) of occupied hours during which indoor operative temperature (or a PMV/PPD comfort category) exceeds a defined upper comfort threshold. Widely used in European building regulations (EN 16798) and national overheating standards.	HoE = Σ [I(T_op,i > T_thr)] × Δt [h] (where I = 1 if condition met) %HoE = (HoE / N_occupied) × 100 [%] Weighted variants apply.	Lower is better. Many national standards specify a maximum allowable %HoE (e.g. ≤ 1–5% of occupied hours above threshold). Simpler than IOD but does not capture severity (degree of exceedance). Two buildings with the same HoE can have very different overheating intensities.	[200]
			System & Energy Performance Metrics *These metrics characterise the energy side response of buildings and their integrated systems during and after supply disruptions.*			
18	**RS**	Recovery Speed	Rate of indoor temperature recovery (°C/h) from the minimum value reached during the outage back to the pre-event setpoint once power or heating is restored. Characterises the ‘recoverability’ dimension of the resilience trapezoid.	RS = (P_ST − P_min) / (t_recover − t_min) [°C/h] where t_min = time at which P_min is reached (end of collapse phase); t_recover = time at which T_indoor recovers to setpoint P_ST after power restoration.	Higher is better (faster recovery to normal operation). RS depends on both the installed heating/cooling capacity and the envelope's thermal resistance. Buildings with high thermal mass have low CS (slow collapse) but also low RS (slow recovery), a trade-off to be considered in design.	[177]
19	**RT_rec**	Recovery Time	Total elapsed time (h) from restoration of energy supply until indoor thermal conditions return to the pre-disruption setpoint or comfort band. A simple, operationally useful ‘recoverability’ metric for facilities managers and emergency planners.	RT_rec = t_setpoint_restored − t_power_restored [h] where t_power_restored = moment active heating/cooling is resumed; t_setpoint_restored = moment T_indoor re-enters the comfort band or reaches the design setpoint.	Lower is better. Shorter recovery time reduces occupant exposure to residual adverse conditions after the disruption event. Strongly influenced by heating/cooling plant capacity, distribution system response,	[19]

(*continued on next page*)

Table A3 (*continued*)

#	Metric (abbreviation)	Full name	What it measures (building-scale meaning)	Formula	Implication for resilience	Reference
					and thermal mass of the building.	
20	**E_def**	Energy Deficit during Outage	Unserved energy (kWh) during a disruption: the cumulative shortfall between energy demand required to maintain design setpoints and the energy actually supplied by building systems (grid + any local generation/storage). A supply-demand gap metric.	$E\_def = \int[t0 \rightarrow t1] \max(E\_demand(t) - E\_supply(t), 0)\, dt$ [kWh] where $E\_demand(t)$ = hypothetical energy demand to maintain setpoints without outage; $E\_supply(t)$ = actual energy supplied (grid + PV + BESS + backup).	Lower is better. A high E_def means occupants experience prolonged or severe thermal degradation. E_def is complementary to PHD/HoS, the energy side of the same resilience event.	[201]
21	**SSD**	Self-Sustainment Duration	The maximum duration (h) over which the building can fully serve its defined critical load in island mode without external grid supply, starting from a defined state of charge.	$SSD = \max\{\Delta t$: all defined loads are fully met for $t \in [t0, t0 + \Delta t]\}$ Computed via energy balance considering PV output (weather-dependent), battery state of charge trajectory, critical vs. non-critical load shedding policy, and EV availability (if applicable).	Higher is better. SSD defines the effective energy autonomy window; the maximum outage the building can survive without shedding critical loads.	[202]
22	**WUMTP**	Weighted Unmet Thermal Performance	Composite building-level resilience score that aggregates unmet thermal performance across multiple disruption phases (before/during/after), hazard severity levels, and exposure durations across all occupied zones, weighted by multipliers for each dimension.	$WUMTP\_z = \Sigma_i [W\_P,i \times W\_H,i \times W\_E,i \times \Delta T\_z,i \times \Delta t\_i]$ [weighted °C·h/m^2] $WUMTP\_overall = \Sigma_z WUMTP\_z / \Sigma_z A\_z$ where W_P = phase weight; W_H = hazard severity weight; W_E = exposure duration weight; ΔT = temperature deviation from threshold; Δt = time step; A_z = zone floor area.	Lower is better. WUMTP captures robustness, absorptive capacity, adaptability, and recoverability simultaneously in a single number, weighted to reflect the relative severity of each phase and scenario. Enables single-metric design comparison across the full resilience cycle.	[139]
23	**RCI**	Resilience Class Index	Relative resilience score comparing a building's WUMTP to a defined reference design. Transforms the absolute WUMTP score into a ratio that enables policy-ready classification (e.g. resilience 'classes' A-F similar to energy performance certificates).	$RCI = WUMTP\_reference / WUMTP\_building$ [dimensionless] where $WUMTP\_reference$ = score of the code-minimum or baseline building; $WUMTP\_building$ = score of the assessed design. $RCI > 1$: more resilient than reference; $RCI < 1$: less resilient.	Higher is better ($RCI > 1$ indicates better-than-reference performance). The reference choice (code-minimum, archetype, policy baseline) is critical - must be stated and justified. Enables labelling and benchmarking	[139]
				Physiological & Bioclimatic Metrics *These metrics integrate environmental conditions with human thermal physiology, capturing health-relevant heat or cold stress.*		
24	**HI-DH**	Heat Index Dangerous Hours	Number of hours during a heat event when the indoor Heat Index (a combined temperature–humidity apparent temperature) exceeds defined health-risk thresholds ('Danger' or 'Extreme Danger' bands per OSHA / NWS classification). Used in EnergyPlus-based passive survivability studies.	HI computed from T_air and RH using Steadman's formula. $HI\text{-}DH = \Sigma\, I(HI\_i \geq HI\_thr) \times \Delta t$ [h] Variants: Degree-hour form: $HI\text{-}DH\_deg = \Sigma \max(HI\_i - HI\_thr, 0) \times \Delta t$ [°F·h or °C·h] Thresholds: 'Danger' ≈ 103 °F/39.4 °C; 'Extreme Danger' > 125 °F/51.7 °C.	Lower is better. HI-DH captures the combined temperature-humidity burden which is relevant for care facilities, hospitals, and other settings where occupants cannot thermoregulate effectively.	[203]
25	**WBGT**	Wet-Bulb Globe Temperature	Standard environmental heat-stress index combining natural wet-bulb temperature (humidity + evaporative cooling), globe temperature (radiant heat), and optionally air temperature. The primary international standard for occupational heat stress assessment and increasingly used for indoor environments.	Indoor / simplified (no wind): $WBGT = 0.7 \times T\_nwb + 0.3 \times T\_g$ [°C] Outdoor / full formula: $WBGT = 0.7 \times T\_nwb + 0.2 \times T\_g + 0.1 \times T\_a$ where T_nwb = natural wet-bulb temperature; T_g = globe temperature (radiant); T_a = air temperature.	Higher WBGT indicates higher combined heat load on the human body. WBGT >28 °C is a widely recognised threshold for heat-related illness risk in healthy adults; lower thresholds apply for elderly or medically vulnerable occupants.	[196]
26	**DI**	Discomfort Index	Heat-stress index combining air temperature and wet-bulb temperature (a proxy for humidity). Historically used in meteorology and epidemiology.	$DI = 0.5 \times T\_a + 0.5 \times T\_wb$ [°C] where T_a = dry-bulb air temperature; T_wb = wet-bulb temperature. Threshold: $DI \approx 24$ °C = discomfort begins for most; $DI \geq 28$ °C =	Lower is better. Higher DI indicates higher combined heat and humidity burden.	[204]

(*continued on next page*)

Table A3 (*continued*)

#	Metric (abbreviation)	Full name	What it measures (building-scale meaning)	Formula	Implication for resilience	Reference
				'extreme discomfort' / passive habitability limit often cited.		
27	**CT**	Climate Change Amplification Coefficient	Quantifies how strongly a building amplifies or damps projected future warming; identical to BCVF/aIOD but expressed in terms of absolute temperature change.	ΔT_indoor = CT × ΔT_outdoor where ΔT_outdoor = projected change in seasonal mean (or extreme) outdoor temperature; ΔT_indoor = corresponding change in seasonal mean (or peak) indoor temperature. CT estimated from simulation or monitoring regression across scenario ensemble (slope of linear fit).	Lower is better. CT < 1: building damps future outdoor warming - resilient to climate change. CT > 1: building amplifies future warming - increasingly problematic under climate change. CT ≈ BCVF ≈ aIOD when computed over the same scenarios.	[205]
			Composite & Statistical Risk Metrics *These metrics characterise the distribution, tail risk, or multi-dimensional weighting of resilience performance.*			
28	**CVaR**	Conditional Value at Risk	Tail-risk metric usually used in financial risk theory: the expected value of indoor thermal performance loss in the worst α% of climate scenarios. CVaR captures the severity of rare but catastrophic overheating or underheating events.	CVaR_α = E[L | L ≥ VaR_α] where L = thermal performance loss metric (e.g. overheating degree-hours or temperature exceedance); VaR_α = Value at Risk at confidence level α (threshold such that P(L > VaR_α) = α%); CVaR is the mean of losses exceeding VaR_α.	Lower is better. CVaR quantifies tail risk scenarios where conventional resilience metrics might show acceptable average performance, but rare extreme events cause catastrophic failure. Relevant for future climate where the distribution of risk matters as much as the mean.	[195]
29	**Indoor Warm./Cool. Rate**	Indoor Warming / Cooling Rate	Rate (°C/h) at which indoor conditions change when HVAC is disabled, either heating up under solar and internal gains (heat event) or cooling down due to envelope heat loss (cold event). Indicator of thermal vulnerability determined by envelope performance.	Warming rate (hot season): ΔT/Δt_warm = (T_peak − T_initial) / Δt_warm [°C/h] Cooling rate (cold season): ΔT/Δt_cool = (T_initial − T_min) / Δt_cool [°C/h] Typically estimated over the first 6–12 h of an outage when the rate is approximately linear.	Lower magnitude is better for both heating and cooling. A low rate gives occupants and emergency responders more time to act. Directly related to Collapse Speed (CS).	[206]

Formal Equivalence of Performance-Curve Indices

Let P(t) denote a normalised building performance trajectory over a disruption window [t0, t1], where $P = 1$ denotes baseline (undisrupted) performance and $P = 0$ denotes complete loss of critical function. The Thermal Resilience Index (TRI) is defined as the time-averaged performance deficit over the analysis window:

$$\mathrm{TRI} = \frac{1}{t_1 - t_0} \int_{t0}^{t1} \left(1 - \mathrm{P}(t)\,\mathrm{d}t\right) \tag{1}$$

The event-based resilience ratio (R_{event}) is defined as:

$$R_{\mathrm{event}} = 1 - \frac{1}{t_1 - t_0} \int_{t0}^{t1} \mathrm{P}(t)\,\mathrm{d}t \tag{2}$$

Expanding Eq. (2):

$$R_{\mathrm{event}} = 1 - \frac{1}{t_1 - t_0} \int_{t0}^{t1} \mathrm{P}(t)\,\mathrm{d}t = \frac{1}{t_1 - t_0} \int_{t0}^{t1} \left(1 - \mathrm{P}(t)\,\mathrm{d}t\right)$$

Therefore $TRI \equiv R_{event}$ under the following boundary conditions: (i) both indices are computed over the same disruption window $[t_0, t_1]$; (ii) both use the same underlying normalised performance function $P(t)$ (i.e., identical baseline definition and identical degradation metric); and (iii) both apply the same integration/discretisation method (continuous integral or equivalent trapezoidal sum) over the same time step Δt. The two metrics diverge where any of these three conditions are violated, for example, where R_{event} is computed against a rolling or seasonally adjusted baseline rather than a fixed pre-event baseline, or where the integration window differs (disruption only versus disruption plus recovery phase) which results in reported discrepancies across studies using nominally the same metric.

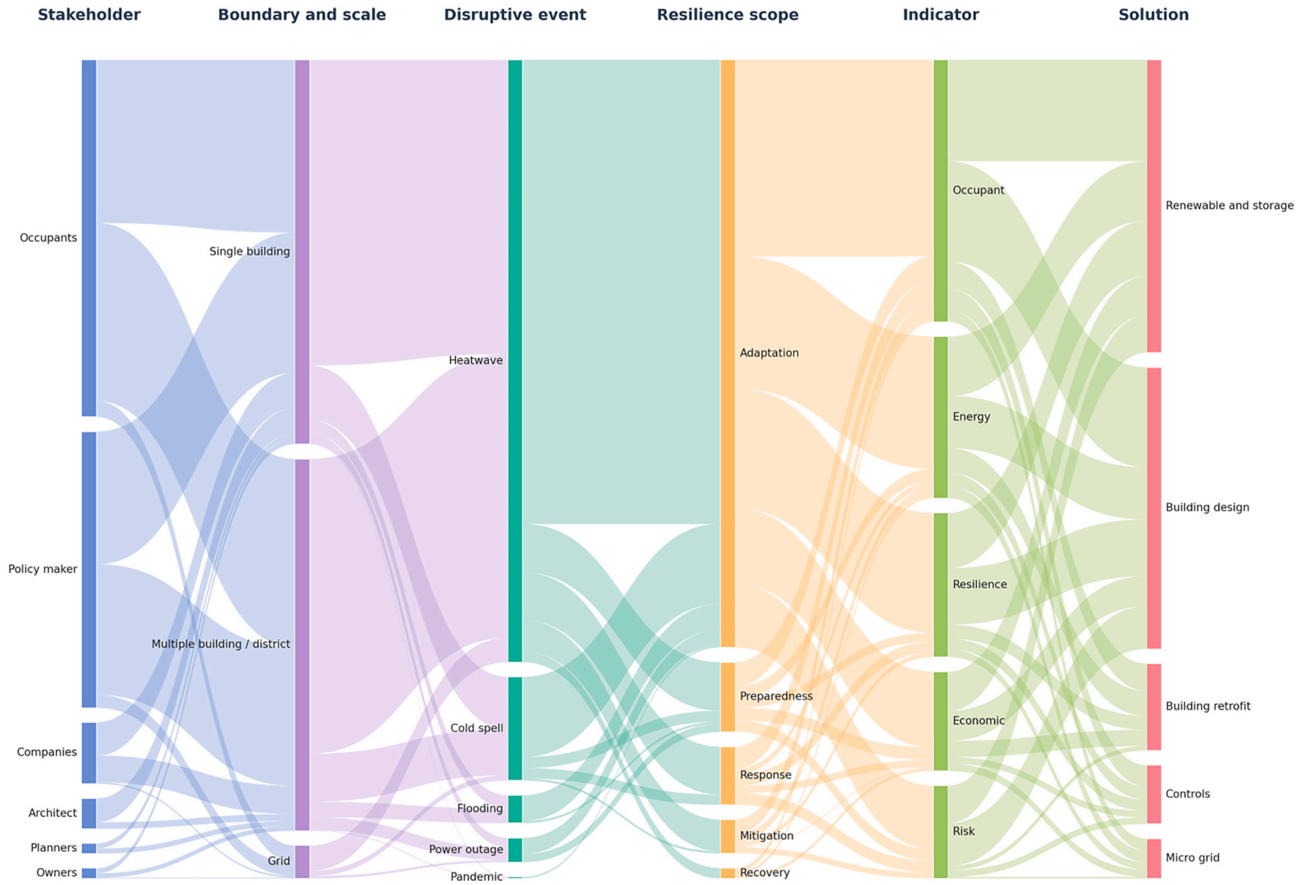

Fig. A1. Sankey Diagram illustrating relationships across resilience dimensions, disruptive events, system scales, and solution strategies.

Data availability

Data will be made available on request.

References

[1] D. García-León, et al., Temperature-related mortality burden and projected change in 1368 European regions: a modelling study, Lancet Public Health 9 (9) (2024) e644–e653, https://doi.org/10.1016/S2468-2667(24)00179-8.
[2] J.-M. Robine, et al., Death toll exceeded 70,000 in Europe during the summer of 2003, C. R. Biol. 331 (2) (2008) 171–178, https://doi.org/10.1016/j.crvi.2007.12.001.
[3] R.A. Bolinger, et al., An assessment of the extremes and impacts of the February 2021 south-central U.S. Arctic outbreak, and how climate services can help, Weather Clim. Extrem. 36 (2022) 100461, https://doi.org/10.1016/j.wace.2022.100461.
[4] N.M. Flores, H. McBrien, V. Do, M.V. Kiang, J. Schlegelmilch, J.A. Casey, The 2021 Texas power crisis: distribution, duration, and disparities, J. Expo. Sci. Environ. Epidemiol. 33 (1) (2023) 21–31, https://doi.org/10.1038/s41370-022-00462-5.
[5] International Energy Agency (IEA), Empowering Ukraine Through a Decentralised Electricity System – Analysis, IEA, 2026 https://www.iea.org/reports/empowering-ukraine-through-a-decentralised-electricity-system.
[6] A. Baniassadi, D.J. Sailor, Synergies and trade-offs between energy efficiency and resiliency to extreme heat – a case study, Build. Environ. 132 (2018) 263–272, https://doi.org/10.1016/j.buildenv.2018.01.037.
[7] D.R. Liyanage, K. Hewage, M. Ghobadi, R. Sadiq, Thermal resiliency of single-family housing stock under extreme hot and cold conditions, Energ. Buildings 323 (2024) 114809, https://doi.org/10.1016/j.enbuild.2024.114809.
[8] D. Wang, Q. Dong, C. Sun, Evaluating the adaptation potential and retrofitting effectiveness of existing residential buildings in severe cold regions of China under climate change, Build. Environ. 278 (2025) 112982, https://doi.org/10.1016/j.buildenv.2025.112982.
[9] T. Ahmed, P. Kumar, L. Mottet, Natural ventilation in warm climates: the challenges of thermal comfort, heatwave resilience and indoor air quality, Renew. Sust. Energ. Rev. 138 (2021) 110669, https://doi.org/10.1016/j.rser.2020.110669.
[10] P. Holzer, P. Stern, P. Czarnecki, International energy agency - resilient cooling of buildings - project summary report (annex 80), , Institute of Building Research & Innovation,, 2024, https://doi.org/10.52776/KKGB4933.
[11] M. Wei, et al., Energy resilience in the built environment: a comprehensive review of concepts, metrics, and strategies, Renew. Sust. Energ. Rev. 210 (2025) 115258, https://doi.org/10.1016/j.rser.2024.115258.
[12] W. Zhang, H. Yang, X. Cao, X. Bao, H. Cui, A review of building energy resilience for maintaining indoor thermal stability during extreme weather events, Energ. Buildings 342 (2025) 115908, https://doi.org/10.1016/j.enbuild.2025.115908.
[13] C. Schünemann, A. Olfert, D. Schiela, K. Gruhler, R. Ortlepp, Mitigation and adaptation in multifamily housing: overheating and climate justice, Build. Cities 1 (1) (2020), https://doi.org/10.5334/bc.12.
[14] Z. Hamstead, et al., Thermally resilient communities: creating a socio-technical collaborative response to extreme temperatures, Build. Cities 1 (1) (2020), https://doi.org/10.5334/bc.15.
[15] J.E. Bennett, M. Blangiardo, D. Fecht, P. Elliott, M. Ezzati, Vulnerability to the mortality effects of warm temperature in the districts of England and Wales, Nat. Clim. Chang. 4 (4) (2014) 269–273, https://doi.org/10.1038/nclimate2123.
[16] C. Dominianni, K. Lane, S. Johnson, K. Ito, T. Matte, Health impacts of citywide and localized power outages in new York City, Environ. Health Perspect. 126 (6) (2018) 067003, https://doi.org/10.1289/EHP2154.
[17] A.C. Tricco, et al., PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation, Ann. Intern. Med. 169 (7) (2018) 467–473, https://doi.org/10.7326/M18-0850.
[18] J. Jasiūnas, P.D. Lund, J. Mikkola, Energy system resilience – a review, Renew. Sust. Energ. Rev. 150 (2021) 111476, https://doi.org/10.1016/j.rser.2021.111476.
[19] H. ur Rehman, M. Hamdy, A. Hasan, Towards extensive definition and planning of energy resilience in buildings in cold climate, Buildings 14 (5) (2024), https://doi.org/10.3390/buildings14051453.
[20] A.E. Stagrum, E. Andenæs, T. Kvande, J. Lohne, Climate change adaptation measures for buildings—a scoping review, Sustainability 12 (5) (2020) 1721, https://doi.org/10.3390/su12051721.
[21] M.J. Page, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ 372 (2021) n71, https://doi.org/10.1136/bmj.n71.

[22] A.A. Williams, A. Baniassadi, P. Izaga Gonzalez, J.J. Buonocore, J.G. Cedeno-Laurent, H.W. Samuelson, Health and climate benefits of heat adaptation strategies in single-family residential buildings, Front. Sustain. Cities 2 (2020), https://doi.org/10.3389/frsc.2020.561828.
[23] M.M. Osman, H. Sevinc, Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan, Sustain. Cities Soc. 47 (2019) 101429, https://doi.org/10.1016/j.scs.2019.101429.
[24] A.F. Krelling, R. Lamberts, J. Malik, T. Hong, A simulation framework for assessing thermally resilient buildings and communities, Build. Environ. 245 (2023) 110887, https://doi.org/10.1016/j.buildenv.2023.110887.
[25] B. Widera, Comparative analysis of user comfort and thermal performance of six types of vernacular dwellings as the first step towards climate resilient, sustainable and bioclimatic architecture in western sub-Saharan Africa, Renew. Sust. Energ. Rev. 140 (2021) 110736, https://doi.org/10.1016/j.rser.2021.110736.
[26] S. Flores-Larsen, C. Filippín, Energy efficiency, thermal resilience, and health during extreme heat events in low-income housing in Argentina, Energ. Buildings 231 (2021) 110576, https://doi.org/10.1016/j.enbuild.2020.110576.
[27] S. Domínguez-Amarillo, J. Fernández-Agüera, J.J. Sendra, S. Roaf, The performance of Mediterranean low-income housing in scenarios involving climate change, Energ. Buildings 202 (2019) 109374, https://doi.org/10.1016/j.enbuild.2019.109374.
[28] G. Lamberti, F. Contrada, A. Kindinis, Exploring adaptive strategies to cope with climate change: the case study of Le Corbusier's modern architecture retrofitting, Energ. Buildings 302 (2024) 113756, https://doi.org/10.1016/j.enbuild.2023.113756.
[29] X. Yang, S. Yu, X. Jiang, P. Jiang, Addressing health inequities in energy-poor households: evidence from China's photovoltaic poverty alleviation program, Energies 18 (10) (2025), https://doi.org/10.3390/en18102620.
[30] C. Howarth, H. Zamzow, N. McLoughlin, G. Shreedhar, Gaps in public perceptions of extreme heat highlight UK'S lack of preparedness, Environ. Sci. Pol. 170 (2025) 104101, https://doi.org/10.1016/j.envsci.2025.104101.
[31] C. Howarth, J. Kantenbacher, K. Guida, T. Roberts, M. Rohse, Improving resilience to hot weather in the UK: the role of communication, behaviour and social insights in policy interventions, Environ. Sci. Pol. 94 (2019) 258–261, https://doi.org/10.1016/j.envsci.2019.01.008.
[32] S. Davoudi, et al., Resilience: a bridging concept or a dead end? "Reframing" resilience: challenges for planning theory and practice interacting traps: resilience assessment of a pasture management system in northern Afghanistan urban resilience: what does it mean in planning practice? Resilience as a useful concept for climate change adaptation? The politics of resilience for planning: a cautionary note: edited by Simin Davoudi and Libby porter, Plan. Theory Pract. 13 (2) (2012) 299–333, https://doi.org/10.1080/14649357.2012.677124.
[33] D. Sánchez-García, D. Bienvenido-Huertas, M. Tristancho-Carvajal, C. Rubio-Bellido, Adaptive Comfort Control Implemented Model (ACCIM) for energy consumption predictions in dwellings under current and future climate conditions: a case study located in Spain, Energies 12 (8) (2019), https://doi.org/10.3390/en12081498.
[34] K.-M. Wai, Is integrating tree-planting strategies with building Array sufficient to mitigate heat risks in a sub-tropical Future City? Buildings 15 (11) (2025) https://doi.org/10.3390/buildings15111913.
[35] A.A. Williams, J.G. Allen, P.J. Catalano, J.D. Spengler, The role of individual and small-area social and environmental factors on heat vulnerability to mortality within and outside of the home in Boston, MA, Climate 8 (2) (2020), https://doi.org/10.3390/cli8020029.
[36] R. Rahif, M. Kazemi, S. Attia, Overheating analysis of optimized nearly zero-energy dwelling during current and future heatwaves coincided with cooling system outage, Energ. Buildings 287 (2023) 112998, https://doi.org/10.1016/j.enbuild.2023.112998.
[37] A. Brambilla, T. Lea, L. Grealy, A. Kuru, Climate change and indigenous housing performance in Australia: a modelling study, Energ. Buildings 273 (2022) 112399, https://doi.org/10.1016/j.enbuild.2022.112399.
[38] M. Guo, J. Zheng, J. Zhang, J. Li, Q. Wang, D.W.L. Lai, Impact of extreme weather events on mental health among older adults in China: a longitudinal study, Sustain. Cities Soc. 130 (2025) 106580, https://doi.org/10.1016/j.scs.2025.106580.
[39] S.S. Bhuvad, R. You, Q. Chen, Assessment of sustainable and accessible water-based cooling interventions during heat events through thermoregulation modeling, Build. Environ. 285 (2025) 113639, https://doi.org/10.1016/j.buildenv.2025.113639.
[40] P. Babon-Ayeng, W. Jung, Personalized indoor heat stress response modeling and assessment for improved building thermal resilience, Energ. Buildings 345 (2025) 115965, https://doi.org/10.1016/j.enbuild.2025.115965.
[41] Y. Liu, M.A. Ghazali, L. Yang, Y. Chen, Sustainable passive design in cold regions: energy and thermal evaluation of traditional Zhuangke dwellings — in Qinghai Province, China, Energ. Buildings 344 (2025) 115969, https://doi.org/10.1016/j.enbuild.2025.115969.
[42] E.A. Grigorieva, J.E. Walsh, V.A. Alexeev, Extremely cold climate and social vulnerability in Alaska: problems and prospects, Climate 12 (2) (2024), https://doi.org/10.3390/cli12020020.
[43] S. Curtis, A. Fair, J. Wistow, D.V. Val, K. Oven, Impact of extreme weather events and climate change for health and social care systems, Environ. Health 16 (1) (2017) 128, https://doi.org/10.1186/s12940-017-0324-3.
[44] Y. Lu, et al., Towards high-performance buildings for thermal resilience and health, Energ. Buildings 347 (2025) 116367, https://doi.org/10.1016/j.enbuild.2025.116367.
[45] H. Wan, J. Zhang, Y. Hwang, Enhancing building resilience in cold climates: integrating heat pump technologies with renewable energy, Energy Res. Soc. Sci. 127 (2025) 104168, https://doi.org/10.1016/j.erss.2025.104168.
[46] R. Quiliche, B. Santiago, F.A. Baião, A. Leiras, A predictive assessment of households' risk against disasters caused by cold waves using machine learning, Int. J. Disaster Risk Reduct. 98 (2023) 104109, https://doi.org/10.1016/j.ijdrr.2023.104109.
[47] M. Öcal, A global perspective on cold wave disasters, Sci. Rep. 16 (1) (2025) 1537, https://doi.org/10.1038/s41598-025-31547-4.
[48] K.R. van Daalen, et al., The 2022 Europe report of the *lancet* countdown on health and climate change: towards a climate resilient future, Lancet Public Health 7 (11) (2022) e942–e965, https://doi.org/10.1016/S2468-2667(22)00197-9.
[49] J. Zscheischler, et al., A typology of compound weather and climate events, Nat. Rev. Earth Environ. 1 (7) (2020) 333–347, https://doi.org/10.1038/s43017-020-0060-z.
[50] C. Raymond, et al., Understanding and managing connected extreme events, Nat. Clim. Chang. 10 (7) (2020) 611–621, https://doi.org/10.1038/s41558-020-0790-4.
[51] M. Laetitia, et al., The hot summer-cold winter region in China: challenges in the low carbon adaptation of residential slab buildings to enhance comfort, Energ. Buildings 223 (2020) 110181, https://doi.org/10.1016/j.enbuild.2020.110181.
[52] T. Tamer, I. Gürsel Dino, D.K. Baker, C. Meral Akgül, Coupling PCM wallboard utilization with night ventilation: energy efficiency and overheating risk in office buildings under climate change impact, Energ. Buildings 298 (2023) 113482, https://doi.org/10.1016/j.enbuild.2023.113482.
[53] K. Sun, M. Specian, T. Hong, Nexus of thermal resilience and energy efficiency in buildings: a case study of a nursing home, Build. Environ. 177 (2020) 106842, https://doi.org/10.1016/j.buildenv.2020.106842.
[54] M. Sheng, M. Reiner, K. Sun, T. Hong, Assessing thermal resilience of an assisted living facility during heat waves and cold snaps with power outages, Build. Environ. 230 (2023) 110001, https://doi.org/10.1016/j.buildenv.2023.110001.
[55] H. Zhou, J. Peng, H. Yang, Experimental study on thermal, electrical and energy performance of solar PV vacuum glazing (SVG) insulated walls in hot climates, Renew. Energy 256 (2026) 124166, https://doi.org/10.1016/j.renene.2025.124166.
[56] N. Eslamirad, A. Sepúlveda, F.D. Luca, K.S. Lylykangas, Evaluating outdoor thermal comfort using a mixed-method to improve the environmental quality of a university campus, Energies 15 (4) (2022), https://doi.org/10.3390/en15041577.
[57] D. Rizmie, L. de Preux, M. Miraldo, R. Atun, Impact of extreme temperatures on emergency hospital admissions by age and socio-economic deprivation in England, Soc. Sci. Med. 308 (2022) 115193, https://doi.org/10.1016/j.socscimed.2022.115193.
[58] A. Panno, G. Carrus, R. Lafortezza, L. Mariani, G. Sanesi, Nature-based solutions to promote human resilience and wellbeing in cities during increasingly hot summers, Environ. Res. 159 (2017) 249–256, https://doi.org/10.1016/j.envres.2017.08.016.
[59] A. Lehoczky, J.A. Sobrino, D. Skoković, E. Aguilar, The urban heat island effect in the city of Valencia: a case study for hot summer days, Urban Sci. 1 (1) (2017), https://doi.org/10.3390/urbansci1010009.
[60] T. Amnuaylojaroen, N. Parasin, A machine learning perspective on the climatic and socioeconomic determinants of mental health in Southeast Asia, World 6 (2) (2025), https://doi.org/10.3390/world6020048.
[61] S. An, A. Dedekorkut-Howes, The heat is on: how well are densely populated Korean cities adapting to increased temperatures and urban Heat Island effect? Environments 12 (3) (2025) https://doi.org/10.3390/environments12030087.
[62] E. Foroutan, S. Niazmardi, T. Hu, Spatiotemporal analysis of heat-related emergency department visits and hospitalizations in Florida (2005–2021): a Bayesian change point detection approach, Sustain. Cities Soc. 123 (2025) 106288, https://doi.org/10.1016/j.scs.2025.106288.
[63] H. Khaleghi, A. Karatas, An Experimental Framework to Measure Dynamic Thermal Resilience of Wall Panels under Extreme Weather Conditions, 2024, pp. 327–335, https://doi.org/10.1061/9780784485279.034.
[64] M. Bruneau, et al., A framework to quantitatively assess and enhance the seismic resilience of communities, Earthquake Spectra 19 (4) (2003) 733–752, https://doi.org/10.1193/1.1623497.
[65] A.S. Masten, Ordinary magic: resilience processes in development, Am. Psychol. 56 (3) (2001) 227–238, https://doi.org/10.1037/0003-066X.56.3.227.
[66] C. Folke, Resilience: the emergence of a perspective for social–ecological systems analyses, Glob. Environ. Chang. 16 (3) (2006) 253–267, https://doi.org/10.1016/j.gloenvcha.2006.04.002.
[67] International Energy Agency (IEA), Making the Energy Sector more Resilient to Climate Change, Paris, 2015. Accessed: 11, 2026. [Online]. Available: https://www.iea.org/reports/making-the-energy-sector-more-resilient-to-climate-change.
[68] D. Zhu, et al., Medical expenditures under climate change and SSP-informed physiological and socioeconomic scenarios in China, Glob. Environ. Chang. 94 (2025) 103052, https://doi.org/10.1016/j.gloenvcha.2025.103052.
[69] R. Hoggett, R. Lowes, C.E. Ugalde-Loo, F. Khosravi, Hot and cold: policy perspectives on overheating and cooling in United Kingdom homes, Energy Res. Soc. Sci. 118 (2024) 103803, https://doi.org/10.1016/j.erss.2024.103803.
[70] C. Mayer, S. Seerbauer, M. Brenner-Fließer, M. Ala-Juusela, R. Ramesh, H. Hukari, Stocktaking of Energy Resilience and Energy Poverty Via PEDs, 2025.

[71] OECD, Resilience Strategies and approaches to contain systemic threats, Background Paper, Paris, OECD Conference Centre (2019). Accessed: 11, 2026. [Online]. Available: https://one.oecd.org/document/SG/NAEC(2019)5/en/pdf.

[72] B.D. Trump, et al., Threat-agnostic resilience: framing and applications, Int. J. Disaster Risk Reduct. 124 (2025) 105535, https://doi.org/10.1016/j.ijdrr.2025.105535.

[73] A.M. Saleh, V. István, M.A. Khan, M. Waseem, A.N. Ali Ahmed, Power system stability in the era of energy transition: importance, opportunities, challenges, and future directions, Energy Convers. Manag. X, vol. 24 (2024) 100820, https://doi.org/10.1016/j.ecmx.2024.100820.

[74] T. Hong, et al., Ten questions concerning thermal resilience of buildings and occupants for climate adaptation, Build. Environ. 244 (2023) 110806, https://doi.org/10.1016/j.buildenv.2023.110806.

[75] V.M. Nik, K. Javanroodi, Adaptive reinforcement learning for energy management – a progressive approach to boost climate resilience and energy flexibility, Adv. Appl. Energy 17 (2025) 100213, https://doi.org/10.1016/j.adapen.2025.100213.

[76] R. Ramesh, H.U. Rehman, A. Hasan, L. Eerolainen, H. Yin, M. Hamdy, Optimising energy flexibility in Finnish residential buildings: a comparative study of PI, rule-based and model predictive control strategies, Energ. Buildings 338 (2025) 115727, https://doi.org/10.1016/j.enbuild.2025.115727.

[77] D.J. Bednar, T.G. Reames, Recognition of and response to energy poverty in the United States, Nat. Energy 5 (6) (2020) 432–439, https://doi.org/10.1038/s41560-020-0582-0.

[78] C. Xu, X. Nie, R. Xu, G. Han, D. Wang, Burden trends and future predictions for hypertensive heart disease attributable to non-optimal temperatures in the older adults amidst climate change, 1990–2021, Front. Public Health 12 (2025), https://doi.org/10.3389/fpubh.2024.1525357.

[79] H. Brennenstuhl, M. Will, E. Ries, K. Mechler, S. Garbade, M. Ries, Patterns of extreme temperature-related catastrophic events in Europe including the Russian Federation: a cross-sectional analysis of the emergency events database, BMJ Open 11 (6) (2021) e046359, https://doi.org/10.1136/bmjopen-2020-046359.

[80] X. Huang, J. Song, C. Wang, P.W. Chan, Realistic representation of city street-level human thermal stress via a new urban climate-human coupling system, Renew. Sust. Energ. Rev. 169 (2022) 112919, https://doi.org/10.1016/j.rser.2022.112919.

[81] J. Guo, et al., Assessing the winter indoor environment with different comfort metrics in self-built houses of hot-humid areas: does undercooling matter for the elderly? Build. Environ. 263 (2024) 111871 https://doi.org/10.1016/j.buildenv.2024.111871.

[82] M. Gutland, K. Munro, K. Cant, R. Kotha, R. Evins, A *meta*-analysis of the schematic design process of deep retrofit projects, Energ. Buildings 324 (2024) 114868, https://doi.org/10.1016/j.enbuild.2024.114868.

[83] N.N. Taleb, Antifragile: Things that Gain from Disorder, 1. ed., Random House, New York, NY, 2012.

[84] E.D. Vugrin, D.E. Warren, M.A. Ehlen, R.C. Camphouse, A framework for assessing the resilience of infrastructure and economic systems, in: K. Gopalakrishnan, S. Peeta (Eds.), Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering, Springer, Berlin, Heidelberg, 2010, pp. 77–116, https://doi.org/10.1007/978-3-642-11405-2_3.

[85] Sendai framework for disaster risk reduction 2015-2030 | UNDRR, 2015 [Online]. Available: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.

[86] R.D. Meade, et al., Human heat resilience in a warming climate: biophysical and physiological underpinnings of heat vulnerability and personal cooling strategies, One Earth 7 (8) (2024) 1343–1350, https://doi.org/10.1016/j.oneear.2024.06.007.

[87] H. Pallubinsky, R.P. Kramer, W.D. van Marken Lichtenbelt, Establishing resilience in times of climate change—a perspective on humans and buildings, Clim. Chang. 176 (10) (2023) 135, https://doi.org/10.1007/s10584-023-03614-0.

[88] A. Price, M. Rigby, P. Fiévez, K. Mengersen, A spatial vulnerability index for environmental health, Ecol. Indic. 178 (2025) 113793, https://doi.org/10.1016/j.ecolind.2025.113793.

[89] A. Sengupta, D. Al Assaad, J.B. Bastero, M. Steeman, H. Breesch, Impact of heatwaves and system shocks on a nearly zero energy educational building: is it resilient to overheating? Build. Environ. 234 (2023) 110152 https://doi.org/10.1016/j.buildenv.2023.110152.

[90] L. Niggli, C. Huggel, V. Muccione, R. Neukom, N. Salzmann, Towards improved understanding of cascading and interconnected risks from concurrent weather extremes: analysis of historical heat and drought extreme events, PLOS Clim. 1 (8) (2022) e0000057, https://doi.org/10.1371/journal.pclm.0000057.

[91] E. Davidson, Y. Schwartz, J. Williams, D. Mumovic, Resilience of the higher education sector to future climates: a systematic review of predicted building energy performance and modelling approaches, Renew. Sust. Energ. Rev. 191 (2024) 114040, https://doi.org/10.1016/j.rser.2023.114040.

[92] S. Chen, H. Zhao, H. Wu, Q. Li, L. Zhao, Thermal impact zoning of indoor overheating environments on the human body in hot and humid regions, Build. Environ. 287 (2026) 113714, https://doi.org/10.1016/j.buildenv.2025.113714.

[93] A. Velashjerdi Farahani, J. Jokisalo, N. Korhonen, K. Jylhä, R. Kosonen, Simulation analysis of Finnish residential buildings' resilience to hot summers under a changing climate, J. Build. Eng. 82 (2024) 108348, https://doi.org/10.1016/j.jobe.2023.108348.

[94] S. Flores-Larsen, F. Bre, Night-time urban heat exposure: overheating and thermal resilience of south American bedrooms, Build. Environ. 287 (2026) 113757, https://doi.org/10.1016/j.buildenv.2025.113757.

[95] J. Ferdyn-Grygierek, K. Grygierek, Towards climate-resilient dwellings: a comparative analysis of passive and active retrofit solutions in aging central European housing stock, Energies 18 (16) (2025), https://doi.org/10.3390/en18164386.

[96] S. Bhattacharjee, S. Lidelöw, F. Shadram, Energy and indoor thermal performance analysis of a glazed façade high-rise building under various Nordic climatic conditions, Energy Rep. 10 (2023) 3039–3053, https://doi.org/10.1016/j.egyr.2023.09.090.

[97] A. Houghton, C. Castillo-Salgado, Analysis of correlations between neighborhood-level vulnerability to climate change and protective green building design strategies: a spatial and ecological analysis, Build. Environ. 168 (2020) 106523, https://doi.org/10.1016/j.buildenv.2019.106523.

[98] A. Aijazi, T. Parkinson, H. Zhang, S. Schiavon, Passive and low-energy strategies to improve sleep thermal comfort and energy resilience during heat waves and cold snaps, Sci. Rep. 14 (1) (2024) 12568, https://doi.org/10.1038/s41598-024-62377-5.

[99] D. Singh, Y.S. Bekris, C.D.W. Rogers, J. Doss-Gollin, E.D. Coffel, D.A. Kalashnikov, Enhanced solar and wind potential during widespread temperature extremes across the U.S. interconnected energy grids, Environ. Res. Lett. 19 (4) (2024) 044018, https://doi.org/10.1088/1748-9326/ad2e72.

[100] A.M. Brockway, L.N. Dunn, Weathering adaptation: grid infrastructure planning in a changing climate, Clim. Risk Manag. 30 (2020) 100256, https://doi.org/10.1016/j.crm.2020.100256.

[101] D.J. Sailor, A. Baniassadi, C.R. O'Lenick, O.V. Wilhelmi, The growing threat of heat disasters, Environ. Res. Lett. 14 (5) (2019) 054006, https://doi.org/10.1088/1748-9326/ab0bb9.

[102] J. Hu, et al., Resilient or resistant to non-neutral environments? A comparative study on occupant thermal needs in buildings under natural ventilation, fee-free heating, and fee-charged heating modes, J. Build. Eng. 72 (2023) 106651, https://doi.org/10.1016/j.jobe.2023.106651.

[103] A. Aijazi, S. Schiavon, D. Callaway, Building and occupant characteristics as predictors of temperature-related health hazards in American homes, Build. Environ. 275 (2025) 112805, https://doi.org/10.1016/j.buildenv.2025.112805.

[104] P. Hernandez-Cruz, I. Flores-Abascal, J.M. Hidalgo-Betanzos, M. Almeida, A. Erkoreka-Gonzalez, Environmental and energy analysis of the renovation of social housing buildings under various climate change scenarios and user profiles, J. Build. Eng. 98 (2024) 111164, https://doi.org/10.1016/j.jobe.2024.111164.

[105] D.G. Clark, E.H. Jackson, C.M. Hohl, K.E. Liang, Extreme heat impacts on acute care: examining emergency department visits and hospital admissions during the 2021 British Columbia heatwave, J. Clim. Change Health 17 (2024) 100310, https://doi.org/10.1016/j.joclim.2024.100310.

[106] H. Sohail, V. Kollanus, P. Tiittanen, A. Schneider, T. Lanki, Heat, heatwaves and cardiorespiratory hospital admissions in Helsinki, Finland, Int. J. Environ. Res. Public Health 17 (21) (2020), https://doi.org/10.3390/ijerph17217892.

[107] A. Zhivov, W. Rose, R. Patenaude, W.J. Williams, Requirements for building thermal conditions under Normal and emergency operations in extreme climates, ASHRAE J. 127 (1) (2021) 693–704.

[108] D.A. Zhivov, Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates, ASHRAE, Georgia, 2021.

[109] H. ur Rehman, V.M. Nik, R. Ramesh, A. Hasan, 'Modeling the impact of diverse extreme climate scenarios on residential buildings with renewable energy and storage in cold regions: A techno-economic analysis', presented at the Building Simulation 2025, In building simulation, vol. 19, IBPSA, 2025, https://doi.org/10.26868/25222708.2025.1109.

[110] H. ur Rehman, V. Nik, R. Ramesh, A. Hasan, Investigating the energy resilience performance of the old and new buildings integrated with solar photovoltaic and storage under extreme Nordic condition, ', Presented at the eSim 2024, in eSim,. vol. 13, IBPSA-Canada, 2024. . Accessed: 13, 2026. [Online]. Available: https://publications.ibpsa.org/conference/paper/?id=esim2024_5.

[111] J. Li, C. Liang, W. Zhou, A review of building physical shapes on heating and cooling energy consumption, Energies 17 (22) (2024), https://doi.org/10.3390/en17225766.

[112] K.P. Guddanti, A.K. Bharati, S. Nekkalapu, J. McWheter, S. Morris, A comprehensive review: impacts of extreme temperatures due to climate change on power grid infrastructure and operation 21, 2024, https://doi.org/10.48550/arXiv.2410.08425.

[113] Q. Hu, D. Che, F. Wang, L. He, Analyzing the effects of extreme cold waves on urban water supply network safety: a case study from 2020 to 2021, Urban Clim. 58 (2024) 102146, https://doi.org/10.1016/j.uclim.2024.102146.

[114] E. Ortiz-Prado, A. López-Cortés, I.A. Suárez-Sangucho, C. Salazar-Santoliva, J. Vasconez-Gonzalez, J.S. Izquierdo-Condoy, Facing crisis: how Ecuador's energy shortages threaten public health, Front. Hum. Dyn. 7 (2025), https://doi.org/10.3389/fhumd.2025.1607564.

[115] A.R. Nunes, Exploring the interactions between vulnerability, resilience and adaptation to extreme temperatures, Nat. Hazards 109 (3) (2021) 2261–2293, https://doi.org/10.1007/s11069-021-04919-y.

[116] A. Baniassadi, J. Heusinger, D.J. Sailor, Energy efficiency vs resiliency to extreme heat and power outages: the role of evolving building energy codes, Build. Environ. 139 (2018) 86–94, https://doi.org/10.1016/j.buildenv.2018.05.024.

[117] Centre for Research on the Epidemiology of Disasters (CRED), 2024_EMDAT_report, Brussels, 2025. Accessed: 13, 2026. [Online]. Available: https://files.emdat.be/reports/2024_EMDAT_report.pdf.

[118] S. Grynning, B. Time, B. Matusiak, Solar shading control strategies in cold climates – heating, cooling demand and daylight availability in office spaces, Sol. Energy 107 (2014) 182–194, https://doi.org/10.1016/j.solener.2014.06.007.

[119] S. Dagher, B. Akhozheya, H. Slimani, Energy analysis studying the effect of solar shading on daylight factors and cooling hours in an extreme weather, Energy Rep. 8 (2022) 443–448, https://doi.org/10.1016/j.egyr.2022.10.231.

[120] R. Kotireddy, R. Loonen, P.-J. Hoes, J.L.M. Hensen, Building performance robustness assessment: comparative study and demonstration using scenario analysis, Energ. Buildings 202 (2019) 109362, https://doi.org/10.1016/j.enbuild.2019.109362.

[121] R. Phillips, L. Troup, D. Fannon, M.J. Eckelman, Do resilient and sustainable design strategies conflict in commercial buildings? A critical analysis of existing resilient building frameworks and their sustainability implications, Energ. Buildings 146 (2017) 295–311, https://doi.org/10.1016/j.enbuild.2017.04.009.

[122] A. Katal, M. Mortezazadeh, L. (Leon) Wang, Modeling building resilience against extreme weather by integrated CityFFD and CityBEM simulations, Appl. Energy 250 (2019) 1402–1417, https://doi.org/10.1016/j.apenergy.2019.04.192.

[123] R. Levinson, S.H. Lee, 'Cool envelope benefits in future typical weather and heatwave conditions for single-family homes in Los Angeles', *6TH Int.* Conf. Countermeas. URBAN HEAT Isl. UHI, 2023, pp. 933–942, https://doi.org/10.20357/B7DK6T.

[124] P.J. Rosado, D. Faulkner, D.P. Sullivan, R. Levinson, Measured temperature reductions and energy savings from a cool tile roof on a Central California home, Energ. Buildings 80 (2014) 57–71, https://doi.org/10.1016/j.enbuild.2014.04.024.

[125] X. Liu, Y. Wu, A review of advanced architectural glazing technologies for solar energy conversion and intelligent daylighting control, Archit. Intell. 1 (1) (2022) 10, https://doi.org/10.1007/s44223-022-00009-6.

[126] ISO 52016–3:2023 : Energy performance of buildings — Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads 2023 [Online]. Available: https://www.iso.org/standard/75395.html.

[127] International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), 'Categorization of BIPV Applications', in *Task 15 Enabling Framework for the Development of BIPV* [Online]. Available: https://iea-pvps.org/wp-content/uploads/2021/09/IEA-PVPS-T15-12_2021_BIPV-categorization_report.pdf, 2021.

[128] S. Barbosa, K. Ip, Perspectives of double skin façades for naturally ventilated buildings: a review, Renew. Sust. Energ. Rev. 40 (2014) 1019–1029, https://doi.org/10.1016/j.rser.2014.07.192.

[129] X. Loncour, A. Deneyer, M. Blasco, G. Flamant, P. Wouters, Ventilated Double Skin Façades - Classification & illustration of façade concepts, Air Infiltration and Ventilation Centre, Brussels, AIVC-CR03, 2005 [Online]. Available: https://www.aivc.org/sites/default/files/members_area/medias/pdf/CR/CR03_Ventilated_Double_Facades.pdf.

[130] M. Kazemi, L. Courard, S. Attia, Water permeability, water retention capacity, and thermal resistance of green roof layers made with recycled and artificial aggregates, Build. Environ. 227 (2023) 109776, https://doi.org/10.1016/j.buildenv.2022.109776.

[131] M. Radić, M.B. Dodig, T. Auer, Green facades and living walls—a review establishing the classification of construction types and mapping the benefits, Sustainability 11 (17) (2019), https://doi.org/10.3390/su11174579.

[132] N. Kapilan, A.M. Isloor, S. Karinka, A comprehensive review on evaporative cooling systems, Results Eng. 18 (2023) 101059, https://doi.org/10.1016/j.rineng.2023.101059.

[133] International Energy Agency (IEA), EBC Annex62 Ventilative Cooling, IEA, London, 2019. Accessed: 15, 2026. [Online]. Available: https://www.iea-ebc.org/Data/publications/EBC_SR_Annex62.pdf.

[134] P. Liu, Q. Zhang, K. Zhong, Y. Wei, Q. Wang, Climate adaptation and indoor comfort improvement strategies for buildings in high-cold regions: empirical study from Ganzi region, China, Sustainability 14 (1) (2022), https://doi.org/10.3390/su14010576.

[135] A. Hirsch, Y. Parag, J. Guerrero, Microgrids: a review of technologies, key drivers, and outstanding issues, Renew. Sust. Energ. Rev. 90 (2018) 402–411, https://doi.org/10.1016/j.rser.2018.03.040.

[136] D.T. Ton, M.A. Smith, The U.S. Department of Energy's microgrid initiative, Electr. J. 25 (8) (2012) 84–94, https://doi.org/10.1016/j.tej.2012.09.013.

[137] P. Balducci, K. Mongird, D. Wu, D. Wang, V. Fotedar, R. Dahowski, An evaluation of the economic and resilience benefits of a microgrid in Northampton, Massachusetts, Energies 13 (18) (2020), https://doi.org/10.3390/en13184802.

[138] A. Reyes–Ascanio, A. Colmenar–Santos, C. Pérez–Molina, E. Rosales–Asensio, Application of Microgrids to Improve Resilience with a Focus on Healthcare, 2021 4th Asia conference on energy and electrical engineering (ACEEE), 2021, pp. 49–57, https://doi.org/10.1109/ACEEE51855.2021.9575058.

[139] S. Homaei, M. Hamdy, Thermal resilient buildings: how to be quantified? A novel benchmarking framework and labelling metric, Build. Environ. 201 (2021) 108022, https://doi.org/10.1016/j.buildenv.2021.108022.

[140] R. Gupta, A. Bruce-Konuah, A. Howard, Achieving energy resilience through smart storage of solar electricity at dwelling and community level, Energ. Buildings 195 (2019) 1–15, https://doi.org/10.1016/j.enbuild.2019.04.012.

[141] H. Kotani, K. Nakano, Household resilience realized by photovoltaic and battery energy system in natural hazard-triggered blackouts: evidence from Japan, Int. J. Disaster Risk Reduct. 90 (2023) 103656, https://doi.org/10.1016/j.ijdrr.2023.103656.

[142] A. Lagrange, M. de Simón-Martín, A. González-Martínez, S. Bracco, E. Rosales-Asensio, Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: An application to a hospital, Int. J. Electr. Power Energy Syst. 119 (2020) 105865, https://doi.org/10.1016/j.ijepes.2020.105865.

[143] K. Kharbanda, H.W. Samuelson, Quantifying thermal resilience with energy efficiency in residential building stock models, in: U. Berardi (Ed.), Multiphysics and Multiscale Building Physics, Springer Nature, Singapore, 2025, pp. 245–250, https://doi.org/10.1007/978-981-97-8309-0_32.

[144] S.B. Sepúlveda-Mora, S. Hegedus, Resilience analysis of renewable microgrids for commercial buildings with different usage patterns and weather conditions, Renew. Energy 192 (2022) 731–744, https://doi.org/10.1016/j.renene.2022.04.090.

[145] T.M. Azerefegn, R. Bhandari, A.V. Ramayya, Techno-economic analysis of grid-integrated PV/wind systems for electricity reliability enhancement in Ethiopian industrial park, Sustain. Cities Soc. 53 (2020) 101915, https://doi.org/10.1016/j.scs.2019.101915.

[146] A.C. Violante, F. Donato, G. Guidi, M. Proposito, Comparative life cycle assessment of the ground source heat pump vs air source heat pump, Renew. Energy 188 (2022) 1029–1037, https://doi.org/10.1016/j.renene.2022.02.075.

[147] A. Gautier, M. Wetter, M. Sulzer, Resilient cooling through geothermal district energy system, Appl. Energy 325 (2022) 119880, https://doi.org/10.1016/j.apenergy.2022.119880.

[148] S. Mehmood, J. Lizana, D. Friedrich, Low-energy resilient cooling through geothermal heat dissipation and latent heat storage, J. Energy Storage 72 (2023) 108377, https://doi.org/10.1016/j.est.2023.108377.

[149] M.A. Abdel-Mawla, M.A. Hassan, A. Khalil, Impact of placement and design of phase change materials in thermally activated buildings, J. Energy Storage 56 (2022) 105886, https://doi.org/10.1016/j.est.2022.105886.

[150] S. Moslehi, T.A. Reddy, Sustainability of integrated energy systems: a performance-based resilience assessment methodology, Appl. Energy 228 (2018) 487–498, https://doi.org/10.1016/j.apenergy.2018.06.075.

[151] S. Homaei, M. Hamdy, Quantification of energy flexibility and survivability of all-electric buildings with cost-effective battery size: methodology and indexes, Energies 14 (10) (2021), https://doi.org/10.3390/en14102787.

[152] J. Wolf, W.N. Adger, I. Lorenzoni, V. Abrahamson, R. Raine, Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities, Glob. Environ. Chang. 20 (1) (2010) 44–52, https://doi.org/10.1016/j.gloenvcha.2009.09.004.

[153] A. Li, M. Toll, R. Bentley, The risk of energy hardship increases with extreme heat and cold in Australia, Commun. Earth Environ. 5 (1) (2024) 595, https://doi.org/10.1038/s43247-024-01729-5.

[154] A. Gasparrini, et al., Mortality risk attributable to high and low ambient temperature: a multicountry observational study, Lancet 386 (9991) (2015) 369–375, https://doi.org/10.1016/S0140-6736(14)62114-0.

[155] B. Pioppi, I. Pigliautile, C. Piselli, A.L. Pisello, Cultural heritage microclimate change: human-centric approach to experimentally investigate intra-urban overheating and numerically assess foreseen future scenarios impact, Sci. Total Environ. 703 (2020) 134448, https://doi.org/10.1016/j.scitotenv.2019.134448.

[156] M. Marí-Dell'Olmo, et al., Social inequalities in the association between temperature and mortality in a south European context, Int. J. Public Health 64 (1) (2019) 27–37, https://doi.org/10.1007/s00038-018-1094-6.

[157] M. Khan, R. Bhattarai, L. Chen, Assessment of deadly heat stress and extreme cold events in the upper Midwestern United States, Atmosphere 15 (5) (2024), https://doi.org/10.3390/atmos15050614.

[158] R. Cole, et al., Systemic inequalities in heat risk for greater London, Environ. Int. 190 (2024) 108925, https://doi.org/10.1016/j.envint.2024.108925.

[159] D. Zendeli, et al., From heatwaves to "healthwaves": a spatial study on the impact of urban heat on cardiovascular and respiratory emergency calls in the city of Milan, Sustain. Cities Soc. 124 (2025) 106181, https://doi.org/10.1016/j.scs.2025.106181.

[160] P.A. Méndez-Lázaro, et al., Too hot and too humid in the Caribbean: impacts of extreme heat events and non-accidental mortality in the tropical island of Puerto Rico (2015-2020), J. Clim. Change Health 25 (2025) 100484, https://doi.org/10.1016/j.joclim.2025.100484.

[161] A. Maxim, E. Grubert, Anticipating climate-related changes to residential energy burden in the United States: advance planning for equity and resilience, Environ. Justice 15 (3) (2022) 139–148, https://doi.org/10.1089/env.2021.0056.

[162] P. Zeng, et al., Significant social inequalities exist between hot and cold extremes along urban-rural gradients, Sustain. Cities Soc. 82 (2022) 103899, https://doi.org/10.1016/j.scs.2022.103899.

[163] M. Chen, et al., Rising vulnerability of compound risk inequality to ageing and extreme heatwave exposure in global cities, Npj Urban Sustain. 3 (1) (2023) 38, https://doi.org/10.1038/s42949-023-00118-9.

[164] D. Bienvenido-Huertas, D. Sánchez-García, C. Rubio-Bellido, J.A. Pulido-Arcas, Applying the mixed-mode with an adaptive approach to reduce the energy poverty in social dwellings: the case of Spain, Energy 237 (2021) 121636, https://doi.org/10.1016/j.energy.2021.121636.

[165] M.D. Alba-Rodríguez, C. Rubio-Bellido, M. Tristancho-Carvajal, R. Castaño-Rosa, M. Marrero, Present and future energy poverty, a holistic approach: a case study in Seville, Spain, Sustainability 13 (14) (2021), https://doi.org/10.3390/su13147866.

[166] S.E. Grineski, T.W. Collins, J. Chakraborty, Cascading disasters and mental health inequities: winter storm Uri, COVID-19 and post-traumatic stress in Texas, Soc. Sci. Med. 315 (2022) 115523, https://doi.org/10.1016/j.socscimed.2022.115523.

[167] E.T.C. Lai, P.H. Chau, K. Cheung, M. Kwan, K. Lau, J. Woo, Perception of extreme hot weather and the corresponding adaptations among older adults and service providers–a qualitative study in Hong Kong, Front. Public Health 11 (2023), https://doi.org/10.3389/fpubh.2023.1056800.

[168] Y.A. Boafo, E.F. Amankwaa, C. Spataru, P. Carvalho, "It is getting too hot lately": urban households' knowledge, experiences and governance of extreme heat

events in Accra, Ghana, Urban Clim. 59 (2025) 102287, https://doi.org/10.1016/j.uclim.2025.102287.
[169] M. Guardaro, M. Messerschmidt, D.M. Hondula, N.B. Grimm, C.L. Redman, Building community heat action plans story by story: a three neighborhood case study, Cities 107 (2020) 102886, https://doi.org/10.1016/j.cities.2020.102886.
[170] C.J. Gabbe, J.S. Chang, M. Kamson, E. Seo, Reducing heat risk for people experiencing unsheltered homelessness, Int. J. Disaster Risk Reduct. 96 (2023) 103904, https://doi.org/10.1016/j.ijdrr.2023.103904.
[171] C.J. Gronlund, K.P. Sullivan, Y. Kefelegn, L. Cameron, M.S. O'Neill, Climate change and temperature extremes: a review of heat- and cold-related morbidity and mortality concerns of municipalities, Maturitas 114 (2018) 54–59, https://doi.org/10.1016/j.maturitas.2018.06.002.
[172] L. Green, et al., Determining the public health impact of climate change: a national study using a health impact assessment approach in Wales, Int. J. Public Health 69 (2024) 1606972, https://doi.org/10.3389/ijph.2024.1606972.
[173] A. Baniassadi, W. Yu, T. Travison, R. Day, L. Lipsitz, B. Manor, Home ambient temperature and self-reported attention in community-dwelling older adults, J. Gerontol. A Biol. Sci. Med. Sci. 80 (4) (2025) glae286, https://doi.org/10.1093/gerona/glae286.
[174] S. Allison, T. Bastiampillai, S. Kisely, H. Cornell, J.C. Looi, Psychiatrists should champion the care of those with severe mental illnesses experiencing climate change-related heat stress, Australas. Psychiatry 33 (3) (2025) 356–360, https://doi.org/10.1177/10398562251319921.
[175] M.K.K. Rony, H.M. Alamgir, High temperatures on mental health: recognizing the association and the need for proactive strategies—a perspective, Health Sci. Rep. 6 (12) (2023) e1729, https://doi.org/10.1002/hsr2.1729.
[176] D.A. Siddiqi, et al., Assessing the impact of heat waves on childhood immunization coverage in Sindh, Pakistan: insights from 132.4 million doses recorded in the provincial electronic immunization registry (2018–2024), Vaccine 61 (2025) 127424, https://doi.org/10.1016/j.vaccine.2025.127424.
[177] H. ur Rehman, V.M. Nik, R. Ramesh, M. Ala-Juusela, Quantifying and rating the energy resilience performance of buildings integrated with renewables in the Nordics under typical and extreme climatic conditions, Buildings 14 (9) (2024), https://doi.org/10.3390/buildings14092821.
[178] ASHRAE, ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55–2017, Atlanta, 2020 [Online]. Available: https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/55_2017_d_20200731.pdf.
[179] D.T. Novieto, Adapting a Human Thermoregulation Model for Predicting the Thermal Response of Older Persons, De Montfort University, Leicester, 2013.
[180] T. Ma, J. Xiong, Z. Lian, A human thermoregulation model for the Chinese elderly, J. Therm. Biol. 70 (2017) 2–14, https://doi.org/10.1016/j.jtherbio.2017.08.002.
[181] World Health Organization, WHO, WHO Housing and Health Guidelines, WHO, Geneva, 2018.
[182] The Scottish Government, 'A New Definition of Fuel Poverty in Scotland: A Review of Recent Evidence', The Scottish Government, Edinburgh, 2017.
[183] E. Zapata-Webborn, et al., Winter demand falls as fuel bills rise: understanding the energy impacts of the cost-of-living crisis on British households, Energ. Buildings 305 (2024) 113869, https://doi.org/10.1016/j.enbuild.2023.113869.
[184] S. Vandentorren, et al., August 2003 heat wave in France: risk factors for death of elderly people living at home, Eur. J. Pub. Health 16 (6) (2006) 583–591, https://doi.org/10.1093/eurpub/ckl063.
[185] J. Potter, et al., National audit of continence care for older people: management of faecal incontinence, Age Ageing 36 (3) (2007) 268–273, https://doi.org/10.1093/ageing/afm004.
[186] Y. Kim, W. Lee, H. Kim, Y. Cho, Social isolation and vulnerability to heatwave-related mortality in the urban elderly population: a time-series multi-community study in Korea, Environ. Int. 142 (2020) 105868, https://doi.org/10.1016/j.envint.2020.105868.
[187] M. Ach-Chakhar, A.M. El Bat, S. Guernouti, Z. Romani, A. Draoui, Impact of heatwaves on energy performance and thermal comfort in urban buildings: integrated approach with microclimatic modeling, Energ. Buildings 347 (2025) 116258, https://doi.org/10.1016/j.enbuild.2025.116258.
[188] I. Gaetani, P.-J. Hoes, J.L.M. Hensen, Occupant behavior in building energy simulation: towards a fit-for-purpose modeling strategy, Energ. Buildings 121 (2016) 188–204, https://doi.org/10.1016/j.enbuild.2016.03.038.
[189] K. Amada, J. Kim, M. Inaba, M. Akimoto, S. Kashihara, S. Tanabe, Feasibility of staying at home in a net-zero energy house during summer power outages, Energ. Buildings 273 (2022) 112352, https://doi.org/10.1016/j.enbuild.2022.112352.
[190] D. Amaripadath, E. Azar, M.K. Singh, S. Attia, Heat exposure mitigation in renovated nearly zero-energy dwellings during concurrent heat waves and power outages, J. Build. Eng. 91 (2024) 109655, https://doi.org/10.1016/j.jobe.2024.109655.
[191] B. Stone, et al., Climate change and infrastructure risk: indoor heat exposure during a concurrent heat wave and blackout event in Phoenix, Arizona, Urban Clim. 36 (2021) 100787, https://doi.org/10.1016/j.uclim.2021.100787.
[192] M. Rajput, et al., Heat exposure during a power outage: a simulation study of residences across the metro Phoenix area, Energ. Buildings 259 (2022) 111605, https://doi.org/10.1016/j.enbuild.2021.111605.
[193] A.S. Aziz, M.F.N. Tajuddin, M.R. Adzman, M.F. Mohammed, M.A.M. Ramli, Feasibility analysis of grid-connected and islanded operation of a solar PV microgrid system: a case study of Iraq, Energy 191 (2020) 116591, https://doi.org/10.1016/j.energy.2019.116591.
[194] C. Bastholm, F. Fiedler, Techno-economic study of the impact of blackouts on the viability of connecting an off-grid PV-diesel hybrid system in Tanzania to the national power grid, Energy Convers. Manag. 171 (2018) 647–658, https://doi.org/10.1016/j.enconman.2018.05.107.
[195] M. Tavakoli, F. Shokridehaki, M. Funsho Akorede, M. Marzband, I. Vechiu, E. Pouresmaeil, CVaR-based energy management scheme for optimal resilience and operational cost in commercial building microgrids, Int. J. Electr. Power Energy Syst. 100 (2018) 1–9, https://doi.org/10.1016/j.ijepes.2018.02.022.
[196] L. Ji, C. Shu, A. Laouadi, M. Lacasse, L. (Leon) Wang, Quantifying improvement of building and zone level thermal resilience by cooling retrofits against summertime heat events, Build. Environ. 229 (2023) 109914, https://doi.org/10.1016/j.buildenv.2022.109914.
[197] W. Liu, J. An, C. Wang, S. Hu, Comparative study on outdoor heatwave indicators for indoor overheating evaluation, Buildings 15 (14) (2025), https://doi.org/10.3390/buildings15142461.
[198] S. Flores-Larsen, C. Filippín, F. Bre, New metrics for thermal resilience of passive buildings during heat events, Build. Environ. 230 (2023) 109990, https://doi.org/10.1016/j.buildenv.2023.109990.
[199] R. Rahif, A. Fani, P. Kosinski, S. Attia, Climate change sensitive overheating assessment in dwellings: a case study in Belgium, ', presented at the 2021 Building Simulation Conference, Sep., 2021 https://doi.org/10.26868/25222708.2021.30125.
[200] S. Salimi, E. Estrella Guillén, H. Samuelson, Exceedance degree-hours: a new method for assessing long-term thermal conditions, Indoor Air 31 (6) (2021) 2296–2311, https://doi.org/10.1111/ina.12855.
[201] S. Bucking, M. Rostami, E. Ho, 'Quantifying resilience at scale using EnergyPlus and Modelica', in The 4th IBPSA-Scotland Conference, Edinburgh, 2024 [Online]. Available: https://publications.ibpsa.org/proceedings/usim/2024/papers/usim2024_1A-4.pdf.
[202] H. Gong, D.M. Ionel, Improving the power outage resilience of buildings with solar PV through the use of battery systems and EV energy storage, Energies 14 (18) (2021), https://doi.org/10.3390/en14185749.
[203] A.R. Rempel, J. Danis, A.W. Rempel, M. Fowler, S. Mishra, Improving the passive survivability of residential buildings during extreme heat events in the Pacific northwest, Appl. Energy 321 (2022) 119323, https://doi.org/10.1016/j.apenergy.2022.119323.
[204] C. Lin, D. Niyogi, D.B.C. Crawley, Z. Nagy, 'Estimating indoor mortality and heat risk in residential dwellings in extreme weather scenarios', presented at the Building Simulation 2025, In building simulation, vol. 19, IBPSA, 2025, https://doi.org/10.26868/25222708.2025.1127.
[205] D. Coley, T. Kershaw, Changes in internal temperatures within the built environment as a response to a changing climate, Build. Environ. 45 (1) (2010) 89–93, https://doi.org/10.1016/j.buildenv.2009.05.009.
[206] R. Wang, S. Lu, W. Feng, B. Xu, Tradeoff between heating energy demand in winter and indoor overheating risk in summer constrained by building standards, Build. Simul. 14 (4) (2021) 987–1003, https://doi.org/10.1007/s12273-020-0719-x.