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Thermal Resilience of Buildings and Communities: A Multistakeholder Review of Metrics and Approaches

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Keywords

resilience, heat stress, extreme weather, building life cycle, community

Abstract

Increasing temperature-related hazards require a collective effort to assess and enhance the thermal resilience of buildings and communities to protect occupants' safety and minimize property or infrastructure damage. However, limited coordination across stakeholders and lack of standardized procedures for resilience assessment undermine the effectiveness of extreme temperature mitigation and adaptation strategies across the building life cycle. This review examines the current literature on resilience metrics to address thermal stress and risk due to extreme indoor environments. Stakeholders of thermal resilience include architects and engineers, occupants, property owners, real estate developers, urban planners, and policymakers. Additionally, motivations for measuring thermal resilience are emphasized, such as safeguarding occupant health and survivability, protecting property, and ensuring business continuity during extreme weather events. This review provides actionable insights and identifies future research needs for

enhancing resilience through tailored metrics for stakeholders during the planning, design, construction, operation, and retrofitting phases of buildings and communities.

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1. INTRODUCTION

The 2024 Global Risk Report identified extreme weather as the most severe risk for the decade (1), driven by the increasing frequency and intensity of natural disasters (2). It is paramount to future-proof new and existing buildings to withstand extreme events as the main source of protection against weather conditions (3). Failure in doing so will have a cascading effect across the entire building and construction value chain, starting with the occupants (4).

Increases in the average global surface temperatures and more hazardous rainfall patterns are examples of expected chronic hazards with long-term impacts, whereas acute hazards could impact communities in the short-term through heat waves, cold snaps, floods, droughts, and wildfires, for example (4). Such hazards trigger market and policy risks with climate uncertainty reducing the values of assets, increasing costs of insurance and key resources (e.g., water and energy), and demanding stricter regulations and taxation (4). Among these climate hazards, extreme temperatures increase the risk of overheating or overcooling in buildings, especially for those without space heating or cooling systems, or facing power outages during extreme weather. These conditions can severely impact occupants' health, productivity (5), and mortality (6). According to the National Weather Service, over the past 30 years, heat has caused more fatalities on average than any other weather-related disaster in the United States (7). Still, a study suggests that the actual number is significantly higher than reported (8). Additionally, the increasing likelihood of extreme weather events has led to more frequent occurrences of power outages in recent years. In 2021, Winter Storm Uri, in Texas and the southern United States, triggered a series of power failures due to the grid's inability to meet the unexpected demand caused by low ambient temperatures, leading to over \$18 billion in property damage (9). The 2022 heat wave in Sichuan Province, China, led to power outages due to surging energy demand and subsequent droughts, resulting in a shortage of hydroelectric power (10).

Risk: the effect of uncertainty on objectives, characterized by potential events, consequences, and their likelihood of occurrence

Hazard: phenomenon that can cause loss of life, injury or health impacts, property damage, social and economic disruption, or environmental degradation

Extreme heat and cold can cause significant physical damage to buildings, infrastructure, and the environment. Buildings may suffer from material degradation, such as cracking, warping, and fading of finishes. Heating, ventilation, and air-conditioning (HVAC) systems can experience increased wear and failure. Infrastructure, including roads, railways, and bridges, can buckle, crack, and misalign due to thermal stress. Environmental impacts include vegetation stress, higher wild-fire risks, and reduced water supplies due to increased evaporation (11). Unlike the effect of other climate hazards, such outcomes often go undetected because many of the world's most vulnerable regions lack monitoring capabilities to detect impacts of extreme temperatures (12, 13). Financial losses are nonetheless high and compounding, as seen from the 2009 heat wave in Australia, when direct losses were estimated at \$800 million (14) and labor productivity losses were estimated at \$6.2 billion (5).

In spite of increasing climate uncertainties, practitioners in the construction sector still design, build, and operate buildings considering business-as-usual scenarios with typical operation and climate data from the past (15). For instance, design days are curated from the historical weather data that were used in calculating peak cooling and heating loads of buildings and sizing the capacity of HVAC equipment. However, thermal resilience considerations within buildings and communities are crucial for minimizing financial losses and ensuring the safety and comfort of occupants, particularly with growing weather extremes.

Meerow et al. (16) propose a comprehensive definition of urban resilience, which is adapted and considered in this study in terms of thermal resilience of buildings and communities:

the ability of the built domain—and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales—to maintain or rapidly return to desired indoor thermal conditions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.

This definition aligns with that of the International Energy Agency's Energy in Buildings and Communities Programme Annex 80 – Resilient cooling of buildings (<https://annex80.iea-ebc.org/>), which characterizes thermal resilience of buildings over the course of resistance, robustness, and recovery phases. These and other characteristics are described in the literature to estimate resiliency, which is hard to directly measure (17). Multiple metrics have been used to quantify thermal resilience, but consensus on the suitability of the resiliency metrics for different use cases, stakeholders, and across the life cycle stages is needed to develop a flexible thermal resilience assessment framework (18, 19).

Thermal resilience is a collective problem because individual actions may be insufficient to mitigate the negative impacts of overheating or overcooling in buildings (13). Thus, responsibility for mitigating climate risks is shared across different groups in society with complementary areas of collaboration, like governments, researchers, the private sector (12), and public health and community organizations. Integration of the interests across different stakeholders remains limited, hindering the effectiveness of achieving thermal resilience.

Several existing studies have reviewed resilience concepts related to buildings (19–21). The concept of building thermal resilience, from both ecological and engineering perspectives, has been examined, highlighting the urgent need for a systematic conceptual and assessment framework (20). Additionally, existing research has qualitatively reviewed cooling strategies and their effects on improving building thermal resilience, particularly for the design phase or retrofit planning (21).

Yet, based on the existing reviews, it is evident that current literature on building thermal resilience primarily concentrates on the design and retrofit stages and rarely covers both heat and cold stress or risk. To our knowledge, no reviews address the evaluation of thermal resilience

Resistance: resistant buildings maintain adequate indoor thermal conditions during both normal and extreme weather events without experiencing system failures

Robustness: robust buildings may experience failures during extreme conditions but can withstand the impact and transition effectively into a recovery phase

Vulnerability:

susceptibility of individuals, households, businesses, assets, or systems in a city to the impacts of hazards

Supplemental Material >

across the entire building life cycle (planning, design, construction, operation, and retrofitting) and cover both the individual buildings' and communities' scales. Furthermore, current reviews lack an integrated multidimensional categorization and discussion of building thermal resilience metrics considering multiple stakeholders' interests and their decision-making.

This article aims to bridge these gaps by providing a comprehensive review of resilience metrics tailored to different stakeholder needs for measuring and fostering thermally resilient buildings and communities. The scope focuses on the resilience of indoor built environments against thermal (overheating and overcooling) risks and how stakeholders at different scales can act upon these risks using quantitative thermal resilience metrics. This study reviews 175 articles and conference papers, along with relevant reports in the field. The literature selection method and detailed findings are provided in **Supplemental Appendix 1**.

This review was guided by the following questions, which encompass the five W's of urban resilience—resilience for whom, why, what, when, and where (16):

1. Who are the stakeholders of thermal resilience of buildings and communities?
2. Why is there a need to measure thermal resilience and what are the underlying motivations?
3. What can stakeholders do to promote resilience? How would they make contributions?
4. When should resilience be considered within the building life cycle?
5. Where can stakeholders promote resilience?

2. THERMAL RESILIENCE BENEFITS TO STAKEHOLDERS ACROSS THE BUILDING LIFE CYCLE STAGES

Thermal resilience offers significant benefits to stakeholders throughout the building life cycle. Building owners and developers experience reduced exposure to financial losses from climate-related damages and higher chances of operation continuity during extreme events. Occupants enjoy higher levels of thermal comfort, leading to improved productivity and health (22). Emergency responders are better equipped to handle extreme weather events, reducing strain on public services. From planning to operation stages, resilient communities enjoy higher economic stability by minimizing risks (23) and enhancing equitable access to cooling and heating resources. Nonetheless, resilience is often overlooked owing to the lack of clearly defined quantitative valuation approaches, e.g., to estimate the return on investments on resilient systems (24) or monetize the resultant increase in occupants' health or well-being. **Table 1** summarizes the main stakeholders of thermal resilience and their associated benefits across the stages in the life cycle of buildings and communities.

3. REVIEW OF RESILIENCE METRICS

The reviewed articles considered multiple metrics explicitly or implicitly related to thermal resilience. Often these metrics have been borrowed from other fields, like the occurrence of health comorbidities in a population from the medical sciences. Thus, many of them do not explicitly translate into thermal resilience but are part of an information chain that can guide different stakeholders into improving resilience of buildings and communities. Additionally, a variety of new metrics have been created by adopting earlier concepts but naming them differently, as previously noted by Siu et al. (19). To better describe the metrics identified, they were grouped into four types with the intention of mapping to the interests of major stakeholders: (a) occupants' vulnerability metrics, (b) systems vulnerability metrics, (c) financial metrics, and (d) energy performance metrics, as previously described by Hong et al. (29). Quantification of vulnerability in a resilience assessment reveals the susceptibility of buildings, communities, or systems to hazards

Table 1 Stakeholders of thermal resilience throughout the building life cycle and associated resilience benefits

Stakeholders	Life cycle phase ^a					
Architects and engineers	P	D	C	O	R	References
<i>Design innovation and/or code compliance:</i> opportunities for voluntary innovative design solutions that prioritize thermal comfort, energy performance, and occupant well-being; when resilience codes and standards are already in place, they could indicate code compliance	X	X			X	15
<i>Project differentiation:</i> competitive advantage in the market by offering buildings with superior thermal performance and resilience features	X	X			X	15
Building occupants	P	D	C	O	R	Reference
<i>Comfort, productivity, and health:</i> enhanced indoor thermal comfort and improved productivity				X		24, 25
<i>Risk mitigation:</i> reduced exposure to financial losses from extreme weather events, climate-related damages (e.g., food spoilage, damage to medicines, interrupted services), and reduced risks of temperature-related health issues and/or relocation during extreme events				X		24
Building owners and developers	P	D	C	O	R	Reference
<i>Cost savings:</i> lower utility bills due to improved energy efficiency, reduced operational expenses through optimized heating and cooling systems, and lower building insurance premiums				X		24, 25
<i>Risk mitigation:</i> reduced exposure to financial losses from extreme weather events and climate-related damages (e.g., pipes freezing and water heaters bursting); higher chances of sustained operations (business continuity) during extreme temperature events				X		24, 25
<i>Asset value enhancement:</i> higher property value and market competitiveness associated with resilient buildings; enhanced branding and increased buy-in from influential stakeholders; higher rent premiums; lower vacancy rates	X	X		X	X	24, 25
Facility and property managers	P	D	C	O	R	Reference
<i>Risk management:</i> early detection of building performance issues; timely response to maintenance needs; and mitigation of downtime risks				X		25
<i>Tenant satisfaction:</i> higher tenant satisfaction rates; lower tenant turnover; improved tenant retention through thermal safety during extreme events				X		25
Urban planners, policymakers, municipal officials and emergency responders	P	D	C	O	R	Reference
<i>Community resilience:</i> enhanced resilience of communities to temperature-related hazards through resilient building design and urban planning; adequate access to cooling and heating resources	X	X		X	X	
<i>Public health and safety:</i> protection of public health, safety, and welfare through preparedness and response efforts prior to, during, and after extreme events	X			X		26
<i>Economic stability:</i> reduced productivity losses and economic disruptions by providing comfortable working and living conditions even during extreme temperatures	X			X		23, 27
<i>Environmental sustainability:</i> reduced environmental impact from energy consumption, greenhouse gas emissions, and urban heat island effects to foster resilience in the long-term	X					28

(Continued)

Table 1 (Continued)

Stakeholders	Life cycle phase ^a					
Financial institutions and insurance providers	P	D	C	O	R	Reference
<i>Risk management</i> : reduced exposure to financial risks associated with climate-related damages, insurance claims, and property losses	X			X		24
<i>Risk mitigation</i> : lower claim likelihood and severity due to resilient building designs; reduced financial liabilities enabling more competitive premiums	X			X		25
Energy providers and utility companies	P	D	C	O	R	Reference
<i>Grid stability</i> : improved grid reliability, resilience, and stability through energy-efficient buildings, distributed energy resources, and demand response measures	X	X		X		24
<i>Demand management</i> : opportunities for demand-side management programs, peak load reduction initiatives, energy conservation incentives, and enhanced system recovery	X			X		24

^aBuilding life cycle phases: P, planning; D, design; C, construction; O, operation; R, retrofitting.

(30) that threaten thermal resilience. Such information helps inform strategies to enhance adaptive capacity and preparedness against temperature-related disturbances as well as populations and infrastructures most at risk. Thus, understanding vulnerabilities helps foster resistance, robustness, and recoverability capacities that ultimately compose a resilient system (31). Resilience and vulnerability are two interconnected but not opposing concepts. In this review, authors use them together in representing the thermal resilience metrics, aiming for an appropriate qualitative and quantitative illustration for diverse use cases and stakeholders.

Figure 1 maps the stakeholders identified in **Table 1** to the metric categories of their greatest interest. Most stakeholders would look into occupants’ vulnerability metrics to guide design innovation (architects and engineers) and enhance public health and safety (emergency responders), for example. To better operate buildings and manage cities, property managers and municipal officials could be more interested in systems vulnerability metrics that describe the ability of building and community systems to plan for and respond to disruptions and extreme events, whereas insurance providers would look at the financial metrics with a perspective to reduce costs and minimize losses. These metric categories are further described in Sections 3.1 through 3.4. Often, the line distinguishing a metric from being classified into one category or another is blurred, especially because of the interconnected and overlapping relationships between them. This means that such classification does not aim to be definitive but rather to facilitate the identification of metrics within the multidimensionality of thermal resilience, as well as to link these metrics to potential stakeholders.

In this article, the term metric refers to a parameter that measures performance or describes a certain condition of buildings or communities. In contrast to using only raw operational measurements, metrics can be obtained with one or more variables through direct measurement, calculation, or survey instruments.

3.1. Occupants’ Vulnerability Metrics

Occupants’ vulnerability metrics describe characteristics or conditions that, alone or combined, influence the extent to which occupants are affected by a building’s indoor thermal conditions. They may describe (a) occupants’ characteristics that lead to vulnerability, (b) the indoor thermal environment to reflect desirable or undesirable conditions, or (c) a combination of the previous two

Recoverability:
building’s capacity to restore its indoor thermal conditions to acceptable levels after a failure, minimizing downtime and ensuring occupant safety

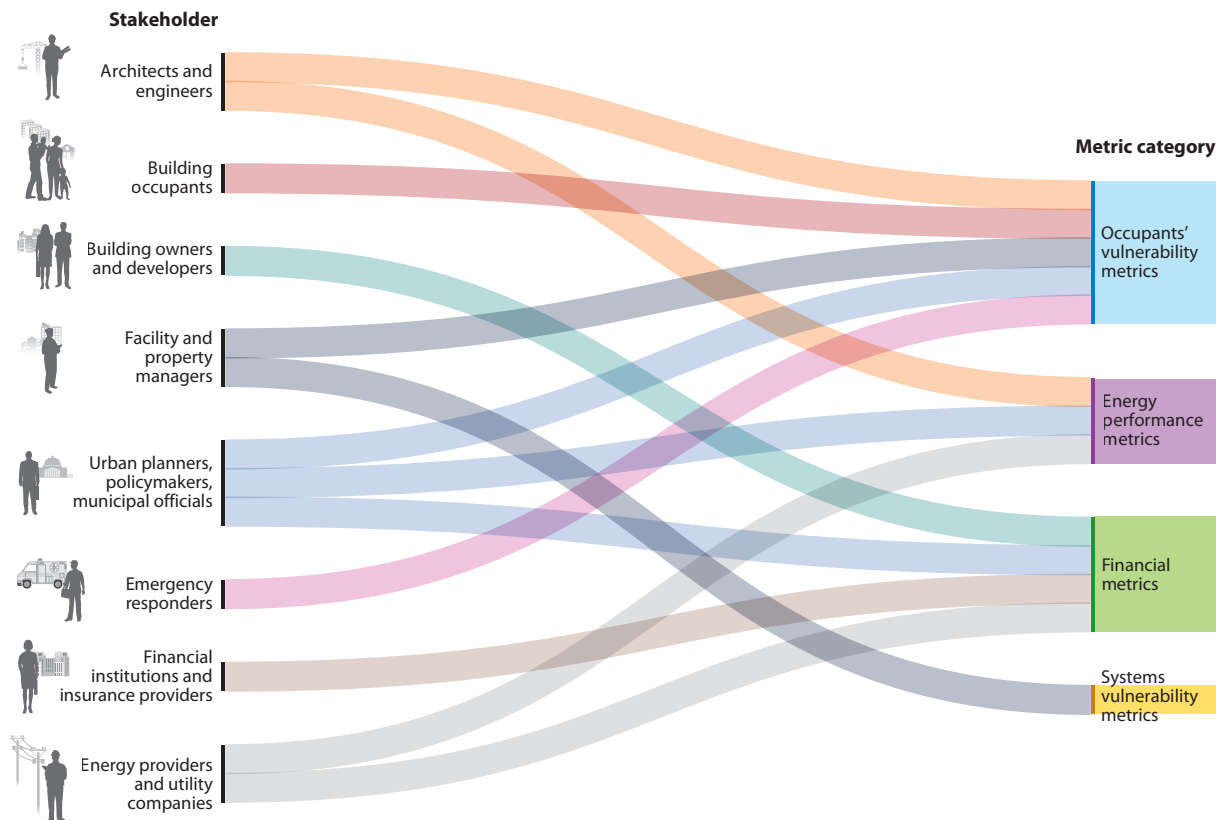


Figure 1

Mapping of stakeholders of thermal resilience to relevant metric categories.

points. In **Supplemental Appendix 2, Supplemental Table 1** summarizes occupants' vulnerability metrics identified in this review.

Occupants' vulnerabilities are often presented alongside influencing social-demographic factors, such as age, presence of health comorbidities, education, social isolation, income (32), and language accessibility. This is because environmental parameters alone do not capture important social variables, perceptions, and networks that influence the level of impact of extreme events (33). Also, diverse compound metrics have been created out of a group of vulnerability metrics. For example, the iHVI (integrated heat vulnerability index) toolkit allows users in Australia to understand the relationships among heat, environmental, and socioeconomic factors through heat sensitivity and adaptive capability metrics. These metrics are ultimately based on land surface temperature and retention of heat in the urban environment, as well as population density, age, population needing care, education level, and income level (34). Despite considering extensive parameters of the population used in iHVI, heat exposure is based on outdoor conditions, not reflecting the influence of the building characteristics, the indoor environment, and the distribution and performance of cooling/heating equipment. This is a common limitation of existing heat vulnerability indexes, as pointed out by Xu et al. (35), who developed a web-based vulnerability mapping tool incorporating both the outdoor and indoor heat exposure for the city of Fresno, California, U.S. By spatially mapping the vulnerability of a city or municipality, heat vulnerability index (HVI) tools can be used to prioritize heat resilience investments or mitigations.

Supplemental Material >

Another approach for understanding occupant vulnerabilities is by examining the building's thermal dynamics to describe the indoor environment in terms of providing adequate thermal conditions to the occupants. To calculate these metrics, the built environment has to be represented with parameters characterizing thermal conditions, which can encapsulate one or multiple variables, from environmental variables (e.g., air dry-bulb temperature and humidity) to occupants' personal variables (e.g., activity level and clothing insulation). In **Supplemental Appendix 3, Supplemental Table 5** describes the most common parameters, including indoor air dry-bulb temperature, heat index (HI), wet bulb globe temperature (WBGT), humidex, and standard effective temperature (SET), and compares them regarding common usage, advantages, and limitations.

Some of these parameters have been directly defined with different thresholds mapping to various heat stress levels or potential health hazards. For instance, the National Oceanic and Atmospheric Administration (NOAA) defines five levels of HI, including safe, caution, extreme caution, danger, and extreme danger (36). Similarly, NOAA identifies five thresholds for WBGT in three regions categorized based on local extremes across the United States to inform potential threats to the human body at work (37, 38). Thresholds for these two common indexes are summarized in **Supplemental Appendix 3, Supplemental Table 6**. Furthermore, the U.S. Leadership in Energy and Environmental Design (LEED), a green building certification system, recommends livable conditions using the metric "Passive Survivability and Back-up Power During Disruptions" as SET between 12 and 30°C and the thermal safety temperatures based on SET across different building types, i.e., not exceeding 120°C SET-hours above 30°C SET for residential buildings while not exceeding 240°C SET-hours above 30°C SET for nonresidential buildings during a seven-day power outage period. When adopting such parameters to calculate diverse metrics, they can directly reflect the multiple levels of hazards for the audience, which is easier for understanding and applications from the user side.

A fundamental research gap is centered on understanding thermal survivability instead of comfort limits in the context of resilience and in light of occupants' adaptive opportunities (39). Current criteria are often too generalized and do not account for differences among population subgroups, failing to account for variations in age, and health and socioeconomic conditions. By focusing on survivability, research can identify specific adaptive measures to improve outcomes in extreme thermal conditions.

Time-integrated metrics are adopted to better understand thermal resilience, especially when evaluated within a long timeframe (e.g., whole-year). Krelling et al. (40) detailed common integration methods considering the frequency, intensity, duration, and severity of targeted indoor thermal conditions (**Figure 2**).

Metrics describing the intensity of events may be useful to portray the worst thermal conditions. Examples found in the literature account for maximum and minimum indoor air temperatures or operative temperatures when an air conditioning system is unavailable, being evaluated daily, annually, or during specific events (e.g., power outages) (41–43). By looking at these metrics, however, one cannot know whether this is a frequent event or an isolated occurrence.

Metrics describing the frequency of events can be applied to understand how often (i.e., the proportion of time) a certain condition happens. A common metric is thermal autonomy (44), which describes the capacity to maintain adequate indoor thermal conditions without the assistance of active cooling or heating systems. The downside of these frequency metrics is that they fail to give a notion of how far indoor conditions are from specific thresholds. In other words, they may consider, for example, crossing the threshold by 0.5 or 4 degrees Celsius the same way.

The duration of events is especially meaningful for assessing the risk of thermal conditions affecting human health, sometimes indicating whether a building should be evacuated (42).

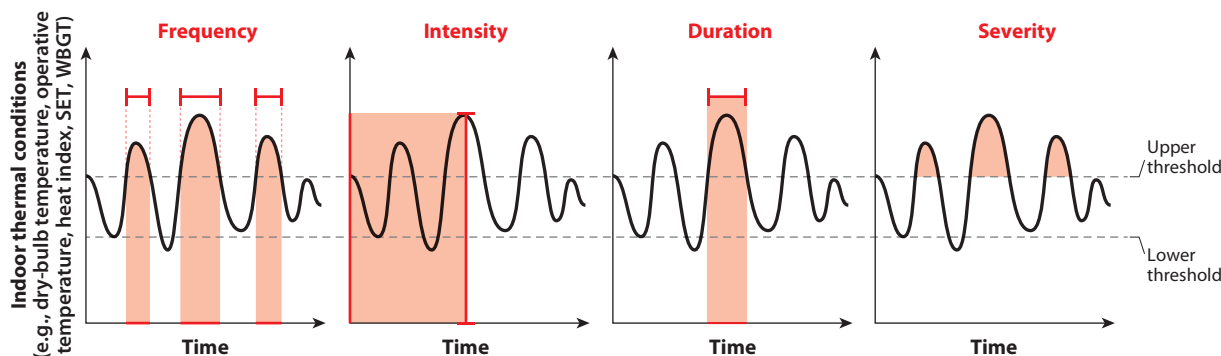


Figure 2

Time-integrated metrics describing the frequency, intensity, duration, and severity of targeted indoor thermal conditions. For frequency, intensity, and duration, the shaded area represents how the indoor thermal conditions are projected along the relevant axis. For frequency, the shading represents all the times when indoor thermal conditions exceed the upper threshold, indicating how often these conditions occur within a certain period (e.g., the proportion of time). For intensity, the shading indicates the peak indoor thermal condition on the y-axis. Similarly, for duration, the shading represents the length of time under thermal conditions above the threshold. For severity, the shading represents the area between the indoor thermal conditions curve and the upper threshold, aggregating both frequency and intensity aspects into the indicator. Figure adapted from Krelling et al. 2023 (40). Abbreviations: SET, Standard Effective Temperature; WBGT, Wet-Bulb Globe Temperature.

Examples of metrics focused on cold events are hours of safety (45) and heating passive habitability (HPH) (42), both of which account for the length of time before a building becomes uninhabitable, which is considered when the indoor temperature reaches a certain threshold. Kesik & O'Brien (42) consider an operative temperature threshold of 15°C, based on the effect of cold on elderly morbidity described by Collins (46). Similarly, cooling passive habitability (CPH) (42) and building heat performance index (BHPI) (47) account for the effect of hot weather, also measuring the time to reach a threshold related to an increased chance of heat morbidity and mortality (30°C or 32°C, respectively).

There are metrics that can encompass both the intensity and frequency of events, with the most common being the degree hours (48, 49). Although degree hours may be calculated in any given time frame, the daily weighted exceedance (We) (50) uses the same procedure but calculates it for each day in order to evaluate whether it trespasses an acceptable overheating limit equal to 6°C-hours/day. Similarly, overheating (51) and SET-hours (52) adopt this same approach but change the operative temperature with other parameters of indoor thermal quality [discomfort index (DI) and SET, respectively]. Homaei & Hamdy (53) propose the overall weighted unmet thermal performance ($WUMTP_{Overall}$), which is calculated based on a resilience test framework that encapsulates the building performance during the disruptive event and a few days after it. It is also based on degree hours, but different penalties are applied depending on the phase when the temperature differential is calculated (during or after disruption), the hazard level (i.e., how far the operative temperature is from the acceptable level), and the exposure time in a given hazard level.

3.2. Systems Vulnerability Metrics

Systems vulnerability metrics describe the capacity of building systems to plan and respond to disruptions and extreme events, as well as possible consequences of failure to respond. This is

closely related to occupants' vulnerability, as failure in building systems would limit coping and adaptability, leading to indoor heat- or cold-related stress. These metrics, however, are tied to the operation of energy systems and services: Building systems should comprise HVAC, automation, local or backup power generation, and storage systems, for example.

Literature explicitly providing such metrics in the context of thermal resilience of buildings is scarce. In **Supplemental Appendix 2, Supplemental Table 2** summarizes the metrics identified herein. Sengupta et al. (54) proposed multiple metrics to classify the variety of shocks to buildings, among them, the degree of system shock (doSS). For instance, when any HVAC component fails and leads to partial or total loss of cooling or heating, the doSS would be calculated based on how severely indoor thermal conditions are impacted, multiplied by the duration of the shock as a fraction of the total operational hours of the system in one day. A limitation to these novel metrics is conveying their meaning and practical implications, specifically considering doSS is dimensionless. A possible use case would be to adopt these within comparative analyses of different possible impacts, as done by Sengupta et al. (54).

Wang et al. (55) investigated the maximum allowable power outage duration within a utility coverage. Such duration was considered as the maximum period that less than 10% of customers would be exposed to overheating risks. For conditions in which failure is unavoidable, this type of analysis incorporates resilience principles of safe failure (also called robustness) (17).

Looking at the building level, the maximum time to repair (MaxTTR)—e.g., a thermal system serving a building—describes how long the repairing process, or downtime, can be sustained in order to prevent uninhabitable indoor thermal conditions and/or damage to systems and structures (e.g., damage to water pipes, mold formation) (56).

HVAC system cooling and heating capacities are typically sized based on the calculated peak thermal loads under design day weather conditions. However, these systems may not have sufficient capacity to provide adequate cooling during heat waves (57) or heating during cold snaps. In fact, the cooling capacity of typical air conditioning equipment can be reduced by 13% if the outdoor air temperature exceeds the rating temperature by 11°C (20°F) (58). With more adoption of heat pump (HP) technologies in buildings, heating capacity can be significantly diminished at cold outdoor conditions. Therefore, a system metric is necessary to represent how well a system maintains its capacity during extreme temperature events, as well as its safe operating temperatures (e.g., HP equipment would be locked out if operating temperatures are too high or too low). On-site power generation and/or energy storage becomes crucial to ensure that the system can provide services for critical needs during power outages. Enhanced cooling and heating control or design, such as dedicated zones or areas, also plays a vital role. These measures, in conjunction with photovoltaic (PV) systems and storage, can maintain essential services during power outages and prevent widespread power disruptions during grid stress emergencies.

3.3. Financial Metrics

These metrics reflect the cost-effectiveness of investing in thermal resilience measures, guiding decision-making and ensuring that resources are allocated efficiently. At the government level, this means guiding budget reallocation and creation of contingency and reserve funds for relief and recovery from extreme events (23).

Financial metrics can also describe the consequences of not being resilient. For instance, catastrophe models are driven by financial considerations on potential hazard events, being used primarily by insurance and reinsurance companies (23). In fact, the insurance industry is at greater risk from increasingly extreme weather as inherent uncertainties might cause premiums to skyrocket. A

better understanding of data and pricing of resilience is fundamental (59). At the building level, extreme heat can affect tenants, infrastructure, operating costs, and consumer behavior, leading to a potential risk of property devaluation. However, limited research has been conducted on this issue. Forward-thinking developers, investors, and designers are aware of these potential impacts and are taking measures to mitigate current heat-related risks and safeguard against future ones (25).

When evaluating financial metrics for thermal resilience, it is essential to consider potential losses resulting from extreme temperature events. These metrics should account for the impact on occupant health, including damage or loss of life, and property damage, such as spoiled food, ruined medicine, and broken pipes. Additionally, business losses should be factored in, including reduced retail sales, decreased worker productivity (60), and impaired student learning and cognitive performance (61, 62). By incorporating these factors, financial metrics can provide a comprehensive assessment of the economic implications of inadequate thermal resilience, guiding investment in more robust HVAC systems and supporting infrastructure. In **Supplemental Appendix 2, Supplemental Table 3** summarizes the identified financial metrics.

A long-established metric, more commonly used in the electricity sector, is the value of lost load (VoLL), which represents the cost of power outages to consumers. For businesses, VoLL includes equipment damage, lost revenue, and productivity losses (63). The normalized value of lost load (NVOLL), which corresponds to the annualized consequence of the event by dividing VoLL by the period of the recurrence (e.g., every ten years). Rostami et al. (64) adapted these principles to develop a cost model, using outputs from building performance simulation, and calculating the NVOLL. A variability analysis of weather parameters was also developed to determine the distribution of total risk by creating a distribution of risk exposures for all events, allowing determination of the value at risk (VaR) and conditional value at risk (CVaR). In the context of thermal resilience, VaR could represent the maximum anticipated economic loss due to extreme temperature events (such as a heat wave or cold snap) that a building or community is likely to experience within a specific period (e.g., annually) with a certain confidence level. CVaR provides the average loss during extreme temperature events that exceed the VaR threshold, offering a deeper insight into the tail end of the loss distribution, capturing the risk of extreme losses more effectively than VaR.

Beyond directly quantifiable financial impacts, another dimension of the resilience value is the cost of degraded health, safety, and economic activity. Nonetheless, determining the impact of extreme events to any one of these is even more challenging, as is translating such impacts into financial consequences to guide stakeholders in decision-making (63). The value of a statistical life (VSL) has been used to estimate the value of saved lives associated with building mitigation measures, for which a variable range of values has already been adopted, ranging around \$10 million per life, based on the year 2020 dollars (65). Note, however, that the VSL is not about placing a value on any one individual's life. Instead, it aggregates the value people place on small reductions in mortality risk. For instance, if each person in a population of 100,000 is willing to pay \$100 to reduce their individual risk of death by 1 in 100,000, then the total amount the population is willing to pay is \$10 million, which is the VSL (66).

Baniassadi et al. (67) quantified the health and climate costs of running HVAC systems. This involved using emission data and estimating the resulting damages from pollutants like PM_{2.5}, SO₂, NO_x, and CO₂. The authors translated electricity savings into dollars by considering the health and climate impacts of these emissions, allowing them to show the avoided costs for each city.

3.4. Energy Performance Metrics

Thermal resilience evaluation requires a comprehensive approach to account for trade-offs with energy efficiency and demand flexibility. Energy performance metrics are, therefore, relevant in

a resilience assessment to preserve adequate indoor thermal conditions while optimizing energy use and reducing dependency on local ecosystems. From these parameters, energy use intensity (EUI) (68) is the most common metric. See **Supplemental Appendix 2, Supplemental Table 4** for a summary of identified energy performance metrics. Taking a look at a demand profile, some aspects of energy use can be described by its intensity (e.g., peak power) and duration, as well as the integration of the demand curve for the overall energy consumption. Furthermore, the shape of a demand profile needs to be addressed, especially when aggregated throughout numerous consumers (i.e., buildings), because it reflects a demand toward the power grid. In this context, demand-side management (DSM) can support resilience by conveying flexibility to the electric grid, thus supporting low-carbon clean grids (69). Greater load flexibility and DSM enhance grid resilience, resulting in fewer power outages and increased building resilience, thereby improving occupants' vulnerability metrics discussed previously.

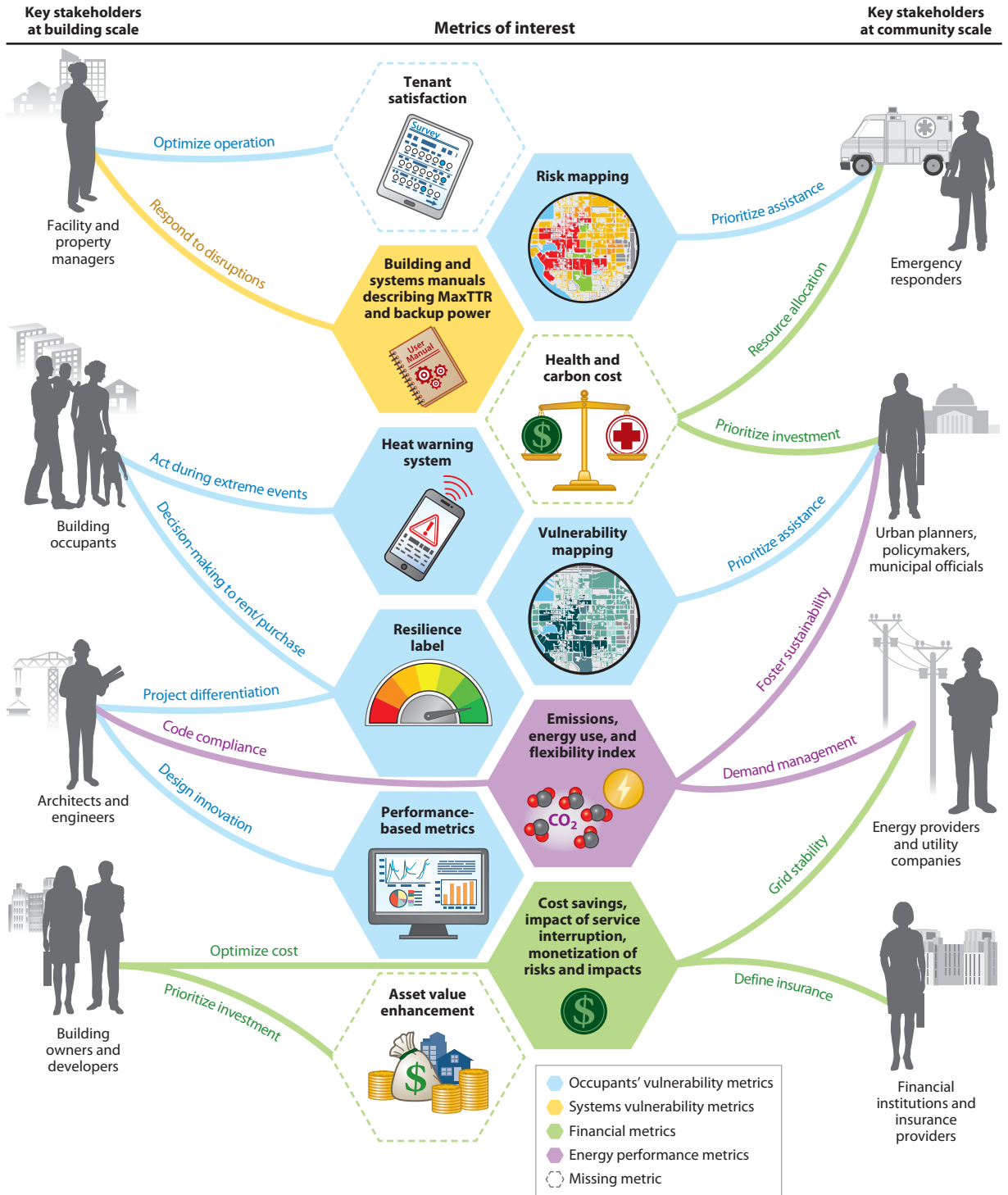
Local power generation and storage at the building level are recommended for thermal resilience during power outages, ensuring that HVAC systems remain operational when the grid fails. This capability is vital for maintaining safe and comfortable indoor temperatures, protecting occupants' health, preventing property damage, ensuring continuous operation of critical systems, and mitigating business interruptions. If not available at the building level, community hubs and centers are crucial to enhance overall community resilience to extreme weather events and other disruptions. When strategies are applied to enhance flexibility, many metrics may be considered, although they commonly fall into some general properties: different categories of temporal resolution when energy and power can be managed, the amount of energy or power, and the associated cost of energy flexibility (70). Although connected to thermal resilience, certain metrics related to distributed energy resources, such as the reliability of photovoltaic systems and storage, are beyond the scope of this review.

4. EFFECTIVE SELECTION AND APPLICATION OF METRICS

After carefully reviewing available metrics to quantify the thermal resilience of buildings and communities, considering the multiple dimensions of interest to different stakeholders, we provide suggestions (not exclusive) on potentially useful metrics in this section. **Figure 3** illustrates the available metrics of interest and missing metrics for different stakeholders. The selection of metrics considered all aspects of effective metrics presented in **Supplemental Appendix 4**, such as reproducibility, actionability, and universality.

A single metric can serve multiple purposes depending on how it is defined and applied. For instance, hours of safety can indicate the effectiveness of a building envelope in resisting overheating or overcooling as well as informing evacuation time for residents and emergency responders. Additionally, the way a metric is measured (e.g., spatial and temporal resolution, statistical aggregation) can lead to significantly different findings, even if the overarching concept remains the same. For example, heat stress can be assessed using daily averages, maximum temperatures, or the number of days exceeding a critical threshold, each providing distinct insights. Transparency in the assumptions underlying metric usage is essential for ensuring comparability across studies. Ultimately, the selection of resilience metrics should be tailored to the specific contexts and interests of each stakeholder.

Sections 4.1 and 4.2 summarize the metrics selected for each stakeholder group, addressing questions of why they would be interested in thermal resilience and what they can do to promote it. Considering that these stakeholders have different scales of action where they can foster thermal resilience, Section 4.1 is focused on resilience at the building scale, and Section 4.2 considers resilience at the community scale.



(Caption for Figure 3 appears on following page)

Figure 3 (Figure appears on preceding page)

Key metrics of interest by stakeholders for thermal resilience assessment in buildings and communities. Stakeholders at the building (*left side*) and community (*right side*) scales are connected to relevant metrics (*middle column*) through specific actions they can take to foster thermal resilience. Each metric is colored according to its metric category. Abbreviation: MaxTTR, maximum time to repair.

Thermal resilience metrics at the building scale require detailed data on indoor temperatures, envelope characteristics, HVAC performance, and occupant behavior. They inform decision makers on tailored strategies to improve resilience in one specific property. Architects and engineers, building occupants, owners and developers, and facility and property managers would be the stakeholders interested in these metrics. In contrast, community-scale metrics focus on infrastructure resilience, urban design, policymaking, and emergency preparedness and response. The challenges at this scale include incomplete data on critical infrastructure (71), insufficient stakeholder coordination (72), limited longitudinal studies, and inadequate integration of socioeconomic factors (13). The main stakeholders are urban planners, policymakers, municipal officials and emergency responders, financial institutions and insurance providers, and energy providers and utility companies. Section 4.3 further explores the uncertainties in quantifying thermal resilience and their potential impact on the accuracy and implementation of resilience metrics and strategies in the future.

4.1. Useful Metrics by Stakeholders at the Building Scale

Architects and engineers are perceived as the main stakeholders responsible for enhancing thermal resilience of buildings. Unsurprisingly, 60% of the articles reviewed for this study adopt—exclusively or not—metrics targeted to these stakeholders. They might be interested in voluntary design innovations that enhance thermal resilience and would require performance-specific metrics centered on assessing occupants' vulnerabilities due to building design. When codes and standards enforcing thermal resilience are already in place, metrics could also indicate compliance. Instead of one single metric, a comprehensive and integrated set of metrics is mostly recommended (18). Siu et al. (19) have thoroughly discussed available metrics using building performance simulation, highlighting a few key aspects that can be considered: the ability to prevent buildings from reaching critical levels, the ability to reduce exposure to thermal stress, and the ability to recover back to a habitable state. Krelling et al. (40) proposed a simulation framework to assess thermal resilience using a combination of six integrated metrics that help designers to make informed decisions about each one of the key aspects listed by Siu et al. (19) (a few of these are listed in **Table 2**). For instance, thermal vulnerability describes the proportion of hours that occupants face indoor thermal conditions that might be detrimental to their health. In Sheng et al. (68) and Krelling et al. (73), the SET of 30°C (74) was used to delimit such an unhealthy condition. Operative temperature (75) and HI (76) have also been used to calculate similar metrics. This definition also needs to consider simplicity of computation and accuracy (i.e., quantifiability; see **Supplemental Appendix 4**) (39), which might be a constraint depending on the application.

A few authors have proposed methods to label thermal resilience of buildings (53, 77, 78). Such an approach is rooted in the successful history of labeling energy efficiency of HVAC systems and appliances through letters (e.g., G–A) (79) or a star rating for the most efficient products in the market (80). Studies show that customers tend to prefer products with higher ratings (81, 82). These metrics are simple to understand and provide actionable information for building occupants to prioritize renting or purchasing properties with improved resilience. Homaei & Hamdy (53) and Ji et al. (77) describe labeling methods centered on a specific disruptive event (a selected heat wave or a cold snap) and that are fit-for-purpose as they detail and account for the building

Table 2 Suitable thermal resilience metrics for stakeholders at the building scale

Who cares and why?	Potential metrics	What can they do?
Architects and Engineers		
Design innovation and/or code compliance	Integrated set of metrics: indoor overheating degree (IOD) (83), thermal autonomy (TA) (39), thermal vulnerability (TV) (40), recovery time (tR) (40), energy use intensity (EUI) (47)	Design buildings and implement measures to optimize thermal resilience
Project differentiation	Resilience label (78), U.S. Leadership in Energy and Environmental Design (LEED) passive survivability (74)	Pursue building certification to communicate the resilience benefits of the project to prospective owners and developers
Building Occupants		
Comfort, productivity, and health	Resilience label (78), hours of safety (45)	Prioritize renting or purchasing buildings with high resilience ratings
Risk mitigation	Heat warning system using strong language guiding appropriate measures during extreme events. Multilingual campaign through multiple channels during typical summer days (26, 92)	Act accordingly during typical summer days and extreme events
Building Owners and Developers		
Cost savings	Cost savings from resilience measures, considering associated up-front costs (76)	Prioritize measures to improve thermal resilience and optimize costs
Risk mitigation	Occupant hours lost (OHL) (88), office thermal resilience (OTR) (89), average cost of repairs (90)	Prioritize measures to improve thermal resilience, sustained operations, and productivity
Asset value enhancement	Missing metrics for asset valuation, including potentially avoided physical, operational, and social costs	Prioritize investing in thermally resilient buildings
Facility and Property Managers		
Risk management	Maximum time to repair (MaxTTR) (56), backup power capacity (68)	Timely response to protect occupants and the property from extreme events using available technologies and strategies
Tenant satisfaction	Missing metrics to guide building operation. Potential alternatives to be leveraged include unmet hours (67) and TA (39)	Optimize occupants' thermal comfort during normal operation

performance throughout each phase of the event (e.g., initial state, during the event, after the event, and in a final state). However, quantifiability and accessibility might be limited for two main reasons: (a) They rely on specific penalty coefficients for each period of the disruptive event, which might be subjective and not generalizable; and (b) they rely on the definition of one specific disruptive event, which might not represent thermal resilience in the long-term (i.e., whole year or future years). Amaripadath et al. (78) proposed a certification scheme that also uses the period of a heat wave for evaluation but uses well-defined metrics [indoor overheating degree (IOD) (83), hours of exceedance (He) (50), WBGT (84), and HI (85)] to compose a score equivalent of one to five stars (worst to best thermal resilience). A limitation of this method is not accounting for a duration parameter (see Section 3.1) for certain relevant thermal conditions, e.g., recovery capacity (86) or hours of safety (45). Building labeling also provides an opportunity to architects and engineers to communicate their project differentiation to an audience less familiar with performance metrics while enabling real estate developers to compare projects with other

market competitors. LEED (87) and WELL (<https://www.wellcertified.com/>) are examples of consolidated sustainability rating systems that are gradually incorporating more aspects related to resilience.

As an important factor to persuade building owners and developers to foster thermal resilience—through certifications or other mechanisms—the cost savings provided by different measures need to be considered as in any other investment feasibility analysis. Sun et al. (76) used the case of a historical heat wave affecting a nursing home to evaluate the energy savings provided by multiple measures and the associated up-front incremental cost of each measure. Such a metric can help decision-makers to carefully evaluate the trade-offs between cost and resilience benefits when selecting energy efficiency and resilience measures. These resilience benefits, for building owners and developers, are related to risk mitigation. For instance, the occupant hours lost (OHL) (88) is an impact-driven metric that quantifies the business productivity lost due to an event that would make the indoor environment unusable for part of the occupants. This metric is easy to understand by different stakeholders and can be translated into economic impacts by assigning a monetary value to each occupant hour (88). Using a similar metric [called office thermal resilience (OTR)], Ismail et al. (89) proposed a regression model equation to estimate the number of safe and comfortable hours before the loss of productivity in office buildings, which could be used to prioritize measures to improve thermal resilience, sustained operations, and productivity using only a few straightforward inputs. Besides operation constraints, owners and developers are also interested in minimizing the average cost of repairs (90) associated with extreme events. All of these costs should be considered when analyzing the return on investment (ROI) (67) of thermally resilient buildings or other general financial metrics. However, fit-for-purpose metrics for asset valuation due to enhanced thermal resilience are still missing, which would ideally reflect physical, operational, and social costs.

Facility and property managers need to be well informed so that they can timely respond to protect occupants and the properties from extreme events using available technologies and strategies. In case of power or system disruptions, the MaxTTR (56) would inform them for how long the building would remain habitable or damage-free. If repair is extended beyond this limit, building managers could take necessary measures to preserve the property and occupants' health, such as guiding an evacuation. To support these professionals, building and systems manuals could contain such metrics, together with guidelines about available technologies to respond to disruptive events [e.g., available backup power capacity (68)]. On a daily basis, tenant satisfaction could be improved through sensing and monitoring of basic metrics such as services unmet hours by the HVAC systems (67), allowing managers to respond to improve these metrics. Building manuals could also include guidelines to reduce HVAC dependence to improve thermal autonomy (39). Nonetheless, suitable thermal resilience metrics for evaluating tenant satisfaction and HVAC dependence during building operation are still missing. A novel approach was proposed by Serdar et al. (91) using a building thermal resilience profile (BTRP) for real-time resilience assessment, disaster planning, management, and response. As a dynamic regularly calibrated tool, such a solution could provide optimized strategies to mitigate and manage extreme events more effectively. However, limitations might arise from the need to tailor the tool to each building, as well as the required expense and expertise to use it on-site.

Besides facility and property managers, mechanical and electrical engineers could also benefit from similar systems vulnerability metrics to design technical systems (e.g., HVAC systems, local generation, and storage) to enhance thermal resilience of buildings. For example, necessary backup power capacity to respond to extreme weather events would be calculated by mechanical and electrical engineers and communicated to facility and property managers through, e.g., building and systems manuals.

Table 3 Suitable thermal resilience metrics for stakeholders at the community scale

Who cares and why?	Potential metrics	What can they do?
Urban planners, policymakers, municipal officials, and emergency responders		
Community resilience	Vulnerability mapping [potential metrics to be leveraged include Healthy Environment Assessment Tool (HEAT) (93), integrated heat vulnerability index (iHVI) (34), heat vulnerability index (HVI) (35)]	Prioritize medium- and long-term investments to enhance thermal resilience of vulnerable populations
Public health and safety	Risk mapping [potential metrics to be leveraged include heat factor (95) and spatial model of population vulnerability related to emergency service demand (ESD) during extreme events (96)], with supplemental metrics based on risk- and disaster-management practices (30)	Prioritize assistance to vulnerable populations during extreme events
Economic stability	Health and climate costs (67). Further studies are needed to develop and compare alternative metrics	Allocate resources to mitigate and manage extreme events
Environmental sustainability	CO ₂ emissions [especially from heating, ventilation, and air conditioning (HVAC)] [e.g., Carlsson et al. (97)]	Implement and enforce policy mechanisms that foster reduction of CO ₂ emissions and, consequently, thermal resilience in the long term
Financial institutions and insurance providers		
Risk management	Conditional value at risk (CVaR) (64). Further studies are needed to develop and compare alternative metrics	Assessment of thermal and incidental risks to better evaluate insurance premium coverage and deductibles
Risk mitigation	Risk reduction from application of resilience measures (64). Further studies are needed to develop and compare alternative metrics	Offer benefits for hazard mitigation
Energy providers and utility companies		
Grid stability	Value of lost load (VoLL) and customer damage function (CDF) (90)	Assess the impact of service interruption and take proactive measures to enhance grid stability while leveraging thermal resilience in buildings
Demand management	Flexibility index (FI) (98)	Prioritize effective flexibility strategies to enhance grid resilience and thermal resilience of buildings through continuous service

Table 2 outlines potential metrics tailored to the needs and specific interests of various stakeholders. It also highlights missing metrics identified by the authors, indicating areas where better-suited and fit-for-purpose metrics need to be developed to enhance thermal resilience and address specific needs.

4.2. Useful Metrics by Stakeholders at the Community Scale

At the community scale (**Table 3**), there's a fundamental necessity of mapping vulnerability and risk. Although these may look similar, they serve different purposes and use diverse metrics. Vulnerability maps could be used by policymakers, urban planners, and municipal officials to assess community resilience focused on identifying medium- and long-term solutions. Examples are (as previously mentioned, see Section 3.1) the iHVI toolkit (34), the Healthy Environment Assessment Tool (HEAT) (93), and the HVI (35). These tools aim to provide a single index (or a few

subindexes) that incorporates multiple aspects of vulnerability from the basic characteristics of the population and their buildings. Some of these aspects might come from previously mentioned performance metrics, whereas others reflect demographics, pre-existing health conditions, and adaptation capacity (due to, e.g., the income level) (35).

Risk mapping encompasses the probability of specific consequences and integrates elements of vulnerability, exposure, and hazard (94). In the context of heat risk, First Street (95) developed a heat factor score assigned to properties in the United States as part of a wider risk factor platform. One important limitation is that the assessment of heat exposure is only based on outdoor thermal conditions, ignoring building thermal characteristics. With the same constraint of using outdoor temperatures, Loughnan et al. (96) demonstrated the capability of a spatial index of vulnerability to predict increases in emergency service demand in Australian capital cities. In the context of thermal resilience of buildings, emergency responders and civil protection agencies could be interested in identifying the at-risk populations during specific events to streamline assistance. One potential metric that could be incorporated into these risk assessments is the hours of safety (45), which communicates the length of time a building can sustain safe conditions during an event [in the case of Ayyagari (45), a power outage during a cold snap]. This information could help in prioritizing assistance and/or coordinating evacuations. Additionally, such a risk map should utilize emergency communication and broadcasting capabilities to guide vulnerable building occupants on appropriate actions during extreme events.

Before, during, and after emergencies, supporting metrics could also be utilized to guide efforts based on risk- and disaster-management practices. The International Organization for Standardization (ISO) standard 37123 (30), Annexes B and C, describe relevant indicators to support thermal resilience. A few examples are the percentage of a city's population covered by a multi-hazard early warning system (including heat wave warnings), the percentage of the city equipped with specialized communication technologies able to operate reliably during a disaster event, and the percentage of hospitals equipped with backup electricity supply. When available, the number, location, and capacity of cooling centers or resilience hubs could also inform emergency response during extreme events.

By providing a better understanding of the risks affecting the community, municipal officials could foster economic stability by allocating appropriate resources to mitigate and manage extreme events. Concerning thermal resilience, this is possible through metrics that quantify health and climate costs. One useful example is the approach adopted by Baniassadi et al. (67), described in Section 4.1. To reflect the value of resilience, Franconi et al. (65) considered the annual energy cost savings, annual greenhouse gas emissions reductions, avoided loss of life, and avoided property damage. Extreme temperatures present uniquely intractable socio-technical challenges compared to other weather-related hazards, as they are largely invisible phenomena with objective measures insufficient to capture people's lived experiences that are crucial predictors of health risk (13). Thus, quantifiability, accessibility and reproducibility of such metrics is very limited because the impacts of disruptive events are site specific, industry specific, and often business specific. However, the ability of monetizing the resilience benefits is essential for a metric because investment costs are also measured in dollars (90).

Facing similar challenges of resilience valuation, financial institutions and insurance providers are already interested in metrics that monetize risk. Rostami et al. (64) used CVaR to quantify extreme weather risks by incorporating a cost model to calculate the average loss in the top 5% of riskiest scenarios (see Section 3.3). Such an approach could be used to inform insurance premium pricing or coverage decisions. Also, risk reduction from application of resilience measures could be quantified and used to provide benefits for hazard mitigation. For instance, a case study by

Rostami et al. (64) had its VaR and CVaR reduced by 89% in relation to code-minimum design with the application of efficient-resilient design.

Energy providers and utility companies need to assess the impact of service interruption and take proactive measures to enhance grid stability. The VoLL and customer damage function (CDF) (90) are common and useful metrics. A potential use case to minimize costs incurred from service interruption and enhance thermal resilience in buildings is the planning of necessary rotating power outages based on allowable durations that avoid overheating risks (55). Such an assessment could encompass supplementary metrics like the number of consumers without power and whether these include critical facilities that should be prioritized (e.g., hospitals and fire stations). Additionally, demand management could be employed to enhance grid resilience and thermal resilience of buildings through continuous service. As an example, Zeng et al. (99) investigated precooling buildings as a measure to reduce overheating risks during heat waves. According to the authors, such a strategy could be further improved with an optimized thermostat setpoint schedule broadcast to residents through early alert messages before a heat wave.

Ultimately, the need to foster grid stability in response to extreme temperature events needs to be reflected in the procedures of overarching regulatory bodies, such as the North American Electric Reliability Corporation (NERC). By incorporating relevant thermal resilience metrics, a regulatory authority like NERC, which serves nearly 400 million people (100), could facilitate information sharing, provide training programs, and support regulatory and policy initiatives to include thermal resilience into planning and operations.

4.3. Uncertainties in Quantifying Thermal Resilience of Buildings and Communities

Quantifying the thermal resilience of buildings and communities involves significant uncertainties that can impact the accuracy and reliability of resilience metrics. These uncertainties arise from various sources. A major source of uncertainty is the projection of future climate conditions and extreme weather events. Climate projection models and emission scenarios provide a range of possible temperature extremes, for example, in heat waves and cold snaps, but there is inherent variability in these predictions (101). There are also limited data on certain phenomena, such as cascading acute events, where one extreme event triggers a series of subsequent events (102). Better understanding of possible sources of stress to the built environment is fundamental for ensuring that the quantification of resilience covers all relevant scenarios (103).

The performance of buildings over time introduces another layer of uncertainty. Factors such as the aging of building materials and systems can degrade thermal performance. For instance, in thermal resilience analyses using building performance simulation, an adequate approach to reflect aging and degradation of building materials and systems over time is still needed as we focus on assessing long-term performances (73).

Economic constraints and funding availability for resilience projects vary widely globally (104), introducing uncertainty into the implementation of resilience measures identified through the metrics. Potential changes in building codes, regulations, and policies can also impact the effectiveness of these measures. Furthermore, population dynamics, such as changes in population density, climate migration (105), urbanization patterns, demographics, and technology adoption (106) or associated market forces, influence the thermal resilience needs and strategies of communities.

5. CONCLUSIONS

This review examined existing literature on thermal resilience metrics for buildings and communities, guided by the five W's of urban resilience. First, we identified the key stakeholders involved in

thermal resilience, including architects and engineers, occupants, property owners, real estate developers, urban planners, and policymakers (the “who” question). Second, we examined the need to measure thermal resilience, highlighting motivations such as safeguarding occupant health, protecting property, and ensuring business continuity during extreme weather events (the “why” question). We then explored the timing of resilience promotion within the building life cycle, emphasizing its importance during the design, construction, operation, and retrofitting phases (the “when” question). We discussed the various locations where stakeholders can promote resilience, such as residential, commercial, and public buildings, as well as the broader community scale (the “where” question). Finally, we provided actionable insights on what stakeholders can do to enhance resilience, including adopting robust HVAC systems, implementing local power generation, and improving building design (the “what” question).

Although numerous metrics exist, a significant gap remains in translating them into actionable insights for different stakeholders using a resilience valuation framework. So far, significant efforts have been placed in quantifying resilience through performance-based metrics that represent occupants’ vulnerabilities, which are primarily useful for architects and engineers in developing a resilient design. This means that most existing methods are centered around a limited highly specialized audience that alone does not have the necessary influence to foster thermal resilience across communities. For instance, expressing resilience benefits in financial terms is essential because it resonates with stakeholders who need to see a benefit-cost ratio to make investment decisions.

Ultimately, the goal is to transition from theoretical frameworks to practical applications and policies that can guide stakeholders in making informed decisions. This involves developing standardized testing conditions and procedures, translating complex physiological responses to heat into accessible metrics, and quantifying the often invisible costs associated with extreme temperatures.

Future research should prioritize comprehensive data gathering using bottom-up approaches leveraging social connections and community-based partnerships, as well as employing innovative approaches such as machine learning techniques to extract information from hard-to-reach populations. Furthermore, aligning resilience with sufficiency principles is crucial to avoid resource overconsumption, thus focusing on a balanced approach incorporating durability and environmental responsibility throughout the life cycle of buildings.

SUMMARY POINTS

1. Extreme temperature hazards require collective efforts to enhance the thermal resilience of buildings and communities to ensure occupant health and safety and minimize property and infrastructure damage.
2. Absence of standardized resilience assessment procedures compromises extreme temperature mitigation and adaptation strategies across the building life cycle.
3. Existing resilience metrics are often limited to specialized audiences (e.g., architects and engineers), lacking translation into actionable insights for broader stakeholder engagement, especially in financial and regulatory terms.
4. A comprehensive set of complementary metrics is often necessary to assess thermal resilience in order to capture resistance, robustness, and recoverability capabilities of buildings and communities.

5. It is fundamental to properly reflect the phenomena that disrupt buildings in resilience assessments through the definition of multiple scenarios appropriate to specific locations and contexts.
6. There's a need to shift from theoretical frameworks to practical policies, including standardized testing conditions and procedures, accessible metrics for heat-related risks, and quantification of hidden costs of extreme temperatures.
7. Fragmented networks among stakeholders can hinder effective resilience strategies. Strengthening cross-sectoral connections, possibly through coordinated roles like Chief Heat Officers, can improve resource allocation, communication, and policy implementation.

FUTURE ISSUES

1. Context-specific assessment: Quantifying thermal resilience largely depends on the use case, specific interests, and stakeholder needs, requiring studies to define testing scenarios for different applications beyond single extreme event analyses.
2. Dynamic climate conditions: Ideal resilience measures may change over time due to evolving climate conditions (73), highlighting the need for adaptable testing conditions or scenarios that account for life cycle stages and evolving environmental factors.
3. Physiological variability: Translating the physiological impacts of extreme heat into quantifiable thresholds is challenging and a key R&D gap, particularly given variations in demographic factors, geographic acclimatization, and data availability to determine metrics such as wet bulb globe temperature and standard effective temperature considering the different needs of populations.
4. Temporal heat stress and occupant behavior: Resilience metrics often overlook the distinct health impacts of daytime and nighttime heat stress, despite their differing physiological effects and risks to vulnerable populations (107), making it crucial to understand occupant behavior during these conditions for accurate representation in building energy models and related applications.
5. Invisible and indirect impacts: Future research should focus on quantifying the broader, often invisible, physical and social costs of extreme temperature conditions, such as health-related expenses, productivity or learning losses, and mortality rates, with an emphasis on monetizing resilience benefits.
6. Data gaps: Vulnerable populations frequently lack sufficient data for accurate resilience assessments. Comprehensive solutions require improved data collection through community engagement, remote sensing, and advanced machine learning techniques like natural language processing and convolutional neural networks.
7. Balancing resilience and sufficiency: Aligning resilience with sufficiency principles (108–110) is a key research need to help optimize resource utilization and minimize waste, thereby promoting buildings that are both durable and environmentally responsible, addressing sustainability and resilience throughout their life cycle.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

Krelling and Wu led the investigation and analysis, with Krelling also developing the methodology, managing the data, and preparing visualizations. Malik and Hong contributed to the study design and provided critical input during the review process, with Hong also overseeing the project's administration. Wei, Lamberts, and Yan were involved in reviewing and refining the manuscript, with Lamberts and Yan also providing supervisory guidance. Perry provided review and editing, as well as project supervision.

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