

A SCOPING REVIEW OF SALIENT PARAMETERS IN THE THERMAL RESILIENCE OF BUILDINGS

Ali Waqas^{1*}, Muhammad Abdullah²

¹ Faculty of Sciences, The University of Lahore, Pakistan

² School of Science, Monash University Malaysia, Malaysia

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ABSTRACT

The growing dangers associated with rising temperatures necessitate a collaborative approach to evaluate and improve the thermal resilience of buildings and communities, ensuring the safety of occupants while reducing property and infrastructure damage. However, the effectiveness of strategies to mitigate and adapt to extreme temperatures is hindered by insufficient coordination among stakeholders and a lack of standardized resilience assessment procedures throughout the building life cycle. This review analyzes existing literature on resilience parameters related to thermal stress and risk in extreme indoor environments. Key stakeholders in thermal resilience include architects, engineers, occupants, property owners, real estate developers, urban planners, and policymakers. The review also highlights the motivations for measuring thermal resilience, such as protecting occupant health and safety, safeguarding property, and maintaining business continuity during extreme weather events. It offers actionable insights and identifies future research needs to enhance resilience through customized parameters for stakeholders involved in the planning, design, construction, operation, and retrofitting of buildings and communities.

Keywords: Resilience review, intense heat, weather changes, buildings design.

*Corresponding Author. E-mail: ali.waqas.makki@gmail.com

INTRODUCTION

Global Risk Report has identified extreme weather as the most significant risk of the decade, driven by the increasing frequency and intensity of natural disasters. It is essential to future-proof both new and existing buildings to withstand these extreme events, as they serve as the primary line of defense against adverse weather conditions. Failing to do so will have a cascading effect throughout the entire building and

construction value chain, beginning with the occupants [1].

Rising average global surface temperatures and increasingly hazardous rainfall patterns are examples of expected chronic hazards with long-term impacts. In contrast, acute hazards can affect communities in the short term, manifesting as heat waves, cold snaps, floods, droughts, and wildfires. These hazards create market and policy risks, as

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climate uncertainty diminishes asset values, raises insurance costs, increases the expense of key resources such as water and energy, and necessitates stricter regulations and taxes. Among these climate hazards, extreme temperatures elevate the risk of overheating or overcooling in buildings, particularly those lacking adequate heating or cooling systems, or facing power outages during severe weather. Such conditions can significantly affect occupants' health, productivity, and even mortality. According to the National Weather Service, heat has caused more fatalities on average than any other weather-related disaster in the United States over the past 30 years; a study suggests the actual number of fatalities is likely much higher. Furthermore, the rising frequency of extreme weather events has led to an increase in power outages in recent years [2]. The heat wave in Sichuan Province, China, led to power outages driven by surging energy demand and subsequent droughts, which created a shortage of hydroelectric power.

Extreme heat and cold can inflict significant physical damage on buildings, infrastructure, and the environment. Buildings may experience material degradation, including cracking, warping, and fading finishes. Heating, ventilation, and air-conditioning (HVAC) systems may suffer increased wear and failure. Infrastructure such as roads, railways, and bridges can buckle, crack, and misalign due to thermal stress. Environmental impacts include vegetation stress, heightened wildfire risks, and diminished water supplies due to increased evaporation. Unlike other climate hazards, these consequences often go undetected because many of the world's most vulnerable regions lack the monitoring capabilities to identify the impacts of extreme temperatures.

Despite increasing climate uncertainties, construction practitioners continue to

design, build, and operate buildings based on business-as-usual scenarios, relying on historical operation and climate data. For example, design days are derived from past weather data to calculate peak heating and cooling loads and to size HVAC equipment. However, considering thermal resilience in buildings and communities is essential for minimizing financial losses and ensuring occupant safety and comfort, especially in the face of growing weather extremes [3].

This study adopts a comprehensive definition of urban resilience in relation to the thermal resilience of buildings and communities:

the ability of the built environment—and its associated socio-ecological and socio-technical networks across various temporal and spatial scales—to maintain or quickly return to desired indoor thermal conditions following a disturbance, adapt to changes, and transform systems that hinder 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, which characterizes thermal resilience through phases of resistance, robustness, and recovery. The literature provides various characteristics to estimate resilience, although it remains challenging to measure directly. While multiple parameters have been developed to quantify thermal resilience, a consensus on their appropriateness for different use cases, stakeholders, and life cycle stages is necessary to create a flexible thermal resilience assessment framework [4].

Thermal resilience is a collective issue, as individual actions may not be enough to mitigate the negative impacts of overheating or overcooling in buildings. Therefore, the responsibility for addressing climate risks is shared among various societal groups, including governments,

researchers, the private sector, and public health and community organizations. However, the integration of interests among these stakeholders is still limited, which hampers the effectiveness of achieving thermal resilience.

Several studies have examined resilience concepts related to buildings, with a focus on building thermal resilience from ecological and engineering perspectives. These studies underscore the urgent need for a systematic conceptual and assessment framework. Additionally, existing research has qualitatively reviewed cooling strategies and their impact on enhancing building thermal resilience, particularly during the design phase or retrofit planning [5].

However, current literature on building thermal resilience predominantly focuses on the design and retrofit stages, often neglecting the interplay of heat and cold stress. To our knowledge, no reviews have evaluated thermal resilience across the entire building life cycle—encompassing planning, design, construction, operation, and retrofitting—while considering both individual buildings and community scales. Furthermore, existing reviews lack an integrated, multidimensional categorization and discussion of building thermal resilience parameters that take into account the interests of multiple stakeholders and their decision-making processes.

This article seeks to address these gaps by providing a comprehensive review of resilience parameters tailored to the needs of different stakeholders in measuring and promoting thermally resilient buildings and communities. The focus is on the resilience of indoor built environments against thermal risks, such as overheating and overcooling, and how stakeholders at various scales can respond to these challenges using quantitative thermal resilience parameters [6–8].

APPLICATIONS OF THERMAL RESILIENCE

Thermal resilience provides significant advantages to stakeholders throughout the building life cycle. Building owners and developers benefit from reduced financial losses due to climate-related damages and increased operational continuity during extreme events. Occupants experience improved thermal comfort, which enhances productivity and health. Emergency responders are better prepared for extreme weather events, alleviating pressure on public services. Resilient communities, from planning to operation stages, enjoy greater economic stability by minimizing risks and ensuring equitable access to heating and cooling resources. However, resilience is often neglected due to the lack of clearly defined quantitative valuation methods, such as estimating the return on investments in resilient systems or monetizing the resulting improvements in occupant health and well-being [9, 10].

RESILIENCE PARAMETERS ANALYSIS

The articles reviewed considered various parameters related to thermal resilience, both explicitly and implicitly. Many of these parameters have been adapted from other fields, such as the incidence of health comorbidities from medical sciences. Consequently, while these parameters may not directly translate to thermal resilience, they form part of an information chain that can guide stakeholders in enhancing the resilience of buildings and communities. Additionally, several new parameters have emerged by reinterpreting earlier concepts under different names. To clarify the identified parameters: 1. occupant parameters, 2. systems parameters, 3. financial parameters, and 4. energy performance parameters. Quantifying vulnerability in a resilience assessment reveals the susceptibility of buildings,

communities, or systems to hazards that threaten thermal resilience. This information is crucial for developing strategies to improve adaptive capacity and preparedness against temperature-related disturbances, as well as identifying populations and infrastructures most at risk. Understanding vulnerabilities fosters resistance, robustness, and recoverability, which together form a resilient system. Resilience and vulnerability are interconnected concepts, and in this review, the authors use them in tandem to represent thermal resilience parameters, aiming for a comprehensive qualitative and quantitative illustration suitable for various use cases and stakeholders.

Most stakeholders examine occupants' vulnerability parameters to inform design innovations (for architects and engineers) and enhance public health and safety (for emergency responders). Property managers and municipal officials are particularly interested in systems vulnerability parameters, which detail the ability of building and community systems to plan for and respond to disruptions and extreme events. In contrast, insurance providers focus on financial parameters aimed at reducing costs and minimizing losses. The distinction between these categories is often blurred due to the interconnected and overlapping relationships among them. Consequently, this classification is not intended to be definitive; rather, it serves to facilitate the identification of parameters within the complex landscape of thermal resilience and to connect these parameters to potential stakeholders [11].

In this article, the term "parameter" refers to a parameter that measures performance or describes specific conditions of buildings or communities. Unlike raw operational measurements, parameters can be derived from one or more variables through direct

measurement, calculation, or survey instruments.

Vulnerability Parameters

Occupants' vulnerability parameters describe characteristics or conditions that, whether individually or in combination, influence the extent to which occupants are affected by a building's indoor thermal conditions. These parameters may address occupant characteristics that contribute to vulnerability, or the indoor thermal environment reflecting desirable or undesirable conditions, or a combination of the two.



Figure 1: Metric category.

Occupants' vulnerabilities are often analyzed alongside key socio-demographic factors, including age, health comorbidities, education, social isolation, income, and language accessibility. This is essential because environmental parameters alone do not adequately capture the significant social variables, perceptions, and networks that influence the impact of extreme events. Additionally, various composite parameters have been developed from a range of vulnerability indicators. For instance, the Integrated Heat Vulnerability Index toolkit enables users in Australia to explore the relationships among heat, environmental, and socioeconomic factors through parameters of heat sensitivity and adaptive

capability. These parameters are primarily based on land surface temperature, heat retention in urban areas, and demographic factors such as



Figure 2: Prominent stakeholders.

population density, age, the number of individuals needing care, education level, and income level [12].

However, despite the comprehensive parameters considered in the Integrated Heat Vulnerability Index, heat exposure parameters focus solely on outdoor conditions, neglecting the influence of building characteristics, indoor environments, and the distribution and performance of cooling and heating equipment. This limitation is common among existing heat vulnerability indexes, which can still be useful for prioritizing investments in heat resilience or mitigation strategies.

Systems Vulnerability Parameters

Systems vulnerability parameters evaluate the capacity of building systems to plan for and respond to disruptions and extreme events, as well as the potential consequences of failing to do so. This concept is closely related to occupants' vulnerability because failures in building systems can hinder coping mechanisms and adaptability, resulting in indoor heat- or cold-related stress. These parameters are directly linked to the operation of energy systems and services, which should include components such as HVAC, automation, local or backup power generation, and storage systems [13-15].

HVAC systems are typically sized based on calculated peak thermal loads for design day weather conditions. However, these systems may lack sufficient capacity to provide adequate cooling during heat waves or heating during cold snaps. Additionally, with the increasing adoption of heat pump technologies in buildings, heating capacity can be significantly reduced in cold outdoor conditions.

Therefore, a system parameter is essential to evaluate how well a system maintains its capacity during extreme temperature events and its safe operating temperatures (e.g., heat pump equipment may be locked out if temperatures are too high or too low). On-site power generation and energy storage are crucial to ensure that systems can provide critical services during power outages. Enhanced cooling and heating control, such as creating dedicated zones, also plays a vital role. These strategies, combined with photovoltaic systems and storage, can help maintain essential services during outages and prevent widespread disruptions during grid stress emergencies.

Financial Parameters

Financial parameters assess the cost-effectiveness of investing in thermal

resilience measures, guiding decision-making and ensuring efficient allocation of resources. At the government level, this means informing budget reallocations and the establishment of contingency and reserve funds for relief and recovery from extreme events.

These parameters also illustrate the risks of failing to achieve resilience. For instance, catastrophe models, which are driven by financial considerations regarding potential hazards, are primarily used by insurance and reinsurance companies. The insurance industry faces increased risks from extreme weather, as inherent uncertainties may lead to skyrocketing premiums. A comprehensive understanding of data and resilience pricing is fundamental [14-16].

At the building level, extreme heat can impact tenants, infrastructure, operating costs, and consumer behavior, potentially leading to property devaluation. However, limited research has been conducted on this topic. Forward-thinking developers, investors, and designers recognize these potential impacts and are taking measures to mitigate current heat-related risks and safeguard against future ones.

When evaluating financial parameters for thermal resilience, it is crucial to consider potential losses from extreme temperature events. These parameters should encompass the effects on occupant health, including potential injuries or fatalities, as well as property damage, such as spoiled food, ruined medicine, and broken pipes. Business losses should also be included, which may consist of reduced retail sales, decreased worker productivity, and impaired student learning and cognitive performance.

In addition to the directly quantifiable financial impacts, another aspect of resilience value is the cost associated with degraded health, safety, and economic activity. However, assessing the impact of

extreme events on these factors is complex, as is translating these impacts into financial terms to aid stakeholder decision-making. The value of a statistical life is often used to estimate the worth of lives saved through mitigation measures, with a variable range of approximately \$10 million per life, based on 2020 dollars. It is important to note that the value of a statistical life does not assign a monetary value to any individual's life but rather aggregates the value people assign to small reductions in mortality risk.

Additionally, the health and climate costs of operating HVAC systems were quantified using emission data and estimating the damages caused by pollutants. The authors translated electricity savings into monetary values by considering the health and climate impacts of these emissions, enabling them to present the avoided costs for each city.

Energy Performance Parameters

Evaluating thermal resilience requires a comprehensive approach that balances energy efficiency and demand flexibility. Energy performance parameters play a crucial role in resilience assessments by ensuring adequate indoor thermal conditions while optimizing energy use and minimizing reliance on local ecosystems. Among these parameters, energy use intensity is the most widely utilized [17].

When examining a demand profile, energy use can be characterized by its intensity (e.g., peak power), duration, and the overall energy consumption derived from the integration of the demand curve. The shape of the demand profile is particularly important, especially when considering multiple consumers (i.e., buildings), as it impacts the demand on the power grid. In this context, demand-side management can enhance resilience by providing flexibility to the electric grid, thereby supporting low-carbon energy systems. Improved load flexibility and demand-side management contribute to grid resilience, resulting in fewer power outages and increased building resilience, which in

turn enhances the vulnerability parameters previously discussed [18-20].

To ensure thermal resilience during power outages, local power generation and storage at the building level are recommended. This capability is crucial for keeping HVAC systems operational when the grid fails, thereby maintaining safe and comfortable indoor temperatures, protecting occupants' health, preventing property damage, ensuring the continuous operation of critical systems, and mitigating business interruptions. If building-level solutions are unavailable, community hubs and centers become essential for enhancing overall community resilience against extreme weather events and other disruptions [21].

When implementing strategies to improve flexibility, various parameters should be considered. These parameters generally fall into several categories: different temporal resolutions for managing energy and power, the amount of energy or power involved, and the associated costs of energy flexibility.

SELECTION AND APPLICATION OF PARAMETERS

After carefully reviewing the available parameters for quantifying the thermal resilience of buildings and communities, and considering the diverse interests of various stakeholders, we offer suggestions for potentially useful parameters in this section [22].

A single parameter can fulfill multiple roles, depending on its definition and application. For example, "hours of safety" can indicate how well a building envelope resists overheating or overcooling, as well as inform evacuation times for residents and emergency responders. Moreover, the method of measurement (e.g., spatial and temporal resolution, statistical aggregation) can yield significantly different results, even if the overarching concept remains consistent. For instance, heat stress can be evaluated using daily averages, maximum

temperatures, or the count of days exceeding a critical threshold, each providing unique insights. Ensuring transparency in the assumptions underlying parameter usage is crucial for comparability across studies. Ultimately, the choice of resilience parameters should be tailored to the specific contexts and interests of each stakeholder [23-25].

Thermal resilience parameters at the building scale necessitate detailed data on indoor temperatures, envelope characteristics, HVAC performance, and occupant behavior. These parameters guide decision-makers in developing targeted strategies to enhance resilience in individual properties. Stakeholders interested in these parameters include architects, engineers, building occupants, property owners and developers, as well as facility and property managers. In contrast, community-scale parameters emphasize infrastructure resilience, urban design, policymaking, and emergency preparedness and response. Challenges at this scale include incomplete data on critical infrastructure, insufficient coordination among stakeholders, a lack of longitudinal studies, and inadequate integration of socioeconomic factors. The primary stakeholders at this level include urban planners, policymakers, municipal officials, emergency responders, financial institutions, insurance providers, and energy utility companies.

CONCLUSIONS

It was examined the various locations where stakeholders can promote resilience, including residential, commercial, and public buildings, as well as at the broader community level. It was provided actionable insights on how stakeholders can enhance resilience, such as adopting robust HVAC systems, implementing local power generation, and improving building design. Despite the availability of numerous parameters, a significant gap remains in

translating these parameters into actionable insights for different stakeholders using a resilience valuation framework. Much of the current focus has been on quantifying resilience through performance-based parameters that represent occupants' vulnerabilities, primarily benefiting architects and engineers in creating resilient designs.

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

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REFERENCES

1. Hong T, Xu Y, Sun K, Zhang W, Luo X, Hooper B. 2021. Urban microclimate and its impact on building performance: a case study of San Francisco. *Urban Clim.* 38:100871. <https://doi.org/10.1016/j.uclim.2021.100871>
2. Zhivov AM. 2021. Parameters for thermal energy systems resilience. *E3S Web Conf.* 246:08001. <https://doi.org/10.1051/e3sconf/202124608001>
3. Sengupta A, Al Assaad D, Bastero JB, Steeman M, Breesch H. 2023. Impact of heatwaves and system shocks on a nearly zero energy educational building: Is it resilient to overheating? *Build. Environ.* 234:110152. <https://doi.org/10.1016/j.buildenv.2023.110152>
4. Wang Z, Hong T, Li H. 2021. Informing the planning of rotating power outages in heat waves through data analytics of connected smart thermostats for residential buildings. *Environ. Res. Lett.* 16:074003. <https://doi.org/10.1088/1748-9326/ac092f>
5. Homaei S, Hamdy M. 2021. Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric. *Build. Environ.* 201:108022. <https://doi.org/10.1016/j.buildenv.2021.108022>
6. Burgess K, Rapoport E. 2019. Climate risk and real estate investment decision-making. *Res. Rep., Urban Land Institute.* <https://knowledge.uli.org/en/reports/research-reports/2019/climate-risk-and-real-estate-investment-decisionmaking>
7. Alawadhi M, Phelan PE. 2022. Review of residential air conditioning systems operating under high ambient temperatures. *Energies* 15:2880. <https://doi.org/10.3390/en15082880>
8. Yin P, Pate MB, Sweeney JF, Kading J. 2014. The effect of high ambient temperature on the performance of an R410a air conditioner. In *1st International Conference on Energy and Indoor Environment for Hot Climates*, Doha, Qatar, Feb. 24–26, pp. 350–57. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84938850556&partnerID=40&md5=71446a9ed513e39d39104ae78f14647d>
9. Kumar D, Alam M, Sanjayan J. 2022. Building adaptation to extreme heatwaves. In *Engineering for Extremes*, ed. MG Stewart, DV Rosowsky, pp. 189–216. Cham: Springer.

- https://doi.org/10.1007/978-3-030-85018-0_9
10. Murphy C, Hotchkiss E, Anderson K, Barrows C, Cohen S, et al. 2020. Adapting existing energy planning, simulation, and operational models for resilience analysis. Tech. Rep. NREL/TP-6A20-74241, National Renewable Energy Laboratory, Golden, CO. <https://www.nrel.gov/docs/fy20osti/74241.pdf>
 11. Park RJ. 2022. Hot temperature and high-stakes performance. *J. Hum. Resour.* 57:400–34. <https://doi.org/10.3368/jhr.57.2.0618-9535R3>
 12. Park RJ, Goodman J, Hurwitz M, Smith J. 2020. Heat and Learning. *Am. Econ. J. Econ. Policy* 12:306–39. <https://doi.org/10.1257/pol.20180612>
 13. Rostami M, Green-Mignacca S, Bucking S. 2023. A novel method for quantifying risks to climate change events using conditional value at risk: a multi-unit residential building case study in London, Ontario. *Sustain. Resilient Infrastruct.* 9:72–90. <https://doi.org/10.1080/23789689.2023.2257511>
 14. Li H, Wang Z, Hong T, Piette MA. 2021. Energy flexibility of residential buildings: a systematic review of characterization and quantification methods and applications. *Adv. Appl. Energy* 3:100054. <https://doi.org/10.1016/j.adapen.2021.100054>
 15. Franconi E, Hotchkiss E, Hong T, Reiner M. 2023. Enhancing Resilience in Buildings Through Energy Efficiency. Richland, WA: Pacific Northwest National Laboratory. <https://www.energycodes.gov/energy-resilience>
 16. Baniassadi A, Heusinger J, Gonzalez PI, Weber S, Samuelson HW. 2022. Co-benefits of energy efficiency in residential buildings. *Energy* 238:121768. <https://doi.org/10.1016/j.energy.2021.121768>
 17. Sheng M, Reiner M, Sun K, Hong T. 2023. Assessing thermal resilience of an assisted living facility during heat waves and cold snaps with power outages. *Build. Environ.* 230:110001. <https://doi.org/10.1016/j.buildenv.2023.110001>
 18. Reynders G, Amaral Lopes R, Marszal-Pomianowska A, Aelenei D, Martins J, Saelens D. 2018. Energy flexible buildings: an evaluation of definitions and quantification methodologies applied to thermal storage. *Energy Build.* 166:372–90. <https://doi.org/10.1016/j.enbuild.2018.02.040>
 19. Sun K, Specian M, Hong T. 2020. Nexus of thermal resilience and energy efficiency in buildings: a case study of a nursing home. *Build. Environ.* 177:106842. <https://doi.org/10.1016/j.buildenv.2020.106842>
 20. Nirandjan S, Koks EE, Ward PJ, Aerts JCJH. 2022. A spatially-explicit harmonized global dataset of critical infrastructure. *Sci. Data* 9:150. <https://doi.org/10.1038/s41597-022-01218-4>
 21. Sengupta A, Al Assaad D, Steeman M, Breesch H. 2023. Thermal resilience to overheating assessment in a Belgian educational building with passive cooling strategies during heatwaves and power outages. *E3S Web of Conf.* 396:01018. <https://doi.org/10.1051/e3sconf/202339601018>
 22. International Organization for Standardization (ISO). 2017. Ergonomics of the thermal environment - Assessment of heat stress using the WBGT (wet bulb globe temperature)

- index. Rep. ISO 7243:2017, ISO.
[https://www.iso.org/standard/67188.htm](https://www.iso.org/standard/67188.html)
1
23. Jain M, Rao AB, Patwardhan A. 2018. Consumer preference for labels in the purchase decisions of air conditioners in India. *Energy Sustain. Dev.* 42:24–31. <https://doi.org/10.1016/j.esd.2017.09.008>
24. Nakai M, Ravago M-LV, Miyaoka Y, Saito K, Arimura TH. 2023. Consumers' preferences for energy-efficient air conditioners in a developing country: a discrete choice experiment using eco labels. *Energy Effic.* 16:14. <https://doi.org/10.1007/s12053-023-10095-8>
25. Hamdy M, Carlucci S, Hoes P-J, Hensen JLM. 2017. The impact of climate change on the overheating risk in dwellings—a Dutch case study. *Build. Environ.* 122:307–23. <https://doi.org/10.1016/j.buildenv.2017.06.031>