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Ten questions concerning thermal resilience of buildings and occupants for climate adaptation

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ABSTRACT

With climate change leading to more frequent, more intense, and longer durations of extreme weather events such as heat waves and cold snaps, it is essential to maintain safe indoor environmental conditions for occupants during such events, which may coincide with, or even cause, power outages that expose residents to health risks. Analyzing the impacts of extreme weather events on the thermal resilience of buildings can help stakeholders (including occupants) understand the risk and inform them about mitigation and adaptation actions. Moreover, analyzing the technological, social and policy dimensions of thermal resilience is critical for climate-proofing buildings. This paper presents 10 questions that highlight the most important issues regarding the thermal resilience of buildings for occupants in the face of climate change. The proposed questions and answers aim to provide insights into current and future building thermal resilience research and applications, and more importantly to inspire new significant questions in the field.

1. Introduction

Buildings and occupants are facing increasing challenges related to extreme events. Such events are commonly defined as "a time and place in which weather, climate, or environmental conditions rank above a threshold value near the upper or lower ends of the range of historical measurements" [1]. These events, such as heat waves, cold snaps, wildfires, floods or hurricanes are often coincident with grid power outages or high energy prices, thereby making it difficult to maintain habitable indoor conditions for building occupants. A recent report by the World Meteorological Organization [2] stated that about 12,000 extreme events across the globe have occurred over the past 50 years, resulting in over 2 million deaths and over $4.3 trillion of economic losses. The catastrophic effects of extreme events on human health, lives and the economy, along with the projections that the intensity and severity of climate-change related events will continue to increase [3], trigger an urgent need to adapt buildings to cope with and adapt to the changing world.

The global building decarbonization effort, aiming to mitigate the impacts of climate change through energy efficiency upgrades and end-use electrification to reduce energy demand and carbon emissions, presents new opportunities and challenges for building operations, energy flexibility and resilience. For instance, the increased electricity demand due to electrification and severe weather conditions requires more electricity use, and particularly higher peak electricity demand, to run the heating, ventilation and air-conditioning (HVAC) systems to provide safe and habitable indoor conditions. This increased demand can heavily strain the power grid and necessitates an improved understanding of the design and operation of climate-resilient buildings to provide a safe and comfortable indoor environment to occupants.

Resilience refers to the ability of a building to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events [4]. There exists a variety of dimensions to resilience in buildings, such as structural resilience, fire resilience, or seismic resilience, but here we focus on thermal resilience, which is a building's ability to maintain a comfortable and safe indoor thermal environment for its occupants throughout its lifetime; particularly during extreme weather events arising from climate change or building system disruptions due to technical failure or power outages. Thermal resilience in buildings has gained a lot of attention during recent years within the scientific

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literature and industry practices, owing to the increased frequency and intensity of extreme weather events and their growing widespread impacts on infrastructure, human health and economics.

Researchers under International Energy Agency Annex 80—“Resilient cooling of buildings”—have explored the topic from the perspective of assessing and promoting resilient low-energy and low-carbon cooling systems [5–7]. Ongoing efforts are focused on evaluating the potential of several strategies and technologies to enhance the resilience of buildings against overheating through dynamic building performance simulations [8] and providing resilient cooling guidelines, technology profiles and policy recommendations [9]. Within the building energy modeling domain, significant advances have been made in approaches to simulate a building’s dynamic thermal response during extreme weather scenarios, including the projection of its performance under future weather events. For instance, Samuelson et al. [10] analyzed the co-benefits of heat resilient architecture, taking into account not only indoor thermal conditions, but also implications regarding carbon dioxide (CO_2) emissions and heat rejection to the urban climate. Homaei and Hamdy [11] proposed a procedure based on multi-phase thermal resilience curves of buildings exposed to specific short-term events (e.g., a power failure during winter). A standardized methodology to evaluate the value of energy efficiency for energy resilience of residential buildings was jointly developed by three U.S. national laboratories sponsored by the U.S. Department of Energy [12]. However, there is still no consensus among researchers and practitioners regarding appropriate modeling approaches and performance metrics for analyzing the thermal resilience of buildings [13,14] to support decision-making.

The lack of standardized procedures is also reflected in the missing requirements in building codes for thermal resilience, unlike other resilience dimensions (e.g., earthquake, fire) addressed through comprehensive risk management standards. Nonetheless, there is a growing interest in promoting resilient buildings and communities through codes, standards and guidelines. For example, the RELi™ Rating System [15] is now incorporated into the resiliency-related credit strategies of the LEED green building rating system [16]. The RELi system is a holistic, resilience-based rating system that combines innovative design criteria with the latest in integrative design processes for next-generation neighborhoods, buildings, homes and infrastructure. The United Nations Environment Programme developed a practical guide for climate-resilient buildings and communities [17]. There is also an effort towards developing an international standard on indicators for resilient cities: ISO 37123 [18].

This paper aims to provide a deeper understanding of thermal resilience of buildings, particularly occupant-driven buildings such as residences or offices, from the perspectives of designers and policymakers focusing on occupant health and thermal safety. It also identifies future research directions and provides policy recommendations. The 10 questions target a variety of stakeholders such as architects, engineers, building owners, occupants or utility companies, and are intended to stimulate, particularly among young researchers, improvements in the modeling, evaluation and analysis of thermally resilient buildings to support decision-making. The overall structure of the 10 questions (Section 2), as illustrated in Fig. 1, comprise (a) an overview of the key stakeholders and factors influencing thermal resilience of buildings (Q1 & Q2); (b) up-to-date research trends and insights on evaluating thermal resilience-assessment methods (Q3), available metrics (Q4), simulation workflow and scenarios for modeling (Q5 & Q6); (c) achieving thermal resilience in buildings through technology and design (Q7), and human factors (Q8); and (d) considerations for incorporating thermal resilience into climate adaptation and building decarbonization plans (Q9), and within policies, codes and building performance standards (Q10). The final summary (Section 3) sheds light on the research priorities and associated challenges regarding the thermal resilience of buildings for occupants in the face of climate change.

2. Ten questions (and answers) concerning thermal resilience of buildings

2.1. *Who are the stakeholders and decision-makers, and why do they care about thermal resilience of buildings?*

Thermal resilience of buildings can be of value to a variety of stakeholders and decision-makers across the building life cycle (Fig. 2). During the design stages, thermal resilience analysis can help architects and engineers in designing buildings, systems, or spaces to optimize building performance and occupant comfort (e.g., passive design strategies). Architects and energy modelers can take advantage of thermal resilience analysis to evaluate effective retrofit strategies, particularly during extreme weather events and power outages. Real estate developers are often concerned with property values, the ease of selling or alluring investors or buyers. Thermally resilient building design and analysis can help real estate developers attach benefits such as improved occupant comfort, reduced operational disruptions, and possibly lower energy consumption and associated operational cost to their buildings, thereby increasing their marketability [19]. For building owners, the value of thermal resilience analysis can be realized beyond the design phase, particularly during building operations, through reduced operations and maintenance costs due to fewer disruptions triggered by structural damages or operational failures, and a higher resale price due to the buildings’ ability to withstand environmental stressors such as heat waves or cold snaps, and power outages [20].

Another important category of stakeholders is the building occupants, who can gain direct advantages from thermal resilience analysis, including enhanced thermal comfort and associated health and well-being benefits. Additionally, corporate building owners or commercial tenants may also value thermal resilience in buildings given that such buildings reduce occupants’ exposure to temperature fluctuations and offer a comfortable indoor thermal environment that leads to improved occupant productivity. For facility managers, buildings designed for extreme weather events and power outages can help in reducing operational deficiencies such as equipment or system failures. This

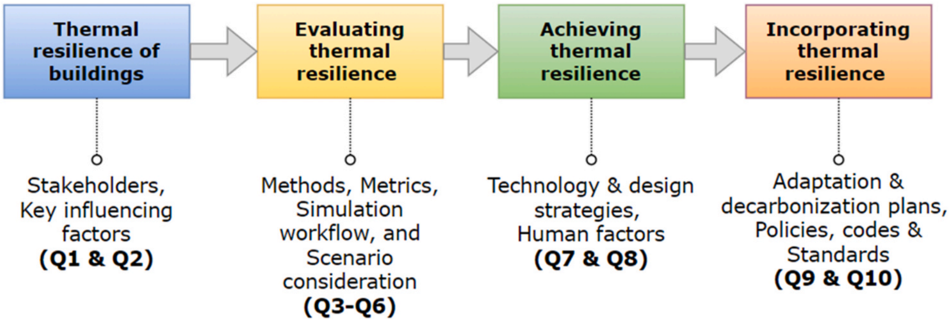

Fig. 1. Structure of the paper with 10 questions.

Fig. 2. Stakeholders across the building life cycle who can benefit from thermal resilience modeling and analysis.

minimizes maintenance efforts and disruptions and reduces occupant complaints, thereby enabling smooth building operations. For property managers, resilient buildings can offer improved tenant comfort and satisfaction, leading to higher occupancy rates and higher rental income.

Thermal resilience analysis can be used by property insurance companies to evaluate the actual risk exposure of the property under extreme weather events and improve the estimation accuracy of premium calculations. Identifying and quantifying the degree of property losses such as structural damage due to freezing temperatures will not only improve insurance business sustainability due to reduced risks, but will also improve underwriting by the introduction of innovative mechanisms such as risk-adjusted pricing to account for a changing climate [21].

Utility providers may also benefit from the thermal resilience analysis of buildings for grid management and response. For example, evaluating thermal resilience of building stock can support informed decision-making during rotating power outages to protect the most vulnerable buildings, neighborhoods or populations and ensure minimal disruptions [22]. Moreover, utilities may be able to develop targeted strategies for peak load reduction and demand flexibility by considering thermal resilience of buildings and their occupants, thereby improving grid resilience and avoiding the cost of additional infrastructure.

Evaluation of thermal performance and impacts of extreme temperature events on buildings can guide policymakers, government and public health agencies to improve the preparedness, response and management of climate change related impacts. For instance, thermal resilience evaluations can support government agencies in the development of effective and targeted building retrofit programs and rebate policies. Public health agencies can develop emergency response protocols in case of temperature-related emergencies by identifying vulnerable communities, thereby reducing risks related to occupant health, well-being or even survivability. Moreover, building codes and standards can leverage thermal resilience evaluations to promote resilient building design practices.

Table 1 summarizes the values or benefits from the thermal resilience analysis of buildings to different stakeholders. Even though thermal resilience analysis is advantageous to all stakeholders in different building life cycle stages, there could be unintended cost implications, such as higher insurance premiums of properties located in areas prone to extreme weather due to improved estimation of risks by insurance companies, or greater time and effort required by architects and energy modelers for designing thermally resilient buildings, and hence higher design fees.

Table 1
Benefits of building thermal resilience modeling and analysis for stakeholders or decision-makers.

Stakeholder or decision-makers	Value/benefit from thermal resilience evaluation of buildings
Architects and energy modelers	Identifying effective design and retrofit strategies for building operations
Real estate developers	Increased marketability of the property due to improved comfort and reduced operational disruptions
Building owners	Reduced operations and maintenance cost, and increased property value
Building occupants (renters, tenants, employees)	Enhanced thermal comfort, health and safety, and improved productivity
Facility managers	Minimal operational disruptions and maintenance effort, smooth building operations
Property managers	Low vacancy rate and high rental income, because of improved indoor conditions
Property insurance companies	Accurate estimation of premiums based on the evaluation of risks related to property damage
Utility providers	Improved grid resilience and demand response planning, avoiding cost for additional infrastructure
Policymakers	Developing resilience-oriented building design and retrofit programs, codes and standards
Government and public health agencies	Developing effective emergency response protocols to reduce risks related to health and survivability

2.2. What are the key factors that influence thermal resilience of buildings?

Understanding the key factors that influence thermal resilience of buildings is essential for effective design and operation of thermally resilient buildings. These factors, as illustrated in Fig. 3, can be broadly categorized into: (1) *Outdoor environment* - climate trend, urban microclimate, urban heat island effects, local weather conditions, weather hazards of the building location; (2) *Building characteristics* - envelope, HVAC system, onsite power generation, energy storage, energy demand, operation and controls; (3) *Occupant characteristics* - social, demographics, and health condition of the building occupants, and climate acclimatization; and (4) *Reliability and resilience of the power grid* serving the building neighborhood. A brief description on how these factors influence the thermal resilience of buildings is presented below.

1. *Outdoor environment*: A building's outdoor environmental conditions, particularly the prevailing weather conditions, is a major factor influencing its thermal resilience. Buildings located in cold or hot climates, for instance, would require thermal control strategies to withstand extreme cold or hot spells, while those located in

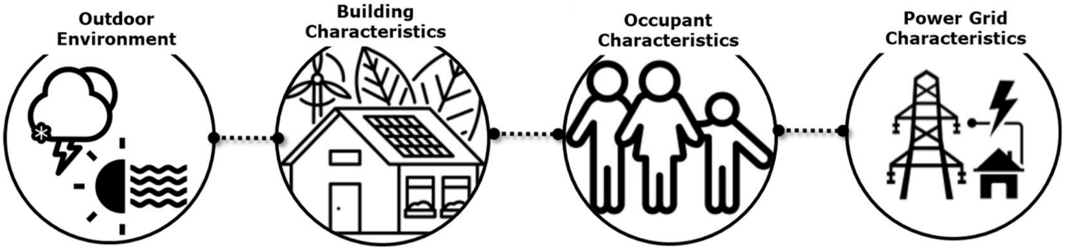

Fig. 3. Four categories of factors influencing thermal resilience of buildings.

temperate climates may require a different approach for resilience, considering both hot and cold events that do not conflict with each other. Moreover, the frequency and intensity of weather hazards such as prolonged heat waves are often associated with the building's location, which influences its ability to maintain a safe indoor thermal environment. In addition to the current weather conditions, the projected climate trends are also crucial, to account for the future weather changes that may occur in the next few years due to climate change disruptions. Lastly, a building's surroundings, such as urban or rural, can greatly influence its microclimate due to urban heat island effects, and in turn the thermal resilience of buildings.

2. *Building characteristics:* The physical characteristics of a building such as its envelope and glazing materials, orientation, window and solar shading device design, and layout can help in improving air tightness, reducing heat transfer across the envelope, managing solar heat gain or losses, and improving airflow and ventilation. The thermal mass of a building structure plays an important role in the dynamic thermal response; a heavy thermal mass building responds much more slowly than a lightweight structure. The HVAC system design and operation, such as a decentralized system or even availability of controls, can help reduce energy demand, thereby minimizing the building's reliance on grid power. Additionally, the availability of onsite power generation, such as solar photovoltaic, energy storage or backup power may also improve a building's ability to enhance thermal resilience by meeting the demand for critical loads (e.g., HVAC, medical devices, phone charging, internet devices), particularly during power outages coupled with extreme temperature conditions when passive measures may not suffice.
3. *Occupant characteristics*: Occupant behavior and their characteristics are known to impact building energy demand [23] and hence significantly influence the thermal resilience of buildings. Thermal comfort requirements and preferences vary greatly among occupants of different age groups, income or health vulnerabilities. For instance, elderly residents with underlying medical conditions may have a narrower comfort temperature range because of their inability to engage in the available adaptive opportunities in comparison to the healthy residents of a multifamily housing. Other factors such as perceived ease of use of controls, shared or private spaces, or external factors such as utility costs may also influence the decisions occupants make to improve their indoor thermal environment. A detailed discussion on the impact of occupant characteristics to adapt to their indoor thermal environment is presented in Section 2.8.
4. *Reliability and resilience of the power grid*: A building's ability to withstand temperature fluctuations and provide a safe indoor thermal environment to its occupants may also be affected by the characteristics and condition of the power grid. The operating reliability of the grid—i.e., its ability to withstand sudden disturbances such as system losses or failure and its adequacy to meet the energy demand of the buildings at all times through integration of renewable energy generation sources or demand response programs [24]—is crucial. Additionally, the resilience of the grid in terms of its ability to adapt to changing conditions and recover from disruptions such as accidents, attacks or natural incidents may also impact the frequency and duration of power outages or sustained system interruptions, thereby influencing the thermal resilience of buildings.

2.3. *What approaches can be used to assess thermal resilience of buildings?*

Thermal resilience assessment of buildings can be performed using three major approaches: (1) on-site measurements through sensing and metering for existing buildings, (2) computational modeling and simulation for new or existing buildings, and (3) qualitative approaches such as surveys and interviews for existing buildings. Each of these methods are discussed below in brief, along with a discussion regarding their suitability, which may vary depending upon the use case and the required resources. Often a combination of these approaches proves more effective in understanding thermal resilience issues and adaptation measures.

1. **On-site measurements:** One approach to assess thermal resilience of buildings is to monitor the outdoor weather, the indoor thermal environment, and occupant comfort. This could encompass sensing and monitoring techniques such as temperature and humidity sensors, IoT based sensors, or even wearable sensors for monitoring occupant heart rate or skin temperature [25,26]. This approach enables real-time monitoring to identify vulnerable buildings or spaces and its occupants, and can be particularly useful for planning building operations during extreme or power outage scenarios. With the availability of low-cost, customizable and easy-to-use environmental sensors [27], on-site measurement proves to be an effective method for resilience assessment and causes minimal disruption to the building operations [28]. However, particular attention must be paid to the sensitivity and calibration of the measuring instruments to minimize measurement errors, and to having battery backup for continuous sensing during power outages. The approach is best suited for use cases concerning existing buildings. For example, architects or engineers may find it useful for evaluating the actual indoor thermal environment using data-driven approaches to develop effective retrofit strategies. Developers or property managers can also adopt in-situ monitoring for post occupancy evaluation.
2. **Computational modeling and simulation:** While building performance simulation (BPS) has been traditionally used for energy and comfort related applications, the past few years has witnessed increasing use of BPS for thermal resilience assessment [14,29,30]. BPS enables thermal resilience analysis for both new and existing buildings considering different scenarios at the required spatial and temporal scale. For instance, resilience modeling can evaluate the freezing potential during winter power outages or provide insights on the year-around resilience of buildings. Moreover, the approach is also capable of analyzing resilience at scale, such as at a community level for designing microgrids or at a utility region scale to inform stakeholders about resilience planning. This method may also be useful for assessing thermal performance of different building design options, risk assessment analysis for property insurance or to inform retrofit decision-making. However, particular attention must be given to the simulation parameters, performance metrics to report,

the model inputs and their resolution, and the modeling approach adopted for analysis to ensure accurate and meaningful results. A detailed discussion of the simulation workflow is presented in Section 2.5.

3. **Qualitative approaches:** Interviews and surveys to collect occupant experiences, feedback, preferences or contextual factors that may influence their interaction with buildings can prove valuable for thermal resilience assessment of existing buildings, particularly when complemented with on-site measurements or walk-through observations. For example, building operators may benefit by understanding occupant preferences to identify critical areas of discomfort in buildings and develop appropriate operational changes to ensure smooth building operations. Interviewing residents in disadvantaged communities to understand their indoor environment experiences and associated constraints such as energy burden, and getting familiarity with building controls may also help prioritize effective technology solutions and design strategies. Additionally, focus group discussions, real-time occupant feedback, or logging thermal experiences over a specified period of time may also benefit from thermal resilience assessment. However, utmost attention is required in designing surveys or the interview process to ensure reliable and representative results. An associated challenge would be to gather meaningful responses from occupants such as their possible behaviors during extreme events when they have not encountered any such events in the past. These qualitative approaches often require significantly more time and effort, as well as the need to address human subject and privacy issues, and thus must be adopted with caution.

2.4. What are the available metrics for assessing thermal resilience of buildings?

Metrics are fundamental to quantifying the thermal exposure, thermal vulnerability, and values of strategies to reduce thermal related mortality. Many metrics have been proposed throughout the years to assess thermal resilience of buildings. Some of these metrics are calculated through novel testing procedures. Some carry similar concepts but are named differently [14]. Part of the challenge of defining such metrics is that the term “resilience” does not have a common definition, nor can it be directly measured [31]. As several stakeholders may be interested in assessing thermal resilience, appropriate metrics will vary with their underlying needs and motivations. Available metrics can be broadly classified into the four categories described in Fig. 4. The term “metric” is considered throughout this article as a parameter that indicates a performance or describes a certain condition or state. They can be obtained through one or more variables or parameters, providing valuable information to understand resilience rather than just using raw operational measurements.

Occupant vulnerability metrics may be either qualitative or quantitative. They are used to identify populations with higher propensity to be affected by extreme events. For instance, vulnerability to heat has been associated with health comorbidities, housing features, income, social isolation and access to financial support [32]. Compound indicators are an alternative to aggregate these different parameters into one metric, such as the heat risk index in Paranunzio et al. [33]; which classified a population using a six-level scale from very low to very high risk. Policymakers, urban planners and public health agencies are some of the stakeholders that can benefit from such metrics because they enable them to make informed decisions when proposing new codes, standards, and social protection programs.

These vulnerability metrics can also be used to dive into a buildings’ thermal dynamics to quantify its capability of maintaining adequate indoor thermal conditions. Design teams and energy modelers are the most interested in these metrics as they can indicate what design aspects should be improved to foster thermal resilience. These metrics are usually calculated from outputs of building performance simulation or from field measurements. For example, metrics can be calculated from hourly values of indoor environmental parameters including air dry-bulb temperature, humidity, air velocity and surface temperatures. Thermal comfort parameters, including PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), have been widely used.

Three examples of metrics on occupant heat exposure and thermal survivability have been used in practices: (1) the Standard Effective Temperature (SET) degree-hours for both hot and cold events, (2) the Heat Index for hot events throughout a period of time, and (3) the Hours of Safety for cold events. These metrics are used to quantitatively evaluate the thermal resilience of the baseline building conditions, as well as to identify improvements to thermal resilience for the efficiency upgrade scenarios.

SET is a temperature parameter that considers indoor air dry-bulb temperature, relative humidity, mean surface radiant temperature and air velocity, as well as the activity rate and clothing levels of occupants. SET has long been adopted in ASHRAE thermal comfort standard 55 [34]. The LEED v4.1 Credit for Passive Survivability and Backup Power During Disruptions defines “livable conditions” as SET between 12.2 °C (54 °F) and 30 °C (86 °F). SET can be used to assess thermal survivability in both hot and cold events. To receive LEED credit for residential buildings, the unlivable SET degree-hours below 12.2 °C (54 °F) or above 30 °C (86 °F) must not exceed 120 (∘C)-hours (216 (∘F)-hours) for a seven-day power outage during an extreme hot or cold event. The SET degree-hours metric is more complex to calculate but considers six thermal comfort parameters and the accumulated severity of the thermal stress during extreme weather events. The metric is hard to measure directly in indoor environments but can be easily calculated using building simulation tools such as EnergyPlus.

Heat Index (HI) combines air temperature and relative humidity to measure the human-perceived equivalent temperature. There are four levels of heat stress based on HI: Caution, Extreme Caution, Danger, and

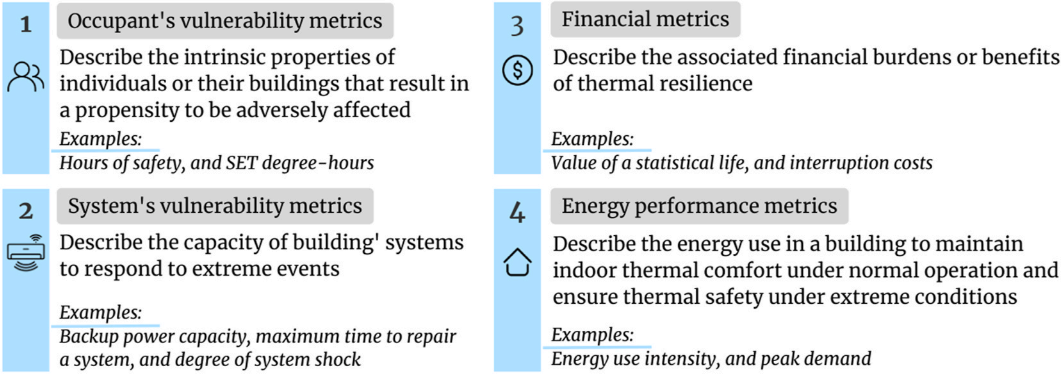

Fig. 4. Categories of metrics for assessing thermal resilience of buildings.

Extreme Danger. The parameter is used for hot events only, and can be analyzed within a timeframe to determine the occurrence of each heat stress level. HI is easy to measure, as it only requires the indoor air temperature and humidity. It should be noted that the heat index ranges and hazard levels are defined for the general population although the vulnerable population is more sensitive to overheating risk.

Hours of Safety is a metric developed by the U.S. Environmental Protection Agency (EPA) and the Rocky Mountain Institute [35] as a measure of the duration of time a building is able to maintain safe conditions above a predefined temperature threshold during a cold event. When indoor air temperature falls below 12.2 °C (54 °F), there is an increased health risk for vulnerable populations; when indoor air temperature drops below 4.44 °C (40 °F), there is an increasing risk of hypothermia for all populations (healthy and vulnerable). The metric of Hours of Safety is simple to understand and easy to calculate via simulations or measurements. It aims to serve as a potential resilience score of buildings, in analog to the ENERGY STAR score for representing energy efficiency of buildings.

For a building with multiple thermal zones (spaces with different temperatures), such as multi-family buildings or nursing homes or assisted living facilities, it is necessary to collect results from multiple spaces, as temperatures are likely to vary by orientation and floor level. Then thermal resilience metrics can be calculated for each occupied space, and results can be presented with the worst, median, 5% or 95% tile of spaces, and the aggregation weighted by the number of residents or bedrooms for the whole building.

Quantitative occupant vulnerability metrics can be divided into four types, depending on what type of information they provide about the indoor thermal environment and its consequences to occupants: frequency, intensity, duration, or severity. Frequency metrics are those that describe how often certain conditions occur. Thermal autonomy [36] is an example of a frequency indicator, describing the percentage of occupied hours a building can maintain indoor thermal conditions within thermal comfort thresholds without the need for mechanical conditioning. An intensity indicator usually describes extreme thermal conditions within the period, like the annual maximum operative temperature [37]. Duration indicates the length of time to reach or recover from certain conditions. An example is the hours of safety [35] previously mentioned. An indicator of severity combines both frequency and intensity, like the degree hours [38], and the SET degree-hours used to determine the passive survivability [39].

System vulnerability metrics may help mechanical and civil engineers to future-proof building technical systems, as well as guide building operators in responding to extreme events. Examples are the backup power capacity and peak demand [29], the maximum time to repair a thermal system serving the building [40], and the degree of system shock [41].

Financial metrics are those associated with the cost of either investing in thermal resilience measures or dealing with consequences of not being resilient. The value of a statistical life is an example of a financial metric that estimates the value of saving lives through mitigation measures [42]. Building property damages may include frozen or burst pipes during extreme cold events and moisture issues such as indoor mold growth if air-conditioning is turned off for too long. The Interruption Cost Estimate (ICE) Calculator [43,44] is a tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements. In Bucking et al. [45]; the value of lost load has been proposed to assess the thermal resiliency of a building during a grid outage. This category of metrics may interest real estate developers, corporate building owners and insurance companies, for example.

As practitioners do not want to focus on thermal resilience at the expense of other indicators, energy performance metrics can also be evaluated as a means to consider energy efficiency in tandem with resilience. Examples are the energy use intensity and peak demand. Other relevant metrics are carbon emissions and utility costs [45]. A resilience analysis should include a comprehensive set of metrics to compose a thermal resilience assessment that will ultimately serve for evaluation, comparison and decision-making.

2.5. *What is a reasonable workflow to model thermal resilience using building performance simulation?*

Building performance simulation (BPS) has long been used to assess the energy and thermal performance of buildings. As resilience assessments gain more attention in the literature, similar procedures are being adopted for thermal resilience modeling with some distinguishing practices and additional points of caution. Fig. 5 illustrates a workflow to effectively simulate thermal resilience in buildings.

The first step is to select an appropriate tool and develop a baseline building model. Common BPS tools, including EnergyPlus, TRNSYS, IDA ICE, IES, and eQuest are described and compared in Attia et al. [46]; Mazzeo et al. [47]; and Pan et al. [48]. The minimum capabilities expected from a BPS tool to model resilience [14] include the following:

- Ability to run full-year or partial-year analyses at least at an hourly frequency
- Comprehensive consideration of weather variables as input in the simulations
- Capacity to model failure events (e.g., technical systems and grid failures)
- Ability to model the occupant behavior and their adaptive measures
- Ability to model detailed zoning, including multiple floors and rooms
- Capacity to model natural ventilation, shading effect, and other strategies and technologies that may influence thermal resilience

Assumptions regarding occupants and building operation greatly influence the resilience assessment as they define, implicitly or explicitly, a level of expectation towards the indoor environmental quality and adaptation abilities. Mechanically cooled/heated buildings often require different design choices and adaptation strategies than occupant-controlled naturally conditioned buildings or mixed-mode buildings do [49].

Based on the operation mode, it is necessary to define or choose parameters that characterize the indoor thermal environment and can represent thermal resilience. Depending on the chosen BPS tool, it may implement some of the thermal resilience metrics that can be reported directly or may have to output relevant hourly variables that are further post-processed to calculate the thermal resilience metrics.

The fundamental definition of resilience is associated with how buildings respond and recover from a shock [5], such as heat waves, cold snaps, and power outages. Thus, unlike conventional BPS that consider buildings under typical meteorological and normal operational conditions, a thermal resilience analysis should account for multiple scenarios that may impact a building's coping capability. The selection of scenarios for a robust thermal resilience analysis is further discussed in Section 2.6.

After running simulations that consider multiple scenarios, metrics are calculated from the outputs. They should quantify occupant's vulnerabilities, as well as the necessary energy used to operate the building and maintain thermal comfort and safety. A resilience assessment will report the obtained results, which can then be used in an optimization process targeting and improving vulnerabilities through appropriate design strategies.

2.6. *What scenarios are needed to consider for robust thermal resilience modeling?*

Unlike conventional BPS, thermal resilience modeling requires accounting for an integrated set of scenarios considering various sources of hazard that can disrupt buildings in a geographic region. Table 2 lists

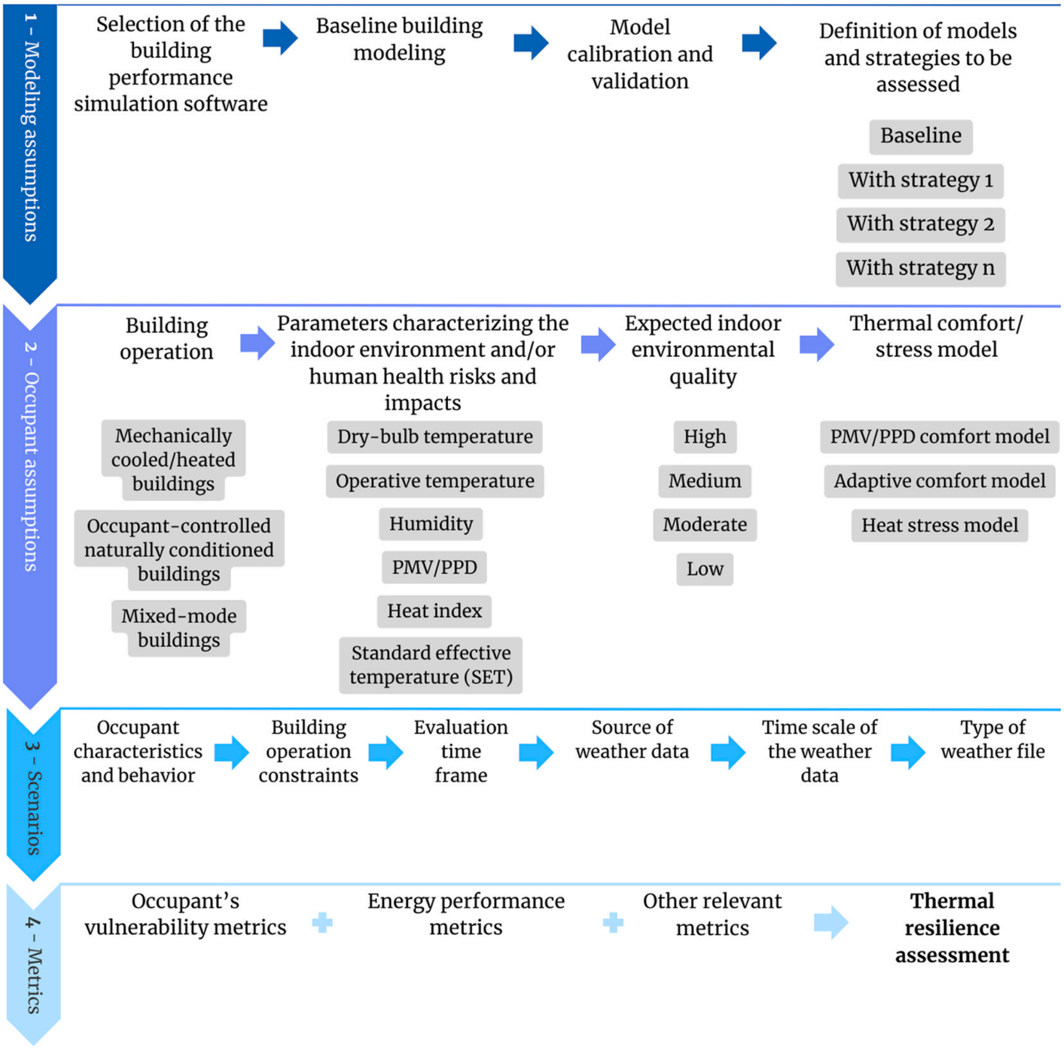

Fig. 5. A workflow to model thermal resilience using building performance simulation.

Table 2
Types of hazards and potential impacts on the indoor thermal environment.

Types of hazard	Consequences to buildings and their indoor thermal environment	Representation in building performance modeling
Air pollution, wildfires	Limit window opening, restraining occupants' adaptability capabilities	Building operation constraints
Pandemics	Alter occupation and operation in relation to design conditions, influencing thermal performance	Diverse occupant behaviors
Power outages, drought	Limit use of systems (e.g., HVAC) to respond to extreme weather events	Power availability constraints and building operation constraints
Heat waves, cold waves, ice storms	Overheating or overcooling	Appropriate weather file
	Damage structures and systems, impacting the capability to respond to hazards	Building operation constraints System performance loss on inputs
	Alter occupation and operation (e.g., limiting commute outdoors)	Diverse occupant behaviors
Earthquakes, flooding, landslides, volcanic activities, wind storm, wildfires	Damage structures and systems, impacting the capability to respond to hazards	Building operation constraints System performance loss on inputs

types of hazards (left column) associated with possible consequences to the indoor thermal environment (central column), such as causing overheating and limiting operability. These events may be modeled directly or indirectly in the BPS, with possible approaches listed in the right column. For instance, heat and cold waves can be directly modeled through appropriate weather files from a historical event or a projected future event. The impact of wildfires on the other hand would be mostly represented indirectly; the ambient air quality (CO_2, fine particulate matter [$PM_{2.5}$]) may not be provided in the weather files. These fires can compromise the air quality in a region, preventing occupants from opening windows, which can limit occupants' adaptability capabilities and compromise thermal resilience. When a building does not need to be evacuated, earthquakes and flooding can damage structures and technical systems, which also affect building operation and system performance, limiting the capacity to respond to hazards.

Occupants' characteristics are also relevant when selecting scenarios, as they will influence not only the expected indoor thermal quality but also adaptation capabilities. The COVID-19 pandemic recently demonstrated how building occupation and operation patterns can deeply change, consequently impacting building performance [50, 51]. Considering diversity in occupant behavior can be an opportunity to stress the model [52] and test its resiliency.

Fig. 6 summarizes the main steps to formulate scenarios within a modeling workflow. Beyond fully functional buildings, power availability constraints should be considered, especially for buildings that

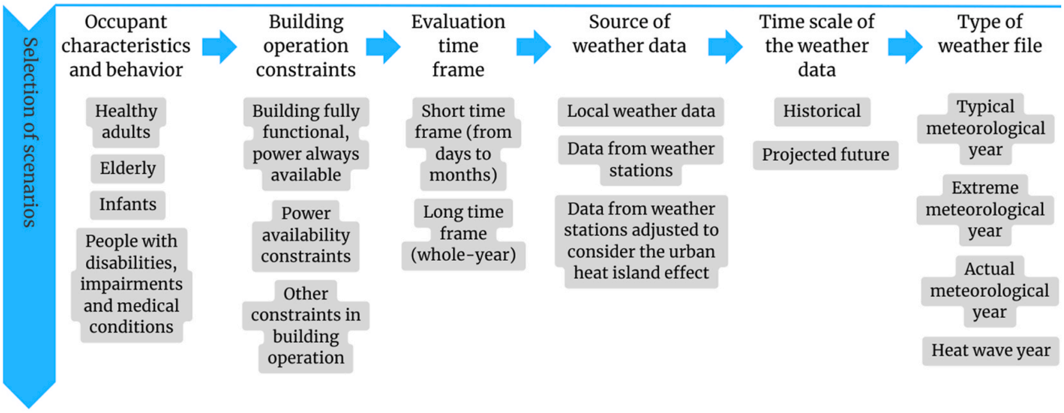

Fig. 6. Key dimensions to consider in defining simulation scenarios for evaluating thermal resilience.

rely on active systems to guarantee survivability. Partial power, complete power outages at different durations, and rotating power outages are some of the scenarios adopted, often concurrent with a heat or cold wave. When analyzing the effectiveness of phase change materials in residential buildings, Baniassadi et al. [53] verified that the severity of overheating highly depended on the time of day that the air-conditioning system lost power. Other constraints in building operation can be related to failure in building technical systems (e.g., automatic solar shading) and the inability to open windows due to occupants' physical limitations or exterior factors (e.g., wildfires and security concerns). Sengupta et al. [41] evaluated the impact of multiple types of shock on resilience to overheating in a nearly-zero energy educational building and concluded that the impact of heat waves was significantly higher than any system failure, with a future heat wave being the most extreme shock.

When analyzing a specific event (e.g., historical heat wave), authors usually run simulations for a shorter time frame (from days to weeks) comprising that event plus a warm-up period [11,54]. When analyzing the overall thermal autonomy of buildings, whole-year simulations are used, which are able to better represent the impact of weather seasonal variability [13]. The source of weather data is fundamental to enable an accurate evaluation. As extreme scenarios are often intensified by local urban characteristics (e.g., urban heat islands), local weather data are preferred.

Learning from past events is an important part of resilience planning, thus simulation with historical weather data is relevant, such as when considering historical extremes. However, it is increasingly important to start designing for the future, as new buildings are expected to last at least 50 years. Authors have developed future weather files based on the Intergovernmental Panel on Climate Change (IPCC) scenarios [55], leveraging the assessment of thermal resilience under 2050s and 2090s climates [56], for example. A prominent initiative to generate future weather files can be found in the works of the International Energy Agency Annex 80 [57] which provided future Typical Meteorological Years (TMY) and Heat Wave Years (HWY) for multiple cities worldwide.

Available techniques to generate future weather data are based on downscaling general circulation models. Examples are time series adjustment (morphing), interpolation, stochastic weather generation, and dynamic downscaling [58]. The latter consists of using regional climate models (RCM), which are climate models obtained from global climate models (GCM) after a dynamic downscaling to improve spatial resolution (10–50 km [km]). RCMs can be obtained from the Coordinated Regional Downscaling Experiment (CORDEX) database, where worldwide multi-year projections are available [59]. The Weather Research and Forecasting (WRF) model, coupled with the urban canopy model, can further downscale the climate data to the 1 km resolution considering the urban heat island effects and anthropogenic heat from buildings [60].

Weather data can be provided for building performance simulation in different types of weather files, depending on the application. For a resilience analysis, ideally a set of different weather files would be adopted to provide a range of climate conditions that a building may be exposed to (D. B. [61]. For instance, in an eXtreme Meteorological Year (XMY) [62], more extreme months are selected to build the meteorological year, unlike TMY, which considers median weather conditions [63]. Heat wave years represent actual years in which at least one heat wave has been detected.

A standard definition of a heat wave is still absent, and detection methods differ in literature and practice. Flores-Larsen et al. [64] evaluated heat waves that were identified through three methods comparing their potential impact on indoor thermal conditions. The authors rendered Ouzeau's method as the most suitable for building applications. In Ouzeau et al. [65]; a set of criteria is defined to identify heat waves, together with three metrics to characterize them: duration, maximum temperature, and global intensity. Thus, multiple heat waves can be identified within a period, allowing users to select the longest heat wave, the most intense, and the most severe. However, the minimum number of scenarios to be considered in a robust resilience analysis remains a research gap.

For buildings in mixed climates, e.g., requiring cooling in summer and heating in winter, it is important to include both the extreme hot and cold events in the modeling and evaluation of thermal resilience. Certain mitigation measures may result in conflicting performance between the hot and cold events, e.g., a well-insulated and airtight building envelope helps maintain indoor warm temperature during cold events, but it may trap heat indoors, leading to overheating during hot events if there is a lack of effective ventilation (either natural ventilation or low-energy mechanical ventilation using fans).

2.7. What technologies and design strategies can be used to achieve resilient buildings?

Designing thermally resilient buildings requires an understanding of effective strategies and solutions that can reduce the adverse effects of extreme temperatures on occupants' health. In this endeavor, we can turn towards a wide array of technological solutions, including passive and active measures, backup power and energy storage, and certain behavioral strategies driven by the occupants themselves. This section summarizes the current and emerging technologies to improve thermal resilience (which does not necessarily align perfectly with energy efficiency), and discusses these technologies' potential conflicting impacts between extreme hot and cold events.

2.7.1. Passive solutions

Passive solutions do not require power supply to function, so they can be particularly helpful during power outages. The first line of defense against extreme temperatures is the design of the building itself. Properly designed and insulated building envelopes can significantly improve thermal performance by reducing envelope heat gain in summer and heat loss in winter, modulating (time shifting) indoor temperature changes by storing and releasing heat, and/or removing heat from the building in summer and adding heat to the building in winter.

Passive designs that can effectively reduce unwanted heat gain through the envelope during extremely hot events include (1) thermal insulation, mainly in walls and roofs; (2) window measures, such as high-performance windows, interior and exterior shading devices (e.g., blinds, overhangs, awnings), and solar control window films; (3) solar reflective materials, such as cool roofs, cool walls, and radiant barriers [30,66]; (4) evaporative envelope surfaces, such as green roofs, green facades [67], and roof ponds [68,69]. On the other hand, thermal insulation and air tightness are very effective passive designs that can effectively reduce unwanted heat loss during extreme cold events.

The properties and performance of the above passive designs are static throughout the year. In some cases this might cause conflicting impacts between extreme hot and cold events [29,70]. For example, cool roofs, cool walls and solar control window films can reduce heat gain through solar radiation, which is beneficial in decreasing indoor temperature during heat waves, but on the other hand, would have a negative impact during cold snaps [29]. To solve such conflicts, researchers are developing emerging technologies such as dynamic coatings. Dynamic coating materials, with varying thermal and/or optical properties under different circumstances (e.g., temperature, switches between control states), can modulate heat gain and heat loss through the envelope in different seasons. The application of dynamic coatings is mainly on windows and roofs, such as thermochromic smart windows [71] and thermochromic roofs [72–75]. Such dynamic coating technologies have not been deployed widely due to the high investment cost issues.

Natural ventilation can provide free cooling when the outdoor environment is cooler than the occupied space. For buildings with operable windows of reasonable size and orientation, natural ventilation is a very effective passive measure to decrease indoor temperature during heat waves [29,67,76], particularly for top floors [30]. Meanwhile, the benefit of natural ventilation may be moderately curtailed if the exterior environment is too harsh to benefit the interior environment, e.g., outdoor temperature is higher than indoors, outdoor air humidity is too high, or outdoor air is polluted during wildfires [54].

Thermal mass can be an effective passive strategy. It refers to the ability of a material to absorb, store, and later release heat, acting as a thermal buffer. Materials with high thermal mass (such as concrete, brick, or stone) can absorb heat during the day when the temperature is high and release it slowly at night when the temperature drops. This process helps regulate the daily indoor temperature fluctuations, providing a more stable and comfortable indoor environment. However, its effective use depends on the duration of the extreme hot events (thermal mass can be effective for short events, say 1 or 2 days) as well as the occupancy patterns of the building (residential buildings with nighttime occupancy or office buildings with daytime occupancy only).

Passive solar heating and cooling systems, such as Trombe walls, can further enhance the building's resilience [77]. Classic Trombe walls are heating-based, which can catch solar radiation, exploiting the greenhouse effect created in a glazed cavity, and absorb and store heat using a massive wall. Some variations of Trombe wall configurations enable it to provide passive cooling in the hot summer. The Trombe wall is not a new technology (its concept was born in the 19th century); however, modifications have been made to Trombe walls over time to improve their performance and efficiency [77].

2.7.2. *Active solutions*

While passive measures can reduce the risk of dangerous conditions, they may not guarantee safe conditions for occupants [54]. Active measures, backup power, and/or energy storage are needed to provide cooling/heating to maintain safe conditions for occupants. Active solutions need power supply to function, either from the grid or from batteries or on-site backup power systems. A typical active solution is to install an HVAC system or upgrade the existing HVAC system. The HVAC equipment in existing buildings usually suffers from efficiency and capacity degradation as it ages due to various reasons such as duct leakage, refrigerant loss, soiled filters and lack of maintenance. During extreme temperature events, this may cause failure of the HVAC equipment to provide sufficient cooling/heating to maintain thermal safety in the buildings. Upgrading the existing HVAC system to an appropriately sized efficient new system would enable sufficient cooling/heating capacity to secure a comfortable indoor environment during extreme temperature events.

However, there are two caveats with the typical active solution: (1) HVAC systems, especially whole-building central types, consume large amounts of energy. If all buildings run their HVAC systems at full capacity during extreme temperature events, it would be a huge burden to the grid and would largely increase the risk of power outages due to limited grid capacity. (2) If a power outage did happen, the HVAC system could not run without a large capacity backup generator or large capacity battery due to its high energy demand, which would require significant investment. Therefore, low-energy active solutions are highly preferred, as well as active solutions that are based on optimal control strategies.

Low-energy active solutions can function with relatively small amounts of energy, such as ceiling fans, portable fans, evaporative coolers and portable air conditioners (ACs)/heaters. Ceiling fans and portable fans can improve comfort levels by raising the upper boundary of the occupants' comfort zone through increased air circulation. Evaporative coolers and portable ACs, despite their limited capacity and moderate efficiency, can keep a single room from overheating and help to avoid deadly heat hazards [29]. In particular, a combination of evaporative coolers/portable ACs and ceiling fans/portable fans could be a very effective active solution to maintain thermal safety for the occupants.

Personal comfort systems (PCS) are another attractive low-energy active solution. PCS are devices to heat/cool individual occupants directly or heat/cool the localized thermal environment of an individual occupant, under the control of the occupant without significantly affecting the thermal environment of other occupants [34]. PCS examples include cooled/heated chairs, portable or desktop-scale fans, workstation micro-air-conditioning units including personalized ventilation (some including phase change material storage), conductive wearables and variable clothing insulation. By conditioning the immediate surroundings of the occupants, PCS create micro-environments that can extend the range of temperatures that is generally perceived as comfortable, thereby avoiding significant discomfort/hazard and also reducing the energy used by mechanical space conditioning [7].

Optimal control methods can enhance a building's thermal resilience during heat waves by optimizing the building load profile. A good example is pre-cooling. Pre-cooling refers to cooling the building during off-peak hours or periods of lower temperatures to mitigate heat gain during peak hours. Simulation results show that pre-cooling is effective in reducing overheating, and the efficacy of pre-cooling depends upon several building characteristics [78].

2.7.3. *Backup power and energy storage*

Backup power and energy storage technologies ensure the continuous operation of active solutions during power outages or periods of high demand. Solar photovoltaic (PV) systems, backup generators (e.g., wind, diesel), and batteries can provide reliable power, while thermal energy storage systems using water, ice or phase change material store excess thermal energy for later use [79]. Combined heat and power generation may also contribute to a building's energy resilience by optimizing load dispatch [79].

Backup generators and batteries, though reliable, require considerable initial investment. If backup generators and/or batteries are designed to maintain a building's full services during extreme weather events, the required capacity would be significant. Alternatively, if the resilience goal is to maintain the critical services only, the required backup generator and/or battery capacity would be largely reduced [29].

2.7.4. Occupant behavioral strategies

Beyond technological interventions, occupants can adopt various strategies to cope with extreme temperatures. These include self-dousing, foot immersion, misting fans, ice towels, ingesting cold water, adjusting activity levels, and adding or removing clothing layers [80]. Such adaptive behaviors, complementing the technological solutions, can significantly contribute to enhancing the overall thermal resilience of buildings. More details regarding human factors and their impact on thermal resilience will be discussed in Section 2.8.

2.8. What are essential human factors to consider in achieving thermal resilient buildings?

Human factors play two critical roles in the evaluation of building thermal resilience. First, most buildings serve the explicit purpose of protecting occupants from outdoor conditions and often—particularly for conditioned buildings and in developed countries—rely on an uninterrupted supply of external energy inputs and active building systems to provide a comfortable and healthy indoor environment.

Second, occupants often play an active role in improving building performance in the absence of such active energy systems (e.g., opening windows to provide fresh air)—particularly for buildings that are not tightly controlled and automated (e.g., naturally ventilated). While humans have a wide range of physiological, psychological and behavioral means for adapting to extreme conditions [81], the desired range of preferred or habitable conditions depends greatly on the individual and population (e.g., elderly, hospital patients, children, healthy adults). Similarly, the skill, knowledge, experience and ability of occupants to adapt building systems during extreme events will vary. Fig. 7 shows the full spectra of occupant sensitivity and ability, with the trend of those in the bottom left corner being most vulnerable. Another way to view this is that of the three means for adaptation—psychological, physiological, and behavioral—the vertical axis represents the first two, while the horizontal axis represents behavioral adaptation. The severity of consequences from exposure to extreme conditions and recovery (e.g., ranging from full recovery to death) also depend on the combination of the individual and the severity/duration of conditions experienced [81].

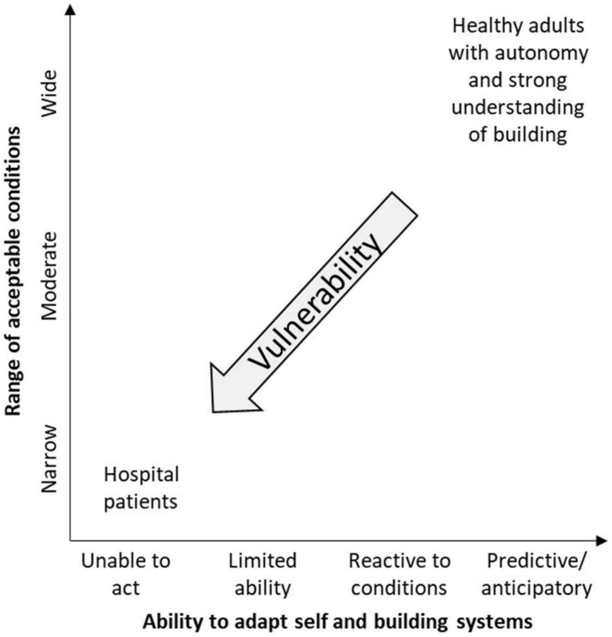

Fig. 7. Two-dimensional space of occupant ability and sensitivity to indoor conditions, with two extreme populations shown as examples.

To ground the theory, consider a study of 740 people who died during an extreme heat event in British Columbia, Canada, in 2021 [82]. Schizophrenia was found to be the top predictor of death. Lee et al. [82] suggested that people with schizophrenia lack an awareness of their own health status and thus may not respond to overheating; their medications may also inhibit thermoregulation. In this case, the same health condition caused the occupants to both be insensitive to indoor thermal conditions and have a limited ability to adapt. During this same heat wave event, a study of all deaths [83] found the majority of decedents were not using their air conditioning or fans at the time of death. This suggests a lack of user knowledge, but also highlights the importance of education and usability of such devices.

2.8.1. Acceptable indoor conditions

Of the four domains of indoor environmental quality (IEQ)—indoor air quality (IAQ), thermal comfort, visual comfort, acoustic comfort—the first two are the most sensitive during extreme events. Visual comfort could also be problematic in the absence of electric lighting—particularly if it is needed to support egress. In this brief section, we review key issues and parameters established by the thermal comfort literature.

The literature on building thermal resilience has developed numerous definitions for the indoor conditions of a building's thermal environment, with two main perspectives: the occupant's or the objective indoor conditions. For example, Homaei and Hamdy [11] defined indoor spaces in three categories of improving conditions for occupants: uninhabitable, habitable, and comfortable/acceptable. Indoor thermal conditions are often defined by various forms of temperature and corresponding thresholds, though standards are not yet widely established. Many overheating and heat stress metrics have been developed [67]; refer to Section 2.4 for more. The duration of exposure to extreme thermal conditions also needs to be considered for defining indoor thermal conditions. For example, Flores-Larsen et al. [84,85] reviewed numerous time-integrated and/or space-integrated discomfort evaluation methods to integrate temperature and exposure duration within resilience assessment. The literature largely focuses on overheating; however, cold conditions also can be a concern (e.g., coincidence of freezing rain that causes power outages and extreme cold conditions). More research is needed to understand resilience in such circumstances.

The literature also considers the extent to which occupants can psychologically adapt or cope with uncomfortable or unhealthy thermal conditions [86]. However, there are many open questions since limited data are available. For example, it is unknown whether occupants in naturally ventilated/free-running buildings are more tolerant to extreme temperatures. Also, can the adaptive thermal comfort model be applied to buildings that suddenly become naturally ventilated by virtue of not having functioning air-conditioning?

While IAQ and thermal comfort are often treated separately (e.g., by codes and standards), we must acknowledge some interactions. First, thermal conditions can affect human sensitivity to IAQ and vice versa [87]. Second, occupants may face a compromising circumstance whereby they wish to open a window to increase fresh air at the cost of admitting air of uncomfortable or extreme temperatures. Conversely, they may be overheating and wish to open a window, yet the outdoor air may be highly contaminated (e.g., wildfire smoke, sandstorms).

2.8.2. Occupant behavioral response to extreme events

Occupants' opportunities to adapt to uncomfortable or extreme conditions depend greatly on the building design, but may include operable windows, moveable shading devices, clothing, and relocating to other parts of the building (or outdoors). O'Brien and Bennet [88] found that occupants' actions, if near-optimal, were as important as building design in achieving desirable resilience. The ability of occupants to act depends on their physical abilities, while the awareness that they should act and how they should act depends on their cognitive abilities, as indicated by the BC example above. As one extreme, occupants who rely on elevators will struggle to leave multi-story buildings during power outages [89]. On a smaller scale, occupants who cannot reach or do not have the strength to open windows or window shading devices will be similarly disadvantaged.

If occupants are able to adapt to extreme events, the question remains on how effective occupant actions are and how predictive the occupants are. For example, occupants may strategically open windows overnight if outdoor conditions cool, while closing them during the day. Occupants' knowledge about strategies and familiarity with the thermal dynamics of the building tend to be best in naturally ventilated or unconditioned buildings, whereby they take an active role in improving the indoor environment during normal circumstances [90].

While we can and should train occupants to act in ways to sustain their well-being during extreme events (e.g., as we conduct fire drills), a priority is to design buildings with systems that are resilient and allow occupants to help themselves in the first place. Ultimately, even the most savvy occupants will be constrained by building design. Redundancies are important to give the ultimate flexibility to occupants; for example, operable windows may help mitigate overheating, but wildfire smoke would necessitate that occupants keep them closed to avoid infiltration. While we focus on occupants in this section, it is noteworthy that other passive features enhance occupants' ability to improve comfort (e.g., well-insulated envelope, thermal mass). Overly complex systems or automated systems with no manual override may be a liability during extreme events.

On the most extreme end of preparedness and long-term decision-making, some consumers devise their own solutions; for example, by purchasing a generator or PV system that allows islanding (i.e., disconnection from the grid) [91].

2.9. How can thermal resilience of buildings be incorporated into climate adaptation and building decarbonization plans?

Climate action plans formulated by governments across the globe for adaptation and mitigation of climate change require integrating thermal resilience objectives to ensure that energy and carbon targets are met in conjunction with minimum losses to buildings and its occupants. A key strategy for climate change mitigation in buildings is to decarbonize through energy efficiency, electrification, renewable generation, and demand flexibility approaches. These decarbonization approaches often have impacts and trade-offs with thermal resilience approaches, and hence it is important to recognize the opportunity to harmonize and synergize decarbonization efforts with thermal resilience efforts. Sun et al. [54], in the context of nursing homes, found that conventional efficiency measures such as reduced air infiltration counteract thermal resilience improvements. They also found that efficiency measures convey different resilience impacts, depending upon characteristics such as location, outdoor climate, nature of extreme weather event or duration of power outage. Moreover, even though the electrification of HVAC systems is at the forefront of decarbonization, the access to heat pumps is associated with challenges such as cost, availability and adoption. There exists a huge opportunity in the buildings' energy transition for lower cost complimentary energy savings approaches such as passive cooling measures and low cost cooling measures such as ceiling fans. Additionally, occupant-centric building controls to minimize overheating or cooling, and personalized cooling systems such as personal fans and cooling chairs during periods of grid stress may offer improved thermal resilience. Cross sectoral approaches such as electrification of the transport sector, along with improved vehicle-to-building (V2B) capabilities, also can prove beneficial for improving thermal resilience within decarbonized buildings.

In terms of renewable energy generation, important considerations for thermal resilience and potential trade-offs in the scale and location and cost of renewable energy sources must be considered. For instance, community distributed energy resources may offer better resilience to buildings and prove to be more reliable and cost-effective than rooftop solar PV with or without batteries. To achieve synergies in improving thermal resilience and use of renewable generation sources, technological innovations are needed to replace fossil-fuel based backup power options such as diesel generators with "passive survival" technologies for low cost emergency use such as low cost HVAC with integrated storage and/or direct DC-coupling to rooftop solar PV. Moreover, uncertainty in future extreme events and lack of quantification of the impact of future events/power outage on non-energy factors such as health mortality, morbidity, productivity, stress and education outcomes may hinder proper valuation of resilience investments in renewable energy planning. Demand flexibility, similar to the other three decarbonization approaches, has a strong interaction with thermal resilience to the extent that it can achieve a more reliable grid. For instance, designing demand response strategies for load shifting such as setpoint adjustments or pre-cooling must account for the building and its occupant's characteristics, such as air tightness of the building envelope and the thermal comfort thresholds of the occupants, to ensure adequate thermal comfort. Intelligent and automated building control systems to optimize thermal comfort and energy use also may prove beneficial. Considering the co-benefits of thermal resilience of occupants, especially during extreme scenarios (extreme weather coupled with power outages), is essential when making decisions about decarbonizing buildings.

Unlike building decarbonization, the relevance of thermally resilient buildings in climate adaptation plans is relatively straightforward. Thermally resilient buildings that can withstand current and future climate change impacts are essential to ensure an optimal indoor thermal environment for occupants and successful climate adaptation. Currently, there is a siloed approach towards climate adaptation plans for buildings, where the focus is mainly on extreme heat (such as California's Extreme Heat Action Plan [92]), while hazards such as snowstorms or wildfires are not accounted for [93]. However, these often ignored hazards may pose a similar degree of threat to the thermal resilience of buildings and thus must be included in the adaptation plans. In summary, there is a need to better integrate thermal resilience that is not limited only to heat events in climate action plans.

2.10 How can building energy codes and standards, building performance rating systems, and policies be adapted to support the design and operation of thermal resilient buildings?

Building codes and standards, as well as performance rating systems, are effective instruments in supporting the creation of sustainable and resilient building stock. Studies have shown building codes with higher energy efficiency requirements improve thermal resilience [12,94].

We considered five different types of regulations, as well as rating systems that could be updated for thermal resilience, using the example of California, a leader in climate legislation, and an area with very diverse climate regions.

- Building codes regulating general building design and construction requirements relating to fire and **life safety, structural safety, and access** compliance (California Title 24, Part 2) [93].
- Building code **energy efficiency** requirements typically for new construction in residential and nonresidential buildings and for remodels and additions (California Title 24, Part 6). Compliance with this code can take the form of mandatory measures, prescriptive measures, or taking a "performance path" of meeting overall performance requirements with a combination of different measures at the discretion of the building designer.
- Building code for **existing buildings** (California Title 24, Part 10). This includes seismic provisions but also requirements for

mechanical, electrical, and plumbing systems and components, e.g., fire alarms.

- "Green building codes" that cover **broader building sustainability areas** such as building and site planning/design, energy efficiency, water efficiency, materials/resource conservation, and indoor environmental quality (California Title 24, Part 11, or "CALGreen"). Within those categories, CALGreen has both mandatory and voluntary measures. Voluntary measures that exceed the minimum standards can be enacted by local jurisdictions and are also known as "reach codes."
- Housing law regulations including **minimum building habitability** standards for health and safety (California Title 25, Division 1) [95]. For example, in California this applies to all existing hotels, motels and apartment buildings.
- There are also **green building rating systems** applied to new construction, the most widely used of which is the Leadership in Energy and Environmental Design (LEED) rating. These may cover similar categories to green building codes such as CALGreen but the requirements for LEED ratings and green building codes such as CALGreen are generally not identical. BREEAM, CASBEE, and Green Star [96] are other Green Building Rating Systems applied worldwide.

Current building codes and performance rating systems are more focused on energy savings and energy efficiency performance than on thermal resilience, with a few exceptions, such as the inclusion of resilience credits in the LEED rating system. For indoor comfort, building codes are more likely to cover minimum heating standards and not minimal cooling requirements. For example, California's building code for safety (Title 24 Part 2) has minimal temperature for heating temperature but not for cooling, and similarly, California housing law (Title 25 Division 1) mandates that existing rental units be capable of maintaining a minimum indoor temperature of 70 °F (21.1 °C). The concept of thermal autonomy also can be recognized in building codes and used to guide effective passive designs.

2.9.1. *Key opportunities*

Thus, there are opportunities in multiple building regulation channels (building codes, green building/reach codes, housing laws) to include greater consideration and requirements of resilience-related measures.

For existing buildings, a starting point would be to building upon existing housing law habitability requirements (Title 25, Division 1) to cover extreme heat and maximum indoor temperatures and to extend the existing coverage of these laws to existing single-family home buildings in addition to apartment buildings, perhaps via Title 24, Part 10 (Existing Buildings).

There is a large opportunity for a newer class of regulation for thermal resilience with greater focus on ensuring inhabitant comfort and safety during emergency situations, acute events, and cascading and/or concurrent emergency events and to ensure passive survivability (survivability during grid power outages).

A starting point for this in new construction is in building reach or "stretch" codes. These codes go beyond minimum acceptable performance standards and may give the option of a tiered or stepped series of enhanced measures for comfort or safety. For example, these could give local jurisdictions wide latitude and options for the greater deployment of low-cost passive and low-energy active energy measures that can save energy and also provide greater resilience. These can be implemented in a similar way to traditional codes but provide additional design and performance options beyond what codes currently prescribe. Similarly, Green Building Rating Systems could be updated and extended to provide more credits for thermal resilience measures.

Researchers within the IEA Annex 80—Resilient Cooling of Buildings—reviewed programs, codes and policies worldwide and proposed a set of 37 policy recommendations to foster resilience against heat waves and power outages [9]. These recommendations cover the consideration of multiple resilient cooling strategies in policies, as well as the main steps to incorporate a resilience assessment into whole-building policies. It is still necessary to set the foundation of a resilience analysis into codes and standards, establishing a standardized procedure to assess thermal resilience considering multiple sources of disruption. Among these disruptions, heat waves and future climate projections should be considered when revising performance parameters, threshold values, and recommendations related to technologies in policies. Comprehensive metrics, data sharing, and labeling systems need to be established to quantify resilience and allow benchmarking and communication across different audiences.

2.9.2. *Challenges and barriers*

While the performance path approaches in building codes could accommodate a simulation-based assessment of resilience (e.g., as presented in Section 2.5), enforcing resilience using a prescriptive path is more challenging. This is because the resilience of a building depends on how design features and systems work together, rather than any individual building feature.

Updating code and housing law for greater incorporation of thermal resilience would face several barriers depending on the avenue taken to implement that measure, such as cost, enforcement challenges, and modeling capability to justify code additions.

One broad challenge is that with additional resilience generally comes additional cost, and the question becomes, exactly how much resilience is required, where, and at what cost? Another challenge for heat resilience is that planning should be made to ensure that passive and low-energy or low-carbon active cooling measures are deployed to the maximum extent possible to ensure that air conditioning demand is minimized, to reduce investment costs, to constrain utility bills increases, and to reduce stress to the grid during heat waves.

Housing law or building code changes that would require greater equipment or cooling requirements would face opposition from property owners, and an extension to the general residential sector would face cost of compliance and enforcement challenges in existing buildings.

To the extent that a cost/benefit framework and cost effectiveness is a requirement for building code updates, resilience measures have multiple challenges. For example, resilience metrics and performance criteria need to be more fully defined and developed, and the benefits of resilience investments to safeguard public health and safety needs fuller quantification and monetization.

The current practice of building modeling and characterization of building measures does not adequately handle the risks associated with both summer and winter extreme climate events of increasing frequency, duration and intensity, and needs to be updated to fully encompass future climate risks. This may include updated weather files that better capture regional weather extremes and a more comprehensive risk assessment of future risks, possible investments, and more comprehensive evaluation of the projected benefits of those investments.

3. Summary and future perspectives

In this paper we explored 10 questions on thermal resilience of buildings focusing on the occupant's health and thermal safety during extreme weather events coincident with power outages. With the growing risk of extreme temperature events and power outages, it is essential to consider the costs and benefits of improving thermal resilience in the design of new buildings or retrofitting existing buildings towards carbon neutrality. Building codes and policies need to define clear requirements on thermal safety of occupants, provide credits towards climate resilient designs, and define backup power requirements to provide critical services (heating and/or cooling) to critical facilities (e.g., senior housing, nursing homes, assisted living facilities). There remains a need to develop a practical standardized methodology for assessing thermal vulnerability and evaluate benefits of passive and active technologies, and occupant behavioral strategies in improving thermal resilience. The assessment methodology should include a well-defined set of thermal resilience metrics that can be quantified through measurements or building performance simulation. Standardized definitions and datasets of extreme temperature events (heat wave and cold snaps) covering major global cities are also needed.

For people living in hot climates, the distinction between extreme/acute heat and chronic high heat is starting to blur. For example, in California's central valley city of Fresno, in 2021 there were 69 days of heat with high temperatures exceeding 100 °F (37.8 °C), which is practically the entire summer. This also may apply to many parts of the Middle East and a growing region of India and Southern China. Cooling (air-conditioning) during the hot summers becomes an essential life need for the population living in the hotter and hotter regions.

As the thermal resilience of buildings and occupants involve different stakeholders, building design and operation, codes and standards, and policies, an effective strategy or policy to regulate or improve thermal resilience should be based on multi-disciplinary approaches. People living in disadvantaged communities tend to be more vulnerable to extreme heat due to limited resources for adaptation, therefore climate equity issues deserve more research. With the global trend to decarbonize the building sector for meeting economy-wide carbon neutrality in the next 30 years, there is an unprecedented opportunity to do this right—not only for reducing energy use and carbon emissions of buildings but also for improving their climate resilience for human health and thermal safety at the same time.

CRediT authorship contribution statement

Tianzhen Hong: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jeetika Malik:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Amanda Krelling:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **William O'Brien:** Writing – review & editing, Writing – original draft, Methodology. **Kaiyu Sun:** Writing – review & editing, Writing – original draft, Conceptualization. **Roberto Lamberts:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Max Wei:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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