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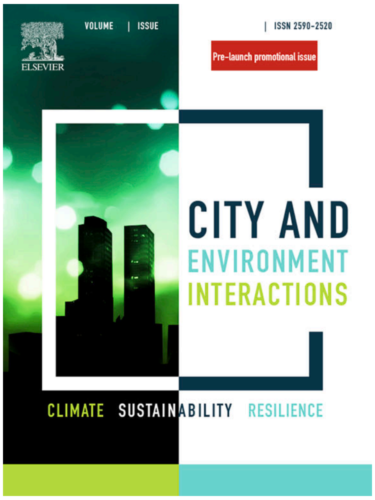

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Conceptualising a resilience cooling system: a socio-technical approach

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Conceptualising a resilient cooling system: a socio-technical approach

Abstract

Prolonged and/or extreme heat has become a natural hazard that presents a significant risk to humans and the buildings, technologies, and infrastructure on which they have previously relied on to provide cooling. This paper presents a conceptual model of a resilient cooling system centred on people, the socio-cultural-technical contexts they inhabit, and the risks posed by the temperature hazard. An integrative literature review process was used to undertake a critical and comprehensive evaluation of published research and grey literature with the objective of adding clarity and detail to the model. Two databases were used to identify risk management and natural hazard literature in multiple disciplines that represent subcomponents of community resilience (social, economic, institutional, infrastructure and environment systems). This review enabled us to characterise in more detail the nature of the temperature hazard, the functionality characteristics of a resilient cooling system, and key elements of the four subsystems: people, buildings, cooling technologies and energy infrastructure. Six key messages can be surmised from this review, providing a guide for future work in policy and practice.

Keywords: antecedent conditions, Built Back Better, disaster risk management, temperature hazard, resilience capacity, resilience dividend

Key Concepts

Antecedent conditions	The social, economic, infrastructural, institutional, community and environmental components that determine how a community can cope with, and recover from, hazards and the risks posed by hazards. These components, collectively and individually, are not in an equilibrium state.
Build Back Better	Reconstruction and recovery practices that focus on implementing positive social change and improving community resilience capacity
Cost-benefit analysis	A traditional cost-benefit analysis, applied to disaster risk management, compares the costs of an action against the benefits of avoided losses from that action. It relies, for example, on probabilistic estimation of risk and losses, and the application of a monetised value on benefits attributed to the actions.
Post-recovery activities	Actions imposed after a crisis that enhance community preparedness and reduce exposure to the hazard or the severity of impact of the hazard. Cost-benefit analysis is often used as the decision process for determining investment decisions in mitigation and recovery actions.
Resilience capacity	The continuing function of a system within the context of change and instability (a non-equilibrium state).
Resilience dividend	An investment, planning and practice strategy that is an alternative to (or an expansion and extension of) the more familiar cost-benefit analysis. It specifically targets risk management investment actions that provide tangible and intangible co-benefits in times of crisis and non-crisis. It is not restricted by either the probability of future risks, or the monetised value of benefits.
NOTE: The terms reliability, resilience, robustness and redundancy are deliberately not defined in this table. The paper describes how different disciplines utilise these words within the context of the system being studied in this paper. The purpose of this paper is not to arrive at an agreed definition of these terms or to argue that there is a need for agreement on terminology: the focus of the paper is on providing a framework to describe the purpose and function of a resilient cooling system.	

1. Introduction

1.1 The context

The weather event in Texas, USA in February 2021 provides a good example of how buildings, space heating equipment, and the energy network failed to protect people from the extreme cold temperatures (https://www.theguardian.com/us-news/2021/feb/20/texas-power-grid-explainer-winter-weather). People, buildings, cooling equipment, and energy systems are also vulnerable to heatwaves and extended periods of hot weather. Some of the risks associated with these temperature hazards include the possibility of overheating of buildings and technology; equipment failure or reduced ability to provide cooling services; insufficient electricity generation to meet demand; and enforced power outages to protect transmission networks or reduce secondary risks of bushfires.

Risks to humans include heat stress and high rates of morbidity and mortality. For example, there were an estimated 1200 heatwave related deaths in the USA for the period 2004-2013 [1]; heatwaves have accounted for more deaths in Australia than all other natural hazards, and modelling suggests significantly increased rates of morbidity and mortality, and associated public health implications, by the middle of this century [2-4]; and Hajat et al. [5] predict that heat-related deaths due to climate change in the UK are expected to rise by about 257% by the 2050s. This has led to the development of national and regional heatwave plans and strategies in attempts to prepare populations to anticipate and respond to the hazard and hence reduce the associated risks posed by the hazard [6-9]. These responses have typically included protective measures (e.g., warning systems and advisory information) and adaptation strategies, but the efficacy of such strategies is difficult to accurately evaluate due to the differences in hazard intensity, duration, and population exposure [10].

The efficacy of building regulations and product standards to protect building occupants is also under question, as the tools to evaluate the effectiveness of these measures typically utilise historic climate data and design parameters based on probability of exceedance of pre-determined temperature conditions (e.g., reliability or availability figures) [11] and averages of occupant satisfaction (e.g., percentage of persons dissatisfied) [12]. However, changes in mean temperature and temperature distribution are resulting in more frequent hot weather and record hot weather (Figure 1), higher humidity, and worsening ozone levels and air quality [13] and associated impacts on human and ecosystem health [14-16] .

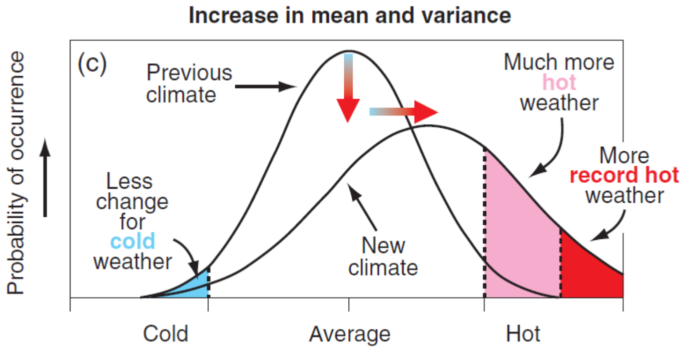

Figure 1 Impact of changes to temperature mean and variance (Source: Ref. [17], page 155)

1.2 The approach of this paper

Against this background, what is “resilient cooling”, the term used by the International Energy Agency Annex 80: Resilient Cooling of Buildings [18]? Resilience of what? For whom? Against what?

In this paper we present a conceptual model of a resilient cooling system and conduct an integrative literature review to characterise the hazard and risks; understand the desired functional state of the system as a whole; and analyse key factors and indicators that apply to different sub-systems or components within the system. Our approach is consistent with the view that resilience is a property of functions and systems [19] and that there is a need to define the elements of impacted physical and social systems [20]. Our approach is also novel in that it extends previous discipline-restricted system boundaries and combines disparate views of core aspects and elements of system functionality. Our approach uses the lenses of Disaster Risk Management (DRM) (understanding and managing risks) and Natural Hazards (NH) (vulnerability and resilience to risks posed by the hazard), thereby incorporating both engineering and social science perspectives into a framework to describe the purpose and function of a resilient cooling system. It is not restricted by a perceived need to have consensus of concept definitions [21], but rather embraces multiple definitions of system performance concepts.

2. Methodology

2.1 Development of the model

Our proposed model for conceptualising the resilient cooling system was developed through Annex 80 expert discussions and examination of existing disaster resilience frameworks. Our model, shown in Figure 2, is an extension of the Disaster Resilience of Place (DROP) model [22] that provides a foundation for representing the relationship between vulnerability and resilience; highlights the antecedent (pre-existing) conditions within communities that serve as a baseline set of circumstances against which improvements in resilience can be measured; and presents resilience as a process. The antecedent conditions are determined by social, economic, infrastructural, institutional, community and environmental components, and play a role in how a community can cope with, and recover from, a hazard and the risks posed by a hazard [23] . Post-recovery activities lead to a 'new' state, through actions that enhance preparedness for future events (thereby reducing negative impact), or through actions that mitigate the hazard or risks (such as reducing likelihood or severity). Post-recovery actions may include both preparedness and mitigation.

To this model we have explicitly incorporated the properties of socio-economic and engineered systems as contributors to a community's coping responses, and the complementary Sendai Framework for Disaster Risk Reduction [24]. This United Nations framework, endorsed by the UN General Assembly in 2015, views resilience as both an outcome (the ability to cope with or bounce back from a hazard) and a process (that is, continual learning and taking responsibility for making better decisions to improve the capacity to handle hazards). Importantly it includes the concepts of social learning and "Build Back Better" (reconstruction and recovery practices that focus on implementing positive social change and improving community resilience) [25], a similar concept to the *resilience dividend (*the term used to describe the net benefit or cost of an investment in resilience, in the absence of a disruptive event). It is an alternative approach to the traditional return-on-investment mindset and assumption that there will always be a financial trade-off between adequate preparedness and potential future disaster response and recovery costs [26, 27].

The other very important addition to the DROP model is the concept that our social, natural, and built environment systems are not an equilibrium state, but in a state of constant change [28, 29]. This means that there is a need to highlight adaptive capacity and resilience capacity, focusing on the continuing function of the system within the context of change and instability, rather than a return to a pre-existing equilibrium state or to a new equilibrium state [1, 30-33]. This resilient cooling system concept is then bounded by the United Nations' Sustainable Development Goals (SDGs) presenting a view that it is the universal right of all people to be protected from, and enabled to protect themselves from, the risks posed by the temperature hazard, and that any strategies adopted to mitigate or adapt to the hazard support rather than undermine the SDGs. Goal 7 – affordable and clean energy – is particularly important in the context of a resilient cooling system.

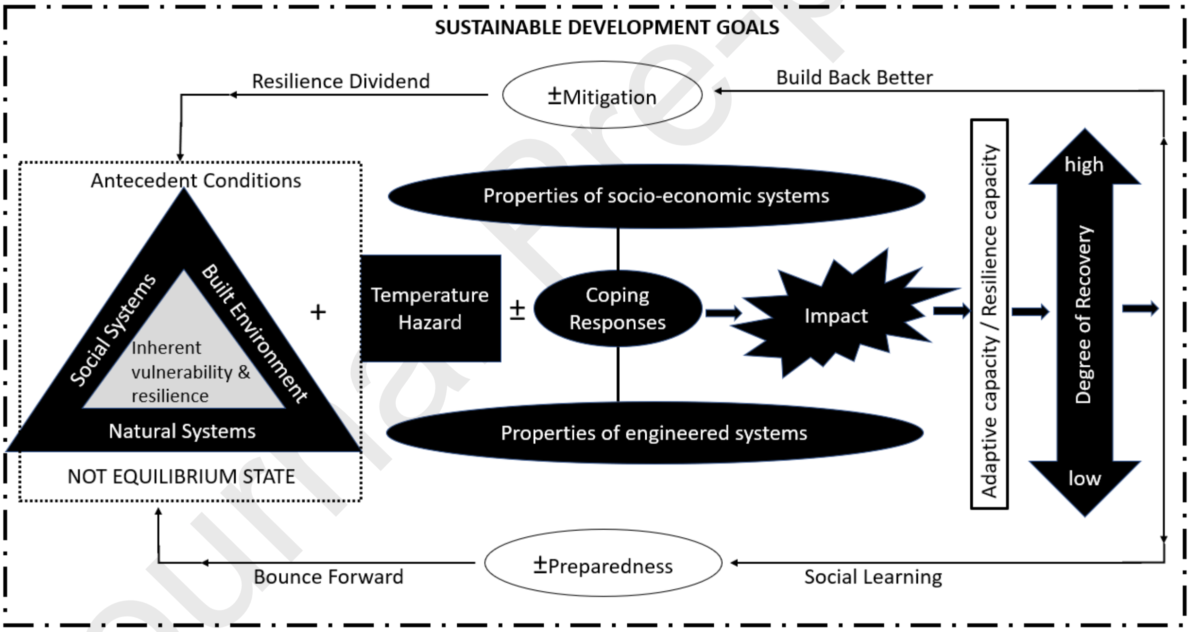

Figure 2: Conceptual model of the resilient cooling system

2.2 Integrative literature review

A critical and comprehensive evaluation of published research and practice was undertaken with the objectives of (a) adding clarity and detail to various components of this resilient cooling system; (b) highlighting the commonalities and differences in the terms used by different disciplines to indicate resilience; and (c) inferring the implication of our model for practice and policy. An integrative literature review process was used as it allows for the inclusion of theoretical and empirical research and perspectives from diverse sources to more fully understand complex phenomena [34]. A two-stage search approach was conducted using two databases (Science Direct and Scopus) for 1990 – 2019. In the first stage, key search terms (disaster, exposure, hazard, resilience, risk, and vulnerability) were applied to titles and abstracts to find literature relating to the subcomponents of community resilience (social, economic, institutional, infrastructure and environment) inferred in the DROP model [15] and other community resilience frameworks, such as Ref. [35] . Inclusion criteria included review papers and original research papers relating to human preparedness for, and responses to, hazards. Papers in languages other than English were excluded, unless the co-authors were fluent in the published language. The second stage extended the search criteria by adding additional functionality key words (such as criteria, definition, evaluation, framework, index, indicators, and metrics) and extending the inclusion criteria to incorporate credible grey literature (such as disaster and hazard related reports by international organisations and national governments) that might provide operational views and practices. The identified literature was then read in full and screened for relevance to the scope of this paper (temperature hazards, the need for cooling, and the systems on which cooling relies). Data from the resultant literature were then extracted and coded under three categories: (i) hazards and risk management; (ii) system functionality; and (iii) key factors and indicators relevant to the system or subsections of the system.

3. Characterising the hazard, risks and consequences

For the purposes of this paper, the term “temperature hazard” is used to denote increases in high temperature frequency, duration and magnitude that present a risk of overheating in buildings, threatening human health, activities, and productivity.

3.1 Temperature hazard criteria

The temperature hazard encompasses the concepts of sudden perturbations (shocks to the system beyond normal variability, such as heatwaves or sudden spikes in electricity demand) and slow or continuous stressors to the system (for example, gradual changes in temperature distribution and mean minimum and maximum internal or external temperature) [36]. Literature reveals seven key criteria that can be used to further characterise temperature hazards (Table 1), and each of these have implications for coping, adaptation and risk management strategies.

Table 1 Characterisation of the nature of the threat

Criteria	**Sub-criteria**	**Reference(s)**
Predictability	Regular; Irregular; Outside of collective experience	[37, 38]
Origin of the threat	Internal; External	[37]
Spatial distribution	Household, community, city, region, nation	[39, 40]
Temporal distribution	Timing of the hazard (e.g., early summer, during holidays, at night) and duration	[40]
Speed of onset	Slow; Rapid; Prolonged	[39]
Scope and magnitude of impact	Scale of population impacted or displaced Emergency, crisis, disaster, catastrophe	[40-42]
Number of threats	Single or multiple stressors	[22, 32, 43, 44]

Some metrics that are used to characterise one aspect of the temperature hazard - heatwaves - include Excess Heat Factor (EHF) (enabling localised comparison of heatwave intensity) [45], heatwave duration (HWD), heatwave magnitude (HWMt) and heatwave amplitude (HWAt) [46] . These are not resilience indicators, but metrics that characterise the hazard, in order to evaluate exposure and vulnerability. Electricity-related threats related to temperature are discussed later in this paper.

3.2 Vulnerability to temperature hazards

A NH approach, such as used in the social sciences, focuses not on the hazards or risks, but on community vulnerability and resilience to the risks posed by the hazard [47, 48]. The resilience of a community is influenced by policies and actions to manage the risks, as well as on the communities' wider context, changes, and disturbances [49]. Individual and societal risk preparedness and risk management actions can also be influenced by personal, cultural, social and religious beliefs, such as fatalism, determinism, dependency, hopelessness, nationalism, collectivism and empowerment [50-53], and by the language used to convey risk. In 2004 the World Health Organisation (WHO) defined "natural disaster" as "a serious disruption triggered by a natural hazard causing human, material, economic or environmental losses, which exceed the ability of those affected to cope" [54]. Note that the hazard is natural, but the disaster is a consequence of the level of exposure and vulnerability of people, their structures, and their activities to natural hazards, and their capacity to cope with natural hazards. Some governments present a view that a natural hazard becomes a disaster when it impacts on what we value [55], and therefore use the term “natural disaster” when there is significant loss of life or property. In contrast, some academics argue that linking the terms “natural” (inferring outside of human control) and “disaster” (inferring impact on human life and property) can promote fatalism and helplessness, be an excuse for inaction, and limit risk mitigation actions such as better planning of human infrastructure and activities [56]. The importance of risk mitigation has been highlighted in long-term insurance industry data that showed that increasing insurance losses were predominantly driven by higher exposed values (i.e., human property and human life exposed to higher risk from natural events), rather than increasing hazards [41]. That report argued that investments in loss prevention (risk mitigation) were cost effective because they decrease losses (direct economic and human life costs). The financial and social benefits of investing in long-term resilience building (reducing exposure and vulnerability) were also reported by Cutter [57].

3.3 Managing temperature hazard risk

A DRM approach focuses on understanding and managing risk. The significance of the consequence of a disruptive event (a multiplication of likelihood and severity) considers the spatial scale and magnitude of *impact* as a continuum (Figure 3), with each scale having a different range of effects and being managed with different resources from local, regional, national, or international authorities. This manner of communicating the scale of the impact is used, for example, in health-, energy-, and weather-related events [41, 58]. It was recently evidenced in the U.S.A. government’s Disaster Declaration [59] in response to the February 2021 cold-weather event in Texas that resulted in the failure of homes, heating appliances, and electricity generation and distribution systems to provide heating services to residents.

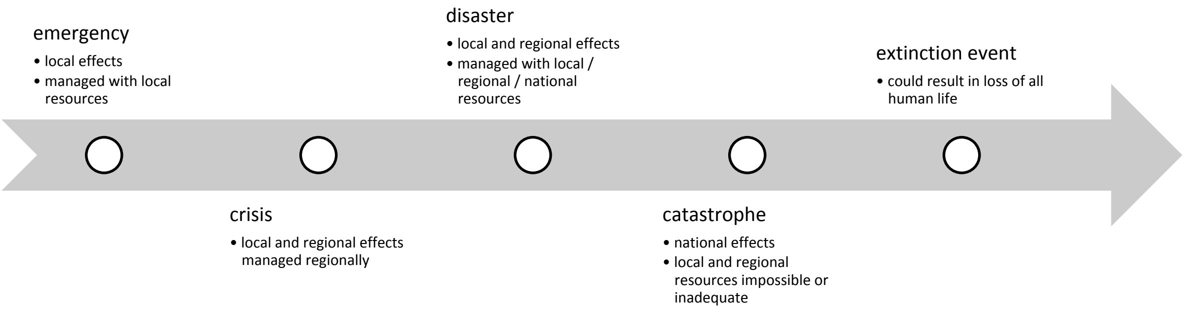

Figure 3 The DRM continuum of the impact scale of consequences of hazards and risks

Some aspects of DRM are already embedded into our built environment, such as building codes, standards, codes of practice, and product declarations. In addition to general performance criteria such as functionality, robustness, and service life, DRM-driven criteria are typically added retrospectively in response to an undesirable impact of a hazard [11, 60]. For example, local building regulations may change as a result of property damage or loss of life due to earthquakes, storms, floods, and hurricanes. Similarly, equipment may have risk mitigation requirements addressing electrical safety, fire safety, or indoor environmental quality. Technical equipment and infrastructure may have requirements to shut down in certain circumstances when safe operating conditions are close to being breached—for example, when overheating is imminent. These are all examples of strategies undertaken by societies to minimise future loss from these hazards.

This DRM approach, as applied to our built environment, has some limitations. The temperature hazard presents a significant risk to humans and the buildings, technologies, and infrastructure on which they currently rely to provide cooling, and it is widely accepted that the implications of climate change will need to be reflected in future building forms, materials, and services [61]. Despite this, the continuing utilisation of historical weather files to determine cooling loads and thermal comfort goals are arguably inadequate for evaluating the effectiveness of cooling solutions to prevent or reduce exposure of humans to overheating in buildings into the future [62]. This practice does not seem to recognise the dynamic nature of the climate system, and the social and built environment systems within the "resilient cooling system". This may be because design and engineering approaches to the built environment can encompass two different views of "resilience", both with limitations: a *redundancy* approach that accounts for some future uncertainty (e.g., oversizing components and spaces) but has no real adaptation to changing conditions; and a *robustness* approach that optimises safety, resource consumption and functionality to a specific brief and set of functions (i.e., a fail-safe system within a defined range of uncertainty) [62-65].

The adequacy of the engineering redundancy and robustness approaches to our built environment and risk management is being questioned, driven by (a) more frequent and intense natural hazards, new hazards, and growing potential for cumulative or concurrent large-scale natural hazards; (b) the interconnectedness, interdependencies, and complex interactions between infrastructure (e.g., essential services), people, environment, economy and technology and the reliance of our societies on these connections; (c) increased exposure and vulnerability of people and assets to natural hazards; and (d) the intangible, indirect, flow-on and cumulative effects of impacts that can trigger long-term challenges [55]. The following section presents characteristics of a functioning resilient cooling system, and subsystem characteristics and indicators.

4. System functionality and subsystem indicators

This section identifies key characteristics that conceivably relate to the functioning of the proposed model of the resilient cooling system, and components and indicators relevant to the different subsectors of the system.

4.1 Characteristics of socio-technical system functionality

One view of system resilience is from the perspective of exposure, dependent on the characteristics of both the hazard and the system [66]. It would seem obvious that the core function of a resilient cooling system is to provide cooling at different scales (individual, household, community, region) [67, 68] in such a way that these stakeholders can "plan and prepare for, absorb, recover from, and more successfully adapt to" [69] the temperature hazard. A more nuanced understanding of system functionality (and hence exposure) can be gained from understanding community disaster resilience from different domains [70]. Table 2 proposes desirable system functionality characteristics, extracted from domains such as population and community resilience; humanitarian aid and community development; and health, financial, food and engineering systems.

Table 2 Characteristics of a resilient cooling system functionality

Proposed desirable characteristics of a resilient cooling system	**Reference(s)**
Identifies and maps risk, exposure and vulnerability (to temperature hazards) at different scales	[71, 72]
Anticipates (temperature hazards and associated risks and impacts) and builds a culture of safety and adaptation through knowledge, innovation and education	[6, 8, 10, 23]
Withstands, copes with, absorbs impacts of, and recovers from (temperature hazards and associated risks and impacts)	[22, 73]
Embraces change and uncertainty (i.e., a continual state of change, as opposed to a state of equilibrium or "norma")	[28, 74]
Learns from shocks (by enhancing protective factors; reorganising; implementing diversity of strategies; increasing the buffer to reduce risk of failure and impact of failure; creating alternative paths in case of failure; using flexible decision making; and tracking the transformation process and outcomes)	[23, 35, 72, 74-76]
Works collaboratively across all sectors (community, government, institutions) to implement transformational change	[71, 73]
Retains control over the structure and functioning of the system, including planning for "orderly failure" to retain the system's main function (i.e., cooling for people)	[64, 77]
Protects human life and health outcomes in daily function as well as during a temperature hazard and its aftermath (i.e., resilience dividend)	[78]
Recognises the global nature of the temperature hazard, and the roles and responsibilities of all stakeholders	[79]
Implements legal and policy frameworks to guide responses and establish accountability	[79]
Accounts for household learning and coping mechanisms; and decision-making agency and power	[30]

An Intergovernmental Panel on Climate Change (IPCC) report [8] stresses the importance of understanding the difference between "coping" and "adapting", words that are frequently used in resilience definitions and frameworks. This review indicates that these words elicit different strategies based on different perceptions of the nature of the hazard and elicit different response timeframes and strategies (Table 3). This is evidenced, for example, in multiple existing community heatwave response mechanisms that appear to be based on perceptions that heatwaves are "events" that are infrequent and of short duration; hence, communities are advised to "cope" with the hazard by reducing their exposure (e.g., retreat to a local swimming pool or shopping centre) or reduce their vulnerability (e.g., drink more water, cease strenuous activities, and look out for neighbours). While these responses to immediate threats are important, one could argue that the increasing intensity, duration, and magnitude of both heatwaves and extended periods of hot weather presents our communities with challenges beyond their ability to withstand and cope.

Table 3: Differentiating coping and adapting (derived from [8])

	Coping	***Adapting***
Hazard / Stress	Imminent	Future
Response timeframe	Quick response, short timeframe	Continual, long term
Constraints	Knowledge of previous experiences	Assumptions about the future
Strategies	Previously successful tactics	Anticipating change
Goal	Protecting the individual	Protecting the system

As indicated by our resilient cooling model, system functionality is inherently dependent on the antecedent conditions and changes to these conditions over time. Table 4 shows examples of indicators that could be used to quantify some of these antecedent conditions at different scales, depending on data availability.

Table 4 Quantitative indicators for antecedent conditions (derived from Refs. [23, 30, 72, 80, 81])

Component	**Indicators of resilience assessment (antecedent conditions)**
Social	% of population that is elderly, infirm, or very young (under 5 years of age) % of population living in dense urban environment % of population that is a minority or does not speak the predominant language
Economic	Per-capita income % of homeownership Household income, savings, and assets
Institutional	Presence of a temperature-hazard mitigation plan (offers a vision for the future) Presence of an insurance program (a means to reduce loss and promote recovery)
Infrastructure	Housing typology and density Emergency services and temporary shelters per 1,000 population
Community health and well-being	Social assistance programs per 1,000 population Health services per 1,000 population Communication services per 1,000 population Environmental Public Health Indicators (EPHIs)
Environment	Frequency of loss-causing weather events % of green space / tree cover / land available for temperature hazard mitigation (to address the urban heat island effect)

4.2 Key characteristics and indicators of subcomponent functionality

4.2.1 People

In the medical profession, stress resistance (of humans) incorporates the concepts of robustness and resilience, where “robustness” is defined as the ability to resist deviation from the original state, and “resilience” as the ability to recover after such deviation [82]. The human stress response is two-staged, involving first deviation, then recovery. Measures of robustness (deviation) include the magnitude of deviation and the time taken to reach the peak deviation. Measures of resilience include the time to recover and the completeness of the recovery. While both robustness and resilience can decline with age, these authors consider that resilience decline is universal, but robustness decline is not. They suggest that there are differences between robustness and resilience between men and women (better health but worse survival in men compared with women) and that robustness and resilience have different effects on all-cause mortality. Some components of physiological aging (e.g., the slowdown) may universally contribute to the decline in resilience, but not necessarily in robustness. Blood pressure, for example, may deviate as a result of heat stress, and elderly individuals will likely recover (return to their usual blood pressure) less quickly and completely than younger individuals.

The indoor environment quality of our buildings often uses a “thermal comfort” criterion – an attempt to determine occupant satisfaction with the building’s indoor thermal conditions. Physiological, psychological, and environmental factors influence occupants’ thermal comfort over the course of a day and over time [83], but the temperature hazard requires consideration of more than thermal comfort. In the context of heat, an individual’s protective factor can be interpreted as the capacity of the body to respond to heat. Acclimatisation and thermoregulation determine human heat tolerance and vulnerability to heat stress [10], requiring consideration of a range of factors and conditions, as summarised in Table 5.

Table 5 Factors and conditions affecting individual responses to temperature hazards (derived from Refs. [10, 84-97])

Factors	**Key conditions**
Thermoregulation - physiological	Range is very narrow (core body temperature 36.8 °C +/- 0.5; heat stroke occurs at 40 °C) and varies between individuals The upper range of heat exposure that humans can tolerate has not been defined, and may not be definable Heat sensitivity is affected by factors such as obesity, age, illness, medication, aerobic fitness, gender, and acclimatisation, with individual influencing factors of sweat capacity, cardio capacity and blood volume
Thermoregulation - behavioural	Relies on individual's perception of body temperature and an individual's ability to modify the environment to reduce body temperature Older people have less ability to perceive temperature Relies on personal actions: adjusting clothing (type and level), reducing activity, moving to a cooler space, hydrating, wetting the skin Relies on actions within buildings: operating windows, shades, or fans to reduce heat or increase air movement to enhance evaporation from skin The evaporative effect can be enhanced or restricted by clothing: not just the insulation level (clo), but also by fabric breathability and garment fit
Acclimatisation	Heat tolerance can be improved due to physiological adaptation to a new climate Sudden or extreme heat events can impact on typically acclimated residents New arrivals to a region can be unacclimated People experiencing predominantly air-conditioned environments can be unacclimated
Vulnerability	Physiological and behavioural factors are closely linked, and the impairment of either of these reduces thermal tolerance and increases sensitivity to heat Older people are particularly vulnerable to heat-related morbidity and mortality Physical and social vulnerability can limit adaptive capacity and increase exposure

In practice, some "temperature threshold limits" are being identified, based on the outdoor temperature at which there is an increase in ambulance callouts, presentations of patients to doctors and emergency departments, and an increase in deaths. These thresholds are very location specific, reflecting population and individual acclimatisation, cultural practices, and urban and housing design. Location specific temperature thresholds reported in literature typically correlate heat-related deaths to outdoor ambient temperatures during heatwave events. Key findings from this literature are that (i) excess mortality is higher in tropical climates than in temperate climates [98, 99]; (ii) mortality curves in hot temperature zones are steeper, with less variation in tolerance, compared with mortality curves in cold temperature zones [10]; (iii) mortality is influenced by high maximum (daytime) and high minimum (night time) temperatures [93, 100]; and (iv) mortality per capita is higher in urban areas [99, 101].

The factors discussed in this section have implications for our buildings.

4.2.2 Buildings

A key purpose of buildings is to shelter occupants from the outside environment, providing safety, health, and amenity. This purpose is reflected in many building codes, but these codes are currently reactive rather than predictive and proactive in response to climate [11, 62]. Existing risk management approaches do not account for system vulnerabilities and interdependencies, nor for different levels of threat probability and severity [27, 102]. It is clear that our built environment is failing in its purpose to shelter occupants from the risks associated with temperature hazards, as evidence links excess heat-related morbidity and mortality to a number of building-related factors (Table 6) and there have been calls for more studies in these areas [95, 103]. Poor thermal performance of buildings has arguably contributed to occupants' behavioural adaptations that have resulted in a rapid rise in the reliance on air-conditioning, changing cultural expectations, and practices regarding thermal comfort [104]. These changes are placing increased strain on electricity infrastructure [105, 106] and undermining carbon reduction strategies [107].

Table 6 Factors impacting buildings' ability to protect occupants from overheating

Building Factors	**Reference(s)**
Housing characteristics (e.g., poor thermal efficiency, construction type)	[107, 108]
Urban heat island effect in urban environments	[102, 105, 107]
Adaptation options available to occupants (e.g., operable windows)	[102, 107]
Internal heat gains	[109]
Occupant vulnerability (e.g., age, mobility, pre-existing health conditions)	[102, 107]
Strain on electricity infrastructure	[110, 111]

Climate change will need to be reflected in future building forms, materials, and services [61]—in particular, by acknowledging that adaptive opportunities for occupants are as important as the building envelope, especially if there is a risk of power failure [112]. Electricity network reliability and capacity are also important considerations in overheating risk, with suggestions that buildings could provide “cool retreat” spaces that can be efficiently air-conditioned during temperature hazard events, as opposed to attempting to cool whole buildings [113]. This solution may be limited to climates with infrequent and short duration heatwave events, as its effectiveness as a long-term strategy in climates with prolonged and frequent temperature hazards has not yet been evaluated.

Very few studies directly correlated the number of deaths during temperature-hazard events to temperatures inside buildings. However, there is a significant body of work that considers the role the building envelope plays in protecting people from high outdoor temperatures. Research has attempted, for example, to quantify overheating risk to human life [99, 110]; to quantify the reduction of impact of overheating (e.g., lives saved) due to energy efficiency upgrades to buildings [111]; and to quantify the probability of overheating, based on the building stock [109]. A fairly comprehensive, if somewhat UK focused, review of research lessons relating to overheating in buildings can be found in [114]. A variety of approaches have been used by researchers, such as modelling [108, 112, 113], use of future weather files [115, 116], scenario analysis [117], regulation analysis [118], adaptation [119], advanced technologies [120], occupant education [121], and post-occupancy evaluation and measurement [122].

Building metrics that could be adapted to quantify some aspect of “resilient cooling” in buildings are presented in Table 7. These metrics fall into two broad categories: those that focus on occupant thermal comfort, and those that focus on protection of occupant health (reducing the risk of heat stress). The thresholds set by these indicators can vary depending on the underlying comfort model (steady-state or adaptive comfort), the local climatic conditions, and the part of the building the metric applies to (e.g., bedroom or living room of a home). Some metrics, such as “hours of safety”, attempt to embrace both thermal comfort and safety, while others incorporate consideration of one or more of the characteristics of the hazard, such as magnitude, duration, timing, and speed of onset. In a simplistic manner the thermal resilience of the building could be assessed, for example, in terms of the number of hours the indoor temperature is above a particular threshold. This is sometimes expressed as “exceedance hours”, but that metric does not account for the temporal response of a building to an extreme heat event, the cumulative effect of the duration of a moderate heat event, or changes to occupant vulnerability. Even if some indicators include some cumulative effect, they do not include the risk to occupants due to successive exposure to indoor overheating. Successive exposure is more complex to define, as the thresholds themselves would need to adapt to the duration of the event and the evolution of the occupant’s vulnerability. For example, consecutive warm nights can decrease the sleep capacity of individuals, which increases their fatigue and therefore their vulnerability. The issue of multiple hazards is also poorly addressed. A study by Mavrogianni et al [123] seems to indicate that (i) existing overheating assessment criteria do not take into account the synergistic effects between summertime ventilation behaviour, indoor overheating, and air pollutant concentration, especially in social housing and free-running buildings; (ii) a static single temperature exceedance criteria [124] is simple to use but does not incorporate acclimatisation and adaptive capacity of occupants; and (iii) the adaptive external climate dependent criteria (CIBSE TM52 [125], BS EN 15251 [126]) was considered preferable for free-running buildings where occupants have higher adaptive capacity. The applicability of this criteria in buildings occupied by vulnerable individuals, or buildings in hotter climate zones, requires further investigation, as the standard is based on a running-mean outdoor temperature of up to 30 °C. More research is needed to determine the limits of adaptive comfort and circumstances under which hybrid cooling approaches may be needed. There is also a need to determine how to clearly communicate the limits of a building to protect occupants from the risk of overheating and the circumstances under which it is assumed occupants will need to rely on (and pay for) mechanical cooling technologies and services.

Table 7 Building resilience indicators relating to temperature

Term or Metric	**Reference**
Building Heat Performance Index (BHPI)	[95]
Building Resilience (during power outage)	[127]
Comfort model (static) - Predicted Percentage Dissatisfied (PDD), Predicted Mean Vote (PMV)	[12]
Comfort model (adaptive) – relative to external mean monthly temperature or indoor mean ambient temperature	[12, 128]
Constants of Proportionality - incorporates seasonal changes	[128]
Gain Utilisation Factor (GUF) –annual cooling energy needs	[129]
Hours of Safety (free running mode)	[130]
Indoor Heat Stress	[131]
Occupied Thermal Comfort Percent (occTCP)	[132]
Overheating Criterion	[124]
Overheating Escalation Factor	[117]
Passive Habitability	[132]
Passive-Survivability-Winter (PSW) and Summer (PSS)	[102]
Thermal Autonomy (TA) – with passive means only	[132]
Ventilation Autonomy (VA) – with passive means only	[133]

4.2.3 Cooling technologies

Passive, active and hybrid cooling systems in buildings are engineered systems. The resilience of engineered systems is often articulated using four properties: robustness, rapidity, redundancy, and resourcefulness [23, 35]. *Resilience engineering* focuses on the safety and efficiency of system functionality, and the system's ability to respond, monitor, learn and anticipate [134]. Resilient active cooling systems within buildings, by inference, should exhibit the following operational behaviours:

- Response to regular or irregular disruptions or disturbances
- Monitoring of potential threats and the impact they can have on the system
- Ability to learn from experience (successes and failures)
- Anticipation of developments, threats, and opportunities into the future

Reliability engineering is another aspect of systems engineering, focusing on the aspects of dependability and availability. Cai et al. [135] espouse that availability comprises of a stable state of functionality, the time taken to recover from an event, and the number of events. This view takes account of one of the characteristics of the threat (number of events) as mentioned in Table 1, but assumes a stable state and a return to that state after an event. A different approach by Mahmoud et al [40] incorporates temporal and spatial threat characteristics to evaluate cumulative disruption and recovery while also acknowledging the reliance on infrastructure, such as housing and power.

While active cooling appliances are typically supplied with performance and reliability data, to the authors' knowledge, they do not include consideration of all of the characteristics of the temperature hazard, the cumulative effect of multiple hazards, characteristics of the people for whom cooling is provided, or the reliance on infrastructure to continue functionality. This latter point is particularly important for engineered systems that rely on electricity for operation.

4.2.4 Electricity infrastructure

Electricity infrastructure (generators, transmission, and distribution networks, and distributed energy resources) is particularly important in the context of the temperature hazard because much of society is reliant on electrically driven cooling devices, and the electricity system itself is affected by temperature hazards. Similar to buildings and mechanical cooling devices, electricity systems are designed and rated to function within defined temperature limits [136]. When those limits are reached, the assets need to be de-rated for self-protection. High and extreme temperature events are challenging for power grids because (a) the ambient thermal conditions are more severe; (b) power demand often increases with the increase in ambient temperatures; and (c) more Ohmic heat is generated and accumulated in the power grid due to both higher electricity flows and temperature-induced increases in wire resistance. This means that the actual loading of electrical assets increases unless there are other control mechanisms, resources, pathways of energy supply, or load shedding. Increased loading puts electrical equipment under stress and accelerates aging, both contributing to the possibility of outages during extreme temperature events.

Within electric power engineering, resilience is often used interchangeably with, or seen to be equivalent to, reliability and robustness [137-140], but the links between these terms depends on the context and application. Traditionally, reliability in the power system includes two aspects: adequacy and security [141]. This results in power system design and operation for "normal conditions” and for abnormal but foreseen contingencies (low-impact high-probability events) [142]. In practice, the security component of the power system is often dealt with separately —for example, in terms of economic stability in energy systems [143]. Reliability is used to refer to the probability of no disconnection or load shedding [144].

One group of power grid resilience definitions considers reliability as complementary to resilience, rather than a component of resilience. For example, the U.S. National Infrastructure Advisory Council (NIAC) includes robustness, resourcefulness, rapid recovery and adaptability in its infrastructure resilience model [145], while the Pacific Northwest National Laboratory (PNNL) focuses on stress resistance and strain compensation [146]. A dominant reason for excluding reliability from resilience is the perception that a resilient grid would not experience outages, and reliability is the probability term for outage [139]. The differences between reliability and resilience in power engineering are summarised in Table 8.

Table 8 Distinguishing between reliability and resilience in power engineering studies (derived from [137, 138, 147-149])

Criteria	Reliability	Resilience
Probability of events	High probability	Low probability
Impact	Low impact	High impact
System states	Evaluates power system states	Evaluates power system states and transition between states
Temporal features	Static, retrospective	Adaptive, ongoing (short and long term)
Areas of concern	Concerned with customers’ interruption time or frequency of interruption	Concerned with prevention, customers’ interruption and recovery

In contrast, other infrastructure resilience models include reliability, allowing for the possibility of power system failure [150] and hence electricity utility management practices to include reliability considerations in multiple aspects of the power system (including stakeholder engagement, communication, supply chain investment, and services) [151], and strategies to deal with reaction to disturbance [152].

Resilience and robustness, often used interchangeably in other disciplines, have different meanings or impacts in electric power system studies, as summarised in Table 9. One of the key differences is that robustness often refers to targeted improvement of one defined class of failures. Such targeted actions, however, may result in increasing the vulnerability of another part of the electricity system. For example, a database topological error caused the 2003 US-Canada Northeast blackout [139]. The database was implemented to improve visibility of network, but this robustness improvement in the network caused a large-scale system failure resulting in billions of dollars in losses. Therefore, a resilient power system may need to be robust in quite a few areas and be flexible, agile, and adaptable at the same time. The focus of power system resilience frameworks such as those found in Refs. [138, 151, 153-155] appears to remain on risk-assessment for high-impact low-probability events, with no indication of how power system design and operation is responding to natural hazards that may be high-impact and high-probability (i.e., increased frequency extreme heatwaves).

Table 9 Distinguishing between robustness and resilience in energy systems (derived from Refs. [137, 139, 148, 155, 156])

Criteria	**Robustness**	**Resilience**
Target areas	Robust to a specific class of failures	System wide resilience, multifaceted
Event types	Predictable	High impact rare
Features	Stiff (may be brittle and fragile in some other ways)	Flexible, agile, adaptable, self-healing
Application	Network hardening	Network flexibility
Enterprise focus	Assets	Services
Security approach	Passive	Active
Value proposition	Design	Operation
Key function	Resistance to change in predictable events	Flexibility and survivability in unexpected extreme events

The most used power system indicators relate to reliability [142, 149, 154, 157], with a few less-used indicators encompassing sustainability [139, 149], security [156], financial impact [149], or redundancy [158]. One resilience indicator combines three capability criteria (absorptive, restorative, and recovery capabilities) in an attempt to take into account interdependencies [159], while another seeks to quantify the relationship between the number of customers affected by a disruption and the time to restoration [160]. A contrasting perspective to these engineering and network perspectives of resilience in energy systems proposes four sustainability-related dimensions: availability, accessibility, affordability and acceptability [161], displaying a stronger socio-economic approach. It has also been highlighted by Molyneaux et al [142] that there is a need for more research in the energy sector regarding the characterisation of different hazards; the estimation and criticality ranking of each component in the system; the development of more accurate fragility curves; better modelling of the complex process of restoration; and assessment of interdependencies with other key sectors.

As the climate changes, energy use and peak power demand are increasing. It may not be sensible to rely on the power grid alone to provide cooling; a broader systems-approach encompassing power systems, buildings and building equipment is required [162]. Methods of improving resilience within the power system include utilising and sharing renewable energy [163], leveraging distributed energy resources [164], incorporating energy storage, and developing active distribution networks [165]. The diffusion of rooftop solar equipment in Japan [166] is one example of the role that renewable energy can play in Building Back Better (a concept incorporated into our model of a resilient cooling system). The "bouncing forward" concept of our model is encapsulated in a recent definition of resilience with regard to modern energy policy: "the adaptive capacity of improving performance, as a result of learning and adaptation, informed by continuous change" [29].

5. Discussion and Further Work

This integrative review has shown that while each sector is in general agreement of resilience as a system outcome and process, the system boundaries, and the words used to describe functioning of that system, are quite varied. The need to fully understand the nature of the hazard, to protect people from the temperature hazard, and to appreciate the dependency of people on buildings, technology and energy infrastructure to provide this protection, lends support to our proposed model of the resilient cooling system. This conceptual model has served as a useful tool for evaluating the literature to add clarity to the concept. By focusing on the characteristics of the hazard and the system and subsystem functionality, we have demonstrated that it is not necessary to agree on exact definitions of terms used by different disciplines. The literature highlights that NH and DRM approaches provide concepts that enable the integration of both engineering and non-engineering perspectives. This integration into a conceptual model will help enhance the resilience of individuals, communities, buildings and engineered systems to temperature hazards. Six key messages from this review could be summarised as follows.

1. Resilient cooling strategies, first and foremost, do not start with buildings and engineered cooling systems, but must start with individuals, households, and communities as active agents in managing their own exposure and vulnerability, and in the selection and development of indicators that enable them to track progress towards resilience. This goes hand in hand with building design, engineered systems, regulations, and policies that need to collectively enhance adaptive capacity, resilience capacity, and the resilience dividend.
2. The natural, social, and built environment conditions in which people live are in a state of constant change, not a state of equilibrium. System resilience encompasses embracing change, adaptive capacity and flexibility, with an eye on implementing strategies that can benefit society in all situations (present and future), not just in times of disaster.
3. Resilience needs to be considered at different time and spatial scales.
4. The characteristics of the threat, the functioning of the system, and the vulnerabilities of system components need to be clearly understood and communicated to all stakeholders.
5. The performance boundaries of each of the components of the system also need to be clearly understood and communicated, and the system devised in such a way that different components can “fail safely” without compromising the ability of the system to provide

cooling. This means that there is a high dependence on the role of buildings – without engineered systems – to provide a level of safety and protection to occupants.

6. Cooling strategies to enhance resilience should satisfy sustainability, energy efficiency, affordability, and greenhouse gas reduction goals, as well as provide a resilience dividend.

Our examination of socio-technical multidisciplinary resilience perspectives clearly demonstrates that some useful indicators already exist, within parts of the system, but that a single performance indicator cannot adequately quantify “resilient cooling”. The complexity of resilience, and of our built environment, means that several indicators will be required. These indicators need to both quantify and communicate the nature of the threat and the nature (and limitations) of the cooling strategies. Further work is required to develop indicator sets relating to heat events, socio-cultural systems, buildings and their cooling systems, and energy networks. Evaluation of these candidate indicators will identify combinations of indicators that can be used for technical purposes such as benchmarking and measuring progress [23, 167], as well as social purposes such as informing decision making and improving stakeholder participation [168]. These combinations of indicators could then be used to evaluate specific cooling technologies via building simulation and via case study reports.

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