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ABSTRACT

The global effects of climate change will increase the frequency and intensity of extreme events such as heatwaves and power outages, which have consequences for buildings and their cooling systems. Buildings and their cooling systems should be designed and operated to be resilient under such events to protect occupants from potentially dangerous indoor thermal conditions.

This study performed a critical review on the state-of-the-art of cooling strategies, with special attention to their performance under heatwaves and power outages. We proposed a definition of resilient cooling and described four criteria for resilience—absorptive capacity, adaptive capacity, restorative capacity, and recovery speed —and used them to qualitatively evaluate the resilience of each strategy.

The literature review and qualitative analyses show that to attain resilient cooling, the four resilience criteria should be considered in the design phase of a building or during the planning of retrofits. The building and relevant cooling system characteristics should be considered simultaneously to withstand extreme events. A combination of strategies with different resilience capacities, such as a passive envelope strategy coupled with a low-energy space-cooling solution, may be needed to obtain resilient cooling. Finally, a further direction for a quantitative assessment approach has been pointed out.

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1. Introduction

Climate change and extreme heat are critical issues faced by all countries. The Intergovernmental Panel on Climate Change (IPCC) defines climate extreme as "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" [1]. The long duration and high intensity heatwaves are becoming a potential natural hazard that presents significant risk and challenge to humans, buildings, and building-related systems. The extremely high temperatures can cause heatstroke, heat exhaustion and other heat-related diseases, which are particularly dangerous for vulnerable populations, such as the elderly or low-income communities [2]. A most well-known hazard was the European heatwave 2003, which resulted in 14,800 excess deaths in France; 74% of these excess deaths occurred indoors [3]. EuroHEAT estimated that the increase in mortality ranges from 7.6% to 33.6% during heatwaves by analyzing the impact of long heatwaves in nine European cities (Athens, Barcelona, Budapest, London, Milan, Munich, Paris, Rome and Valencia) [4].

Resilience is a concept widely applied in disaster risk management. It refers to "*the ability of a system and its components parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions*", as defined by IPCC [5]. Resiliency in the context of the building environment refers to the ability of buildings and their systems to continue functioning as intended in the face of natural hazards imposed by climate change [6]. Buildings shelter humans from the outdoor environment and it is crucial that buildings maintain safe thermal conditions during extreme events, such as heatwaves. Current building and building-related system designs strongly focus on energy efficiency to mitigate climate change through reducing carbon emissions. However, energy efficient strategies (technologies and practices) are not always consistent with strategies that improve resilience to extreme heat; often there is a trade-off between these two objectives [7]. Ren et al. [8] contend that "Excessive striving for energy efficiency" could compromise a building's ability to maintain comfortable thermal conditions during heatwaves, such as higher insulation and airtightness. Another limitation for current building and building system design is the use of typical weather or historical weather files for the calculation of cooling demand and evaluation of the effectiveness of cooling strategies [9,10]. As a consequence, the building and its systems may not be prepared to cope with heatwaves or climate change. This is supported by the findings of several studies [11,12,13], which show that the low-energy cooling strategies that work well today might not remain effective under long-term climate change, or in extreme events such as a heatwave or a power failure.

Like energy efficiency, sustainability and economic affordability, resilience should be considered as an important property of buildings and their systems in the early design phase. Ceré et al. [14] note that resilience is already part of recent architectural and structural building design practices.

The recently formed International Energy Agency (IEA) Energy in Buildings and Communities Programme (EBC) Annex 80 "Resilient Cooling of Buildings" addresses this need by developing, assessing and communicating strategies for resilient cooling and overheating protection against climate change and the consequent hazards or events [15]. Many cooling technologies and solutions

Table 1
Definitions provided in literature for the concepts of resilience.

Ref	Definition	Characteristics	Threats	Scale	Year
[29]	"Building resilience is defined as a building's ability to withstand severe weather and natural disasters along with its ability to recover in a timely and efficient manner if it does incur damages."	Withstand, recover, rapidity	Climate and natural disasters	Building	2013
[26]	"A resilient building is a building that not only is robust but also can fulfill its functional requirements (withstand) during a major disruption. Its performance might even be disrupted but has to recover to an acceptable level in a timely manner in order to avoid disaster impacts."	Withstand, absorb, recover, rapidity	Climate extremes	Building	2019
[24]	"A resilient built environment as one designed, located, built, operated, and maintained in a way that maximizes the ability of built assets, associated support system (physical and institutional) and the people that reside or work within the built asset, to withstand, recover from, and mitigate the impacts of threats."	Withstand, recover, mitigate	Natural hazards (geo-hazards and hydro-meteorological hazards)	Built environment	2008
[14]	"The intrinsic ability of the built environment to react positively before, during and after the presence of the adversely exogenous input (e.g., landslides), i.e., the ability to absorb external disturbances, in order to maintain the system's original states or reach a new set of steady states for serving its normal functionalities."	Vulnerability, adaptive capacity, recoverability	Geo-environmental hazards	Built environment	2017
[21]	"Resilient urban energy system needs to be capable of "planning and preparing for", "absorbing", "recovering from", and "adapting" to any adverse events that may happen in the future. The complex, dynamic, and adaptive systems (e.g. cities) would not necessarily return to an equilibrium state."	Preparation, absorption, recovery, adaptation	Disruptions in energy supply	Urban energy systems	2016
[27]	"Resilience can be understood as the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance)."	Robustness, redundancy, resourcefulness, rapidity	Earthquake	Community (technical, organization, social, economic)	2003
[5]	"The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions."	Anticipate, absorb, accommodate, recover	Climate extremes and disasters	System	2012
[28]	"Resilience is a continuous process starting from a reliable initial condition, followed by a vulnerability-survivability state after a disruptive event and eventually a recoverability phase aimed at achieving a new stable equilibrium condition."	N/A	Flood	Infrastructure system	2012

are available both in the market and are under development. Previous studies have systematically compared various active and passive cooling strategies in terms of energy performance [16,17,18], thermal comfort and air quality [19], capital expenditure [16,18] and applicability in different climate zones [20]. However, the resilience of cooling strategies has not been widely discussed in the literature and it lacks a clear definition of resilient cooling and the criteria for assessing it.

The present study aims to fill this knowledge gap. First, we define resilient cooling and propose the criteria that can be used to assess the resilience of a cooling strategy. Second, we review the state-of-the-art of existing cooling strategies, assessing their physical principle, typologies, and performance, with special attention to resilience, applicability and technology readiness level. Finally, we use the proposed resilience criteria to qualitatively evaluate cooling strategies under various extreme events, such as, heatwaves and power outages.

2. Resilience and characteristics of resilient cooling

This section reviews the definition of resilience and the characteristics of resilient systems, and further discusses resilient cooling and the criteria for assessing it.

The concept of resilience originated in physics and psychology, where it described the ability of an object to return to its initial condition after a disruption [21,22]. The definition and interpretation of resilience vary from one discipline to another. Table 1 summarizes various definitions of resilience within the context of buildings and building-related systems.

One critical prerequisite for a comprehensive definition of resilience is to identify the threats or external perturbations to the systems, which can be summarized into an essential question as "resilience to what?"[23]. The threats faced by buildings and building-related systems are diverse and include both natural hazards and human hazards. Natural hazards can further be divided into geo-hazards, such as earthquakes, tsunamis, landslides, hydro-meteorological hazards (e.g., hurricanes and floods), wind storms and extreme temperature [24]. In the concept of resilient cooling, the building and its systems are mainly challenged by extreme heat events (heatwaves) and power outages. High power demand from air-conditioning during a heatwave strains and destabilizes the electrical grid [25]. Extreme heat can also impede power generation. For example, during the heatwave in 2003, the river water levels in France dropped so low that the cooling process of nuclear reactors became impossible and the nuclear power plants had to shut down [26].

Bruneau et al. [27] proposed four dimensions of resilience: technical, organizational, social, and economic. This study will mainly discuss resilient cooling from the technical point of view and the other dimensions will be treated as supplementary conditions. The resilience researches [5,21,27] considered various scales from micro (building or building element) to macro (district, city, or urban). The current study will address the resilience of building-scale cooling strategies over the life of the building.

Some studies tended to define resilience by considering the phases that systems undergo with external disruptions (initial condition, vulnerability-survivability state, recoverability state, new stable equilibrium state) [14,28], but most defined resilience through its features and systems abilities [5,21,24,26,27,29]. Several words commonly found in the literature to characterize resilient systems include "absorb", "withstand", "recover", and "rapidity". Therefore, this study proposes to summarize the resilient characteristics of cooling strategies by four criteria – absorptive capacity, adaptive capacity, restorative capacity and recovery speed.

- **Absorptive capacity** is the degree to which a system is able to absorb the impacts of disruptive events and minimize their consequences with little effort. For example, heavy thermal mass in a building (capacitance) can absorb unwanted solar gain and can minimize and/or delay the air temperature increase in the building without the use of cooling energy.
- **Adaptive capacity** is the ability to adjust undesirable situations by undergoing some changes. The system can learn from the event, evaluate the system performance and modify its configurations, and make it more flexible to future disruptions. Adaptive capacity is distinguished from absorptive capacity in that adaptive systems change in response to adverse impacts, especially if the absorptive capacity has been exceeded. For example, a façade solar shade may be activated, when the air temperature in the building starts to increase because the storage capacity of the thermal mass has been exceeded.
- **Restorative capacity** is the ability to return to normal or improved operation. For example, night cooling can remove unwanted heat gain accumulated in the thermal mass during the day and provide a heat sink for the next day.
- **Recovery speed** is the speed of the recovery process. Recovery may be accelerated if absorption activities are well implemented and the system can quickly mobilize and effectively use all the resources at its disposal [21]. For example, the speed with which night cooling can remove heat from the building's thermal mass and restore the building to its desired condition depends on the ventilation flow rate and the outdoor air temperature.

Therefore, Annex 80 defines resilient cooling as a capacity of the cooling system integrated with the building that allows it to withstand or recover from disturbances due to disruptions, including heatwaves and power outages, and to adopt the appropriate strategies after failure to mitigate degradation of building performance (deterioration of indoor environmental quality and/or increased need for space cooling energy) [23].

3. Review method

To provide an overview of the state-of-the-art of existing cooling strategies, and assessing their resilience under various extreme events, a systematic literature review was performed. The review was carried out through a critical analysis of existing literature. Different databases have been used to identify peer-reviewed academic literature, including Elsevier (ScienceDirect), IEEE, Google Scholar, Scopus, SpringerLink. To address the resilience of cooling strategies under extreme events, the keywords for the search included resilience, overheating, heatwave, climate change, power outage, disruptive events, cooling strategies/solutions/techniques. Additional searches were performed by combining the keywords for each cooling strategy. Take ventilative cooling as an example, the following keywords were used: ventilative cooling, ventilation, natural/mechanic/hybrid ventilation, night cooling, air-based system. Besides peer-reviewed articles, relevant books and technical reports have also been taken into account. There was no strict limitation on the publication period, but priority has been given to recent publications to address the state-of-the-art research. Table 2 summarizes the statistic of reviewed literature for different cooling strategies.

4. Resilient cooling strategies

Annex 80 has created four cooling-strategy categories based on their approaches to cooling people or the indoor environment.

Table 2
Statistic of reviewed literature for different cooling strategies.

Cooling strategies	Number of references	Year of publication
Solar shading/glazing	172	1982–2020
Cool envelope materials	256	1975–2021
Green roofs, roof pond, and green facades	39	1969–2020
Ventilated roofs and facades	47	2001–2020
Thermal mass including PCMs	89	1982–2020
Ventilative cooling	84	1996–2021
Adiabatic/evaporative cooling	33	1991–2020
Compression refrigeration	9	2008–2019
Absorption refrigeration including desiccant cooling	10	1992–2019
Ground source cooling	79	1987–2020
Sky radiative cooling	32	2002–2021
High-temperature cooling system: Radiant cooling	28	1995–2020
Personal comfort systems	26	1979–2020
Dehumidification including desiccant dehumidification	27	1993–2020

A. Reducing heat gains to indoor environments and people indoors
B. Removing sensible heat from indoor environments
C. Enhancing personal comfort apart from cooling whole spaces
D. Removing latent heat from indoor environments

This section will review the above cooling strategies from the following aspects: physical principle, typologies, performance with attention to resilience under extreme events, and technology readiness level (TRL). The technology readiness level is based on the guidelines from the U.S. Department of Energy [30].

4.1. Reduce heat gains to indoor environments and people indoors

4.1.1. Advanced solar shading/advanced glazing technologies

Windows are inserted into walls and roofs to provide a view to the outdoors for occupants, and to admit and control daylight, sunlight, and air. While windows usually comprise only a small fraction of the overall envelope area (typically 5–35%) the impacts of these transparent surfaces on cooling energy use, peak cooling loads, and occupant comfort can be very large. Windows (glass, sash, and frame elements) are commonly accompanied by shading systems. When mounted on the building exterior, shading devices are more effective in managing solar loads, but more costly. The combined ability of window and shading technologies to provide resilient cooling depends on the intrinsic properties of the window/glazing package as modified by any shading technologies. Shading elements are commonly relied upon to manage solar gain in the event of a heatwave or power outage.

To better assess the window/glazing/shading response in terms of resilience it is useful to divide the available technology options into static and dynamic technologies, and to further divide dynamic solutions into manually operated and automatically operated.

Glazing technologies manage cooling loads from solar gain by absorbing, transmitting, and reflecting solar energy by virtue of the materials used in the construction of the glass and glazing system. Traditional clear glass has a very high solar transmittance; glazing systems used in most windows today use body tints and coatings for absorption and reflection, and can be further combined into multiple glazings in an insulated glazing unit with two or more glazing layers that provide a wide range of thermal management capabilities. Several thousand different variants of glass are commercially available with documented wavelength-dependent optical properties [31]. The solar properties of the complete glass package in a window, optimized for structural needs as well as energy control, can be readily determined by simulation [32,33]. The most effective and widely used glazing products incorporate low thermal-infrared emittance ("low-E") coatings which can serve two purposes. All reduce the window thermal transmittance ("U-value") and when properly positioned within an insulating glass unit will reduce solar heat gain. Some low-E coatings provide spectral control and admit most daylight [visible transmittance (Tv) > 60%] while effectively reducing solar gain [solar heat gain coefficient (SHGC) less than 0.30]. A wide range of light-transmitting glazings is available with a light-to-solar-gain-ratio (LSG = Tv/SHGC) ranging from 0.5 to 2.3 [34]. The ability to admit daylight but minimize solar heat gain can reduce building cooling loads attributable to electric lighting.

Glazings with fixed solar optical and thermal properties do not have the flexibility to respond dynamically to changing environmental conditions or to grid demands. After a 20-year R&D effort manufacturers have commercialized several different "smart glazing" products. Thermochromic glass technologies have solar optical properties that vary moderately with temperature [35,36]. The solar-optical properties of electrochromic and liquid crystal-based glazings are altered over a wide range with an applied voltage [37,38]. These show promising performance in laboratory studies and field studies in buildings but adoption has been slow because they are expensive and require new sensors and controls. There is a significant global investment in ongoing R&D regarding new or enhanced electrochromic solutions, as well as in other active glazing technologies based on liquid crystal devices. This is expected to provide new market options in the near term [39,40]. One approach is to control visible transmittance and NIR transmittance independently. This facilitates improved performance in northern climates, and the window can reduce SHGC in warmer climates but still admit daylight [41,42]. An emerging technology solution incorporates transparent or semi-transparent photovoltaic layers in the glazing to manage solar heat gain and generate electricity [43].

Shading solutions for windows are diverse in terms of function, materials, and operation in both homes and commercial buildings. Shading systems can be static or dynamic, and are mounted either exterior or interior to the glazing [44–50]. More complex solutions utilize the cavities between glazing and shading layers to manage air flow and heat removal or recovery; these ventilated facades are discussed in more detail in section 4.1.4. The best-known shading solutions are operable shades, blinds, and drapes on the interior, and screens, shades, blinds and fins/overhangs on the exterior [51–53]. The newest generation of exterior solar shading can incorporate power generation (i.e., PV arrays) in the shading elements [54]. Since the solar loads depend on ever-changing solar position, even fixed shading solutions will have an annual performance that varies with latitude, orientation, and geometry. An interior operable shading system will always be less efficient than a similar exterior system since the absorbed solar radiation is trapped within the building [49]. Operable systems have limited effectiveness and resilience if they are not triggered and operated appropriately in response to climatic stress. The promise of improved controls, wireless sensors, and better integration with building control systems should reduce costs and improve reliability [55–58]. Ongoing studies on occupant response to glare and preferences in managing the tradeoffs between daylight control, solar control, and glare [59,60] are influencing design and deployment trends for the years ahead.

Market availability and acceptance varies across these technology solutions and also by region. Both spectrally selective static glazing as well as high insulating glazing solutions, are widely available. Active and passive smart glazing solutions are still offered by a limited number of companies globally. Fixed exterior shading systems are available in the global market, although they are infrequently used in many countries and for multiple building types. Multiple solutions for operable interior or exterior shading systems are also widely available. Exterior systems are in use in Europe but less widely in the U.S. These systems are commonly operated manually. Automated or motorized solutions are limited but they are entering the market in increasing volumes.

4.1.2. Cool envelope materials

A cool envelope material (CEM), typically a reflective roof or wall product, provides a solar-opaque surface that reduces net radiative heat gain at the envelope [(solar absorption - fluorescence) + (thermal infrared absorption – thermal infrared emission] to decrease heat flow into the occupied space [61–65]. Strategies include static high solar reflectance (light-colored or ultrabright-white CEM) [66–72], static high near-infrared (NIR) reflectance (cool-colored CEM) [73–82], temperature-sensitive high solar reflectance (thermochromic CEM) [66,83–86], angle-sensitive high solar reflectance (directionally selective reflector CEM) [87–89], static solar retroreflection (solar-retroreflective CEM) [90,91], and static near-unity solar reflectance + static selective thermal emittance (daytime sky radiator CEM) [92–94].

Except for daytime sky radiators, CEMs reduce heat flow into the occupied space but do not increase heat flow out of the occupied space. Therefore, CEMs must be coupled with heat modulating strategies, such as thermal storage, or heat-dissipating strategies, such as night ventilation, evaporative cooling, or mechanical cooling, if the outside air is uncomfortably or dangerously hot.

CEMs save cooling energy in an air-conditioned building when power is available; lower indoor temperatures in an unconditioned ("free-running") building when power is unavailable, or the building lacks cooling equipment, and provide a combination of energy savings and indoor temperature reduction when power is available, but the cooling equipment is undersized for an exceptionally hot day. Hernández-Pérez et al. [95] summarize cooling load or cooling energy savings simulated in over 20 studies; additional simulations can be found in later studies [63,66,84,96–108]. They also review space temperature reductions measured or simulated in over 30 studies and discomfort hour reductions simulated in 4 studies; later works also report reductions in indoor temperature [102–119] or discomfort hours [97,101,110–112,114,120], with heat-wave benefits assessed by Porritt et al. [121,122]. Cool-roof monitoring studies have measured reductions of about 1 to 3 K in top-floor air temperature [98,99,123–126] and up to about 5 K in top-floor operative temperature [112,127].

The ability of a CEM to reduce the envelope's net radiative heat gain on a sunny day provides an "absorptive" capacity for heat resilience by helping the cooling equipment meet its load, or by diminishing the temperature rise in an unconditioned building. As passive solar-control measures, CEMs help whenever the sun shines, and continue to mitigate unwanted solar heat gain during a power outage or heatwave. However, their absorptive capacities diminish when cloudy, hazy, or smoky skies reduce incident sunlight. A thermochromic CEM may provide adaptive capacity if a heat event accelerates its switch from low to high solar reflectance. While CEMs do not directly provide restorative or recovery capacity, their abilities to reduce heat flow into the occupied space make it easier for heat-modulating and heat-dissipating strategies to moderate interior temperatures.

Both white and cool-colored roof materials are mature technologies that are widely available to both building owners and building contractors [68,128], and identifiable via mature product rating systems provided by the Cool Roof Rating Council [129] and the European Cool Roofs Council [130,131]. Cool wall materials, such as light-colored paints, claddings, and sidings, and some cool-colored wall products, are similarly mature and available (Appendix P of [70]), but their product rating system is still under development [132]. Some novel CEMS such as directionally selective reflectors are specialty products with limited availability; other CEMs, such as daytime radiators, solar retroreflectors, fluorescent cool colors, and thermochromics remain under development.

4.1.3. Green roofs, roof pond, green facades (evaporative envelope surfaces)

Evaporation on the outside of the building envelope is an efficient cooling technique, which can be managed with vegetated surfaces, water films, ponds, and sprays [133–136] (Fig. 1).

The primary difference between façades (green or watered, Fig. 1a,b,c) and roofs (green roof or roof pond, Fig. 1d,e) is linked to the vertical water runoff, which amplifies the thermal transfer due to the increased sensible and convective heat transfer in the water stream. Moreover, evaporative façades require continuous water spray or water supply to permanently irrigate the upper part, while roof ponds and green roofs may adapt more easily to various climate conditions without water supply.

The water retention potential is a key design parameter for roof ponds [137] and green roofs [138]. A permanent water supply may be required (for façades, or during dry periods), which brings out the optimal control of the evaporative dynamic for a resilient cooling strategy, and low water consumption. E.g., to increase the evaporation process of a roof pond, Erell et al. [139] recommended

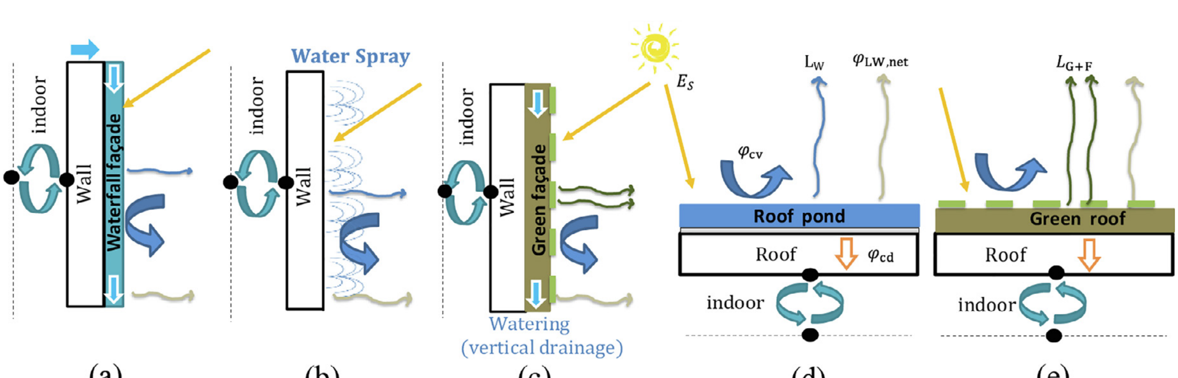

Fig. 1. Heat transfer in evaporative envelope surfaces, including (a) a waterfall façade, (b) a spraying system, (c) a green façade, (d) a roof pond, and (e) a green roof. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

droplet sizes of 0.5 to 1 mm, spray rates of about 1–1.5 volumes of the roof pond per hour, and a spray height of 50 cm.

Innovative evaporative envelopes include the combinations of increased albedo, the development of porous materials, or movable claddings [140,141].

However, for hot, temperate and even cold climates, evaporative envelope surfaces demonstrated strong cooling effects of the roof and façades surfaces for summer conditions [142,143]. E.g., the surface temperature of the south-oriented wall can decrease by 9.8 °C in Moscow, and 18.7 °C in Riyadh [139], while energy cooling loads can decrease up to 100% in Brasilia and Hong Kong with green roof and façades. These cooling techniques are also widely recommended for their stormwater retention potential, and their impact on sewer overflow, which translates into some local policies such as the Toronto (Canada) green roof policy [144]. This can be an efficient solution even considering the effects of climate change, but some parameters like plant species [145] or roof water retention capacity may have to be adapted.

Regarding evaporative surfaces, the most advanced TRL (TRL 9) concerns green roofs and façades, which are widely available, and included in policies and standards. However, few alternatives for water retention systems on roofs exists, e.g., typical gravel roofs (TRL 9). Most of these alternatives are only at a research or prototype stage, including various roof pond typologies with/without radiative protections, or porous material, all mainly available as lab prototypes, or full-scale experiments (TRL 4–6) [146].

4.1.4. Ventilated roofs and ventilated facades (ventilated envelope surfaces)

Ventilated roofs and façades have been widely developed as an adaptive element for both winter heat recovery and summer heat dissipation. An additional opaque or transparent cladding forms a ventilated double-skin, which allows various airflow strategies (see Fig. 2) to cool the external side when required. Ventilation patterns and additional controls, such as venetian blinds [147–150], make these techniques highly adaptable to seasonal changes and climate change.

The air-tightness and winter solar gains of the closed cavity façade (Fig. 2a) are a good option for temperate climates, while it can support high temperatures (up to 90 °C) with a long service life without maintenance [138]. Yet, overheating of the air gap under extreme summer conditions has led to the development of more performant solutions, such as movable blinds and natural ventilation. The solar heat gains observed in an experimental setup in China were reduced from 330 to 28 W/m^2 with Venetian blinds [149]. The cooling performance is improved with ventilation openings designed to remove heat, and outdoor or indoor air ventilation strategies [151]. The indoor ventilation can be designed with air outlets through the roof [152] or the wall (Fig. 2b,e), which can be efficient for air-conditioned buildings even in extreme hot climates. Driven by the outside air–gap stack effect (amplified by solar gains), the airflow may be intensified by the mechanical ventilation system of the building. Similarly, outdoor air can be used as the heat sink for the double-skin air gap (Fig. 2c,d). The study of a ventilated pitched roof in Djibouti [153] demonstrated a heat gain reduction of about 50% for the building, which underlines the effectiveness of this ventilation technique in extreme summer conditions, given the high solar gains of the roof, and the temperature differences between the roof and outdoor air.

The ventilation rate is a key parameter for this technique's cooling efficiency. This ventilation rate is highly dependent on the opening design. Then, the design and the optimal perforation rate of outdoor façade claddings vary greatly depending on the location and orientations [154,155]. The optimal perforated percentage varies between seasons, and variations between 10 and 60% were found to be optimum for Japan [143]. However, these optimal cooling performances will drop under extreme heatwave events and climate change, due to the outdoor air temperature increase. Yet, some design parameters such as solar orientation [156] and prevailing wind direction [156,157], will be much less sensitive to climate change.

Regarding ventilated surfaces, double-skin façades are very well developed in the construction sector, from the first Trombe walls in the 1920′s to the transparent double-skins for high-rise office buildings [158] (TRL 9). These techniques include many innovations, such as the perforated and the closed cavity façades; yet many lab developments are still ongoing (TRL 6), and some biomimetic solutions are arising, such as adaptive façades similar to a natural foliage [159] (TRL8). Ventilated roof for cooling can be found in research studies [153] (TRL5-6), but very few construction products are available for this typology [160] (TRL9).

4.1.5. Thermal mass utilization including PCM

Thermal Energy Storage (TES) systems absorb, store, and release thermal energy on a cyclical basis (usually daily) to regulate internal temperature and improve thermal comfort in buildings [161]. Thermal energy can be stored as a change in internal energy of a material as sensible heat (e.g., ground, water tanks and aquifer energy storage), latent heat (e.g., Phase Change Materials, including organic and inorganic substances and ice storage), or chemical energy (e.g., thermochemical storage). It should be noted that the cooling capacity (in [kWh]) of a latent thermal energy storage comprises both a fraction of sensible and a fraction of latent energy.

TES systems increase the generation capacity by releasing the stored energy during high demand which allows a smaller production unit to be installed.. TES systems operate as a cost-saving measure by shifting the energy demand to low-tariff periods [162]. TES systems also increase the cooling system reliability and can easily be integrated with other functions such as on-site fire protection water storages [163]. However, TES system performance is not guaranteed during the days with small temperature swings. Storage cycle efficiency (i.e., long-term heat loss reduction) and high

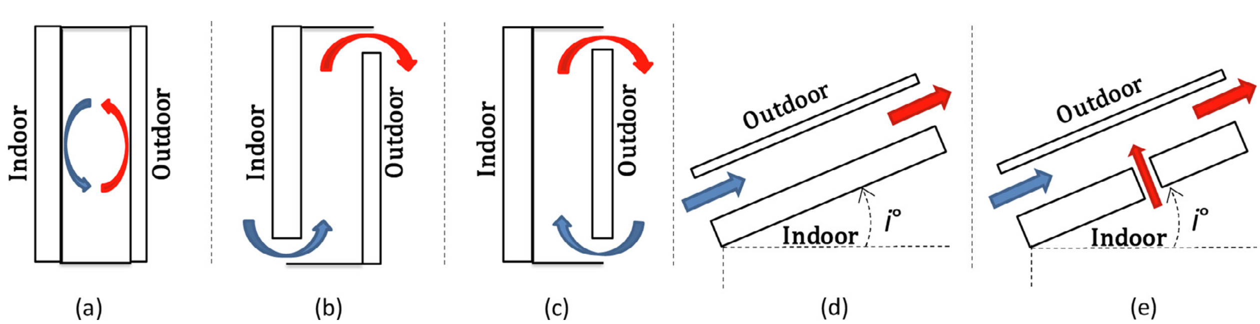

Fig. 2. Typologies of ventilated envelope surfaces: (a) closed cavity façade; (b) exhaust air façade; (c) outdoor air curtain façade; (d) ventilated roof; (e) ventilated roof coupled to a natural ventilation of the building.

investment cost in latent and thermochemical heat storage are further limitations of TES systems [164].

The performance of a TES is characterized by its storage capacity and its ability to provide cooling or heating power as a function of the state of charge of the storage. TES systems have shown to be effective measures in reducing peak indoor air temperature and dampening temperature variations in buildings during extreme events such as heatwaves or power outages. TES cooling performance under extreme conditions is highly sensitive to the temperature gradient between cyclic cold (e.g., night) and warm (e.g., day) periods. For instance, consecutive days with high nighttime outdoor temperatures deteriorate the cooling capacity of TES systems significantly [165]. Kuczyński & Staszczuk [166] indicated that the cooling effect and efficiency of increased thermal mass do not change during the heatwaves and remain independent of the duration and distribution of heatwaves. In their analysis, the use of concrete ground floors and walls in a detached single-family house, combined with nighttime ventilation and shading devices, substantially reduces the risk of overheating and the need for the installation of active cooling systems.

PCMs are applied mostly for energy-saving purposes but have shown some advantages in reducing overheating hours and improving thermal comfort. Similar to increased thermal mass, installing PCMs can reduce indoor air temperature variations [167]. The effectiveness of PCMs in overheating reduction in buildings relies on PCM properties and climate [168]. Some studies report a 50% reduction of discomfort hours [169,170]. However, Kuznik et al. [171] found that while the use of PCMs is beneficial in some periods during the year, it is not effective in very hot days because it remains liquid throughout the day. According to Ramakrishnan et al. [172] who optimized PCM melt temperature for resiliency, parametric optimization for the current heatwave events will not work for future heatwaves. Baniassadi et al. [173] analyzed the effectiveness of wall-integrated PCMs during the loss of air conditioning (i.e., power outage) coincident with heatwaves. They found that although PCM application can mitigate overheating during power outages, its resiliency is highly correlated to temporal factors (initiation time and duration of a power outage), PCM properties, and climate. They stated that the PCM melt temperature is a crucial factor in determining its resiliency. In most climates, the optimum melt temperature for resiliency differs from the optimum temperature for energy efficiency [173]. Considering the fact that energy efficiency is the main driver of the installation of PCMs, in most cases, there is no significant added resiliency advantage by using PCMs [173]. However, in some climates, there is a chance to select a melt temperature that has benefits for both energy efficiency and resiliency [174].

Common materials for thermal mass utilization are concrete, stone or masonry, bricks, and tiles. These materials are available all around the world as they do not necessarily require special technology to be produced. TES systems based on sensible heat such as water tank or underground storage methods are widely available, but devices based on latent heat such as PCM are mostly under development. The higher costs of PCMs is a barrier to widely enter the markets. The cost difference between sensible TES and PCM is even higher in active applications. Another barrier is related to the stability of the PCM materials. Further research and development are needed in PCM to adopt these technologies in more cost-effective manner.

4.2. Remove sensible heat from indoor environments

4.2.1. Ventilative cooling

Ventilative cooling (VC) uses the cooling potential of the outdoor air, and can be achieved with natural solutions (either by wind-driven or buoyancy-driven flows), mechanical technologies (fan), or a combination of both (i.e., mixed-mode or hybrid ventilation). Some studies [175,176] categorized VC into daytime comfort ventilation (or direct cooling) and night cooling (or indirect cooling). Daytime comfort ventilation introduces the flow of outdoor air through the building during the day to directly remove heat gains. It aims to improve the occupant's thermal comfort via convective heat transfer, increasing the evaporative cooling effect on the occupants' skin, and decreasing indoor air temperature. Night cooling has a double effect: on the one side it utilizes the building's thermal mass during the night, where thermal mass works as a heat sink during the occupied period, and, on the other side, it decreases indoor air temperature during the night hours.

The cooling performance of ventilation systems under extreme events is strongly correlated to ventilation types (natural or mechanical), building characteristics, local climate and occupant behavior [177,178]. Alessandrini et al. [179] investigated the overheating risk in a naturally ventilated dwelling during heatwaves under the weather condition of France, Paris. They observed that by natural ventilation, the maximum indoor operative temperature could be maintained 6–9 °C lower than the maximum outdoor temperature which reached 39 °C during the five days of heatwaves. Their study demonstrates that a well-designed natural ventilation system can mitigate the surging cooling demand during an extreme heat event. Architectural elements such as a solar chimney, atrium, or double-skin façade can help facilitate natural ventilation. A study by Lomas and Ji [180] demonstrated that buildings with such architectural elements integrated with advanced ventilation controls could provide greater resilience to future climate change than single-side natural ventilation.

However, ventilative cooling will be less beneficial when climate change makes heatwave events more frequent [181]. Artman et al. [182] quantified the effect of global warming on the night-time ventilative cooling potential in Europe. They compared the climatic cooling potential (CCP) index between monitored climate conditions (1961–1990, European Climate Assessment and Dataset) and possible future climate conditions (2071–2100, IPCC SRES scenarios A2, more divided world, and B2 [183], world more divided but more ecological). Their study indicated that future warming would have a significant impact on the night-time ventilative cooling potential across Europe. The CCP was expected to decrease by 20–50% in Central and Northern Europe by the end of the 21st century. At the same time, for Southern Europe, CCP was found to become negligible in summer and decrease by 20–55% during the transient season at the end of the 21st century. Campaniço et al. [177] evaluated the impact of climate change on direct ventilation for the Iberian Peninsula area. They predicted a 20% reduction of CCP in the future climate (2070–2100) along the annual cycle and up to 60% reduction in the summer season. The impact of climate change on the uncertainty of thermal comfort in a naturally ventilated office was investigated by Breesch and Janssens [184]. The probability of discomfort increases significantly when recent and warmer weather data sets are assumed. To reduce the risk of overheating in a warming climate, natural night ventilation should be combined with additional measures, such as mechanical ventilation coupled with cooling coil or passive cooling strategies (earth-air heat exchanger, indirect evaporative cooling), or increased thermal storage in the building. Mechanical ventilation increases resiliency, on the other hand, it will increase energy consumption. It is therefore recommended to perform a full life-cycle assessment to ensure energy efficiency and overheating resilience over the long-term building life span [185].

Natural ventilation through openings and other passive devices is widely available for most applications. Traditional examples developed through centuries of trial and error are modified to provide contemporary solutions. Mechanical ventilation techniques and solutions are also readily available for most applications. Both natural and mechanical solutions are available on the marked reaching a TRL 9, although specific innovative solutions and control techniques are under development at different TRL levels.

4.2.2. Adiabatic/evaporative cooling

Evaporative cooling is based on an adiabatic process in which the sensible air temperature is reduced. Evaporative cooling may be classified into two main approaches: direct coolers (e.g., desert coolers) and indirect coolers (e.g., evaporative chiller units for fan coil) [186,187]. Direct evaporative cooling (DEC) evaporates the water directly into the air stream, while indirect evaporative cooling (IDEC) evaporates water into a secondary air stream. The secondary air stream cools the main air stream through a heat exchanger without adding humidity.

Direct evaporative cooling systems have been well known since ancient times. Several historical buildings in hot (and dry) climates show DEC solutions, such as the Ziza Palace in Palermo, Italy, or Red Ford in Delhi, India [188,189]. The efficiencies of DEC systems depend on the local wet bulb temperature depression, and they are best suited to hot and dry locations. Performance of IDEC depends on wet bulb effectiveness, dew point effectiveness, cooling power, power consumption, and coefficient of performance [190]. Water scarcity may limit the application of evaporative cooling systems in desert or semi-desert areas.

The impact of climate change on the cooling potential of evaporative cooling has been studied by Campaniço et al. [177]. The climatic cooling potential index has been calculated under past (1970–2000) and future weather conditions (2070–2100) in the Iberian Peninsula. A 10%-15% decrease in CCP (ventilative cooling) is expected in the further climate due to increased outdoor temperature, while evaporative cooling is shown to be more resilient to climate changes than ventilative cooling. Osman et al. [191] found that building design strategies in a hot and arid region should shift from natural ventilation to more active cooling by the year 2070, and that two-stage evaporative cooling comprised of DEC and IDEC is the most resilient strategy for all of Khartoum's seasons in the future climate. Furthermore, the population of arid regions is growing and climate changes are increasing human thermal stress in arid areas. Evaporative cooling solutions and green infrastructure (evapotranspiration from vegetation) are essential technologies supporting resilience, although the potential reduction in water availability requires high efficiency solutions.

Passive DEC systems are generally low cost, nevertheless, they need high maintenance to avoid microorganisms and connected diseases (e.g. legionella). DEC may be a valid dissipative system for open or semi-open spaces, in where the growth of air absolute humidity is mitigated by natural air movements [192,193]. In enclosed spaces, DEC systems can be controlled to prevent too high humidity values by adopting a control system. From the TRL point of view, several DEC systems have been installed in different building typologies. This technology is at the market level (TRL9), nevertheless, new researches are under development for new porous materials, and to develop specific systems connected to ventilative cooling solutions. In these cases, lower TRL may be found. Finally, movable simpler evaporation solutions (e.g. personal evaporator fan systems) independent by building system integration are commercialized in everyday shops.

4.2.3. Compression refrigeration

Vapor compression refrigeration is certainly the most used "active" technology to produce a cooling effect. The system mainly comprises an evaporator, a compressor, a condenser and an expansion device. A working fluid (refrigerant) successively flows through these components and follows a thermodynamic cycle [43].

Vapor Compression Air Conditioning units (ACs) can be classified by the heat source and heat sink (e.g. air, glycol–water, water, or soil), function (AC unit-cooling, heat pump-heating, reversible ACs- heating or cooling modes, AC with heat recovery – heating and cooling simultaneously), compressor technology, refrigerant type (natural or synthetic)), configuration [194] (packaged units (including window ACs and rooftop units), split ACs (including ductless mini-split systems, ductless multi-split systems and central ducted split-systems) and chillers (air-cooled, water-cooled, evaporative cooled). The other classification of interest when considering resilient technologies is cooling capacity. Vapor compression refrigerant technology covers a large range of cooling capacities going from a few hundred watts (household refrigerators) to tens of megawatts (industrial chillers and large-scale heat pumps) [44].

The cooling capacity of compression refrigeration systems is more constrained by the design and size of the machine than by the available capacity of the natural heat sink. Even though the COP of the system might decrease due to the high outdoor temperature during heatwaves, a well-designed system can still retain sufficient cooling capacity to confront the heatwave, indicating that compression refrigeration technology provides a high adaptive capacity. Hajidavalloo and Eghtedari [195] investigated the impact of outdoor air temperature on the COP of a split-air-conditioner with an air-cooled condenser. They found that when the outdoor temperature increases to 49 °C from 35 °C, the cooling capacity of this air-conditioner decreases to 5.6 kW from 6.8 kW, and COP decreases to 3.14 from 4.56. The study also found that this problem could be mitigated by using an evaporative-cooled condenser, which maintained the cooling capacity of the air-conditioner at 6.7 kW when the outdoor air temperature was 49 °C.

Vapor compression systems rely on electricity and are not very robust to the power outage. An approach to increase its robustness is to connect with local electricity production, such as photovoltaic (PV) panels in buildings. Chillers are more likely to operate simultaneously to PV electricity production compared with heat pumps, i.e., the highest cooling demand usually coincides with the large intensity of solar radiation. It is hence a good candidate to improve building self-consumption. On the other hand, chillers connected to energy storage (batteries, thermal storage units of building thermal mass) can also apply as a backup solution to the management of electrical grids by the flexibility provided by such combinations. This flexibility is activated by a time of use tariff as a demand side management (DSM) mechanism. It should be stressed that heatwaves lead to electricity peak demands on the grid and DSM mechanisms become of paramount importance. Average cooling demand around the world is responsible for 15% of peak electricity demand; but during hot days, cooling can be responsible for up to 50% and more of residential peak electricity demand [196]. Moreover, for buildings equipped with on-site generation, the use of thermal storage combined with specific net-metering programs can promote better load matching between production and consumption [197]. Another approach is to integrate the vapor compression system with ice storage systems, which can help limit the impact on the electricity grid of highly fluctuating distributed renewable energy sources. Actually, they offer a mechanism of building electricity consumption flexibility that can take profit of dynamic electricity rates.

Vapor-compression ACs for buildings, with a wide range of capacities and numerous configurations, show TRL values of 9. In 2020, roughly 2 billion AC units were in operation in the world, with residential ACs representing 68% of these units [196]. The market of AC units is growing in an accelerated way, with estimated sales increasing by 10% between 2018 and 2019 (mainly in emerging and developing countries) [196]. Building contractors and engineering offices define the most appropriate cooling/heating plants depending on the availabilities of heat sink/heat source, on the building characteristics, on the ease of installation, on the cost of the solutions, on the cost of energy (and the presence of local electricity production), on local regulation/incentives, but also on the customer's expectations. AC efficiency rating varies from one country to another, but it is always an image of the ratio of the cooling effect to the electricity consumption (W/W). Average efficiency rating of installed AC units has increased by 15% between 2010 and 2020 [196], but still far behind the most efficient products on the market [196].

4.2.4. Absorption refrigeration including desiccant cooling

Desiccant cooling systems were developed to handle sensible and latent heat loads independently [198]. The dehumidifier absorbs the moisture of the supplied air and afterward will pass to the regeneration unit to recover its initial moisture absorption capability [199]. The dry supplied air stream passes the cooling unit for sensible cooling and is then routed to the conditioned space. Additional heat exchangers could be added on different points such as economizers to increase the system efficiency.

Desiccant systems are classified as solid or liquid desiccators [200]. A rotary wheel with solid dehumidifiers is a compact system made from matrix-shaped parallel channels coated with desiccant material, such as SiO_2, $TiSiO_4$, or Al_2O_3, that operate continuously with low corrosion probability [198]. The liquid desiccant materials, such as ClLi, LiBr, $CaCl_2$, TEG HCOONa, HCOOK, CH_3COONa, CH_3COOK, or a combination of these solutions, ideally should be stable, odorless, non-toxic, non-flammable, inexpensive, non-crystalized in the operating temperature range, non-corrosive and non-volatile with good heat transfer characteristics and low surface vapor pressure at the contacting temperature [201]. The low cooling capacity of solid desiccants and the corrosivity of liquid desiccants are important limitations. Therefore, new desiccants including bio-desiccants, composite desiccants, and polymer desiccants have been introduced; some of them could provide an absorption capacity 2–3 times of traditional absorbers [202].

The major benefits of absorption cooling are discussed in Refs. [198,203,204]. The system uses eco-friendly fluids including air and water, which have no negative impact on the environment. It could operate with diverse thermal energy sources, even low-grade resources, in the regenerators. The required electrical energy can be less than 25 % of conventional refrigeration systems and this technique acts as an energy-efficient method, especially for hot dry and hot humid areas. Finally, the desiccant cooling system works near atmospheric pressure, which makes them easy to construct, install, preserve and maintain. The major limitation of desiccant cooling is that it needs an additional heat source for regenerating the desiccant to provide stable operation [199]. However, the heating power can be provided by any source such as the waste heat from industries through a district heating network or via solar collectors or ground source heat pumps. This improves the overall efficiency of desiccant coolers because the heat requirement can be gained from sources with lower primary energy factor, i.e. waste heat from a combined heat and power plant, industry or solar energy which are also available during the cooling season. Moreover, to make the system more environmentally friendly, the required electrical power can be provided by renewable sources, for example, tidal energy in marine facilities, solar cells, or wind turbines.

High outdoor air temperature during a heatwave might decrease the efficiency of absorption refrigeration systems, depending on the type and design of the systems. Kim et al. [205] simulated the cooling performance of an air-cooled LiBr–water absorption chiller in extremely hot weather. It was found that when the ambient temperature increases to 50 °C from 35 °C, the cooling capacity of the absorption chiller decreases 37.5% and 35.6% for direct air-cooled chiller and indirect air-cooled chiller compared with their cooling capacity at 35 °C, respectively. Grzebielec et al. [206] confirmed that the outdoor air temperature plays an important role in the efficiency of absorption refrigeration. However, by using a spray-evaporative heat exchanger, the effect of outdoor temperature can be reduced and the average cooling capacity can be up to 44% higher than those with dry air cooler devices.

Although the absorption refrigeration systems are partially activated by thermal energy, the systems are not robust during the power outage events because the cooling water distribution system cannot operate without power input. Like compression refrigeration, the system could integrate local electricity production and energy storage to increase its resilience during the power outage.

Desiccator wheels are used for residential and primarily for non-residential purposes. However, these usually use a simple system with basic equipment and more advanced systems are not widely implemented, though. Desiccant cooling technology could be categorized in TRL 9 according to the Technology Readiness Assessment Guide issued by the U.S. Department of Energy [207]. TRL 9 signifies that the technology operates and can achieve defined requirements. For instance, desiccators can be used in various applications and are available in the market [208,209]; therefore as a mature technology providing cool and dry air, desiccant coolers can be categorized in TRL9.

4.2.5. Ground source cooling

The working principle of ground-source cooling is based on the fact that the ground temperature below approximately 10 m remains fairly constant all year round at about mean annual ambient air temperature [210]. Thus, ground temperature over the cooling period is less or not affected by hourly and daily temperature variations, regardless of outside air temperature. It rejects heat to the ground by circulating a working fluid through ground heat exchangers. Based on the heat transfer medium (air or liquid), the system can be further categorized as an earth-to-air heat exchanger (EAHE) or a borehole heat exchanger (BHE). Ground-source cooling can also be classified as direct ground cooling (passive) or ground-source heat pump (active). The direct-ground cooling system utilizes ground as the only source for cooling the working fluid without any mechanical refrigeration. In a ground-source heat pump system, the cooling is provided through a mechanical refrigeration system using the ground as a sink for dissipating the heat [211]. Ground source systems may also be used to pre-heat a heat transfer medium in winter seasons, nevertheless, for this paper, only their cooling potential is analyzed.

Since the subsurface temperature below a certain depth is insensitive to seasonal and diurnal variations, ground-source cooling shows a high resilience under heatwaves. However, the cooling capacity of ground-source cooling might be affected by climate change. The sensitivity of ground-source cooling (EAHE) to future climate was investigated by Chiesa et al. [212] considering historical and future North America climate conditions - future climate were based on Five General Circulation Models (GCMs) from the CMIP5 (Coupled Model Intercomparison Project Phase 5) multi-model ensembles [213]. Results showed an expected reduction in climate EAHE sensible cooling dissipative potential in future years, while variations in the soil surface average temperature were identified to be a synthetic index to analyze variations in EAHE cooling potentials.

Several measurement studies have shown that ground-source systems perform better under peak-load conditions than under off-peak load conditions [214–216]. This is partly because under peak load conditions the ground heat transfer is higher, due to a larger temperature difference between working fluid and the ground. The percentage share of the parasitic energy consumption of circulation pumps and other auxiliary equipment under peak load conditions is also lower. Passive ground-cooling systems have larger absorptive capacities than active ground-cooling systems because they are bigger and because of their greater ability to adjust the working fluid conditions to match the cooling demand of the building. The systems can adjust to extreme events including heatwaves in many ways, such as by pre-cooling the building at night and off-peak periods, by using active thermal energy storage systems like chilled water or ice storage for load shifting, or by reducing peak loads at the expense of lower thermal comfort. The restorative capacity of ground-source cooling systems under heatwaves is high, as the heat injected into the ground is dissipated to the earth surrounding the ground heat exchanger. This can be done using dry coolers at nighttime when the ambient air temperature is lower. Depending on the soil's thermal diffusivity, it can take several hours to a few days for the system to fully recover from heat injections to the ground [217,218]. However, the impact of different recovery times have on the restorative capacity of the ground is generally considered in the design of ground-cooling systems.

The resilience of ground-source cooling systems to power outages depends on the degree of disruption and the type of the ground cooling system. The ground-source heat pump systems require substantial electrical energy to operate the refrigeration cycle and the auxiliary components. The direct-ground cooling systems require much less electricity as the only energy input to the system is the work required to drive the circulation pumps.

At the system level, ground-source cooling is a fully mature technology at TRL 9. It has been used worldwide for several decades and there are thousands of actual systems operating over the full range of possible conditions. There exists a great wealth of knowledge concerning design methods, installation procedures, operating practices, and application examples in literature. Moreover, there are several scientific and professional bodies defining norms and standards, protocols and guidelines, and best practices at local, national, and international levels. At the subsystem level, the heat exchangers and grouting materials used in ground-source cooling systems are widely available commercially and are at TRL 9. Nevertheless, there is still ongoing research into developing innovative heat exchanger designs and materials to enhance the ground heat transfer. The TRLs of the new developments range from early lab-scale (TRL 1–3) to commercial demonstration (TRL 8).

4.2.6. Sky radiative cooling

Sky radiative cooling represents the passive process in which any object located on the Earth's surface (sky facing terrestrial object or surface) releases heat to the sky through net loss of long-wave (thermal infrared) radiation [219,220]. The incident solar radiation during the day, the convective heat transfer (for a higher outdoor air temperature than the radiator temperature), and cloud coverage can have a negative impact on the net cooling output [92,221–226]. Thus, currently, this technology is mostly associated with nighttime, when the sky can reach temperatures below 0 °C [222,227] and there is no incident solar radiation. Still, the radiative heat exchange with the sky can take place both during night and day. Heat can be released in the broadband (4–30 μm) or a selective band (8–13 μm), the latter leading to a higher efficiency during an all-day cycle [92,228]. Thus, ideal material properties for radiative cooling should present a maximum reflectivity in the short-wave range (0.25–2.8 μm) to reflect solar radiation while the emissivity should be as close as possible to unity especially in the atmospheric window band (8–13 μm) and zero otherwise [92,228].

In buildings, roof paints can be employed as a passive radiative cooling solution to increase both solar reflectivity and emissivity of the surfaces, although this may increase the heating energy use during the heating season [92,228]. However, buildings can also make use of roof ponds, movable insulation systems, radiators, or existing solar heating systems integrated as passive or active systems (with or without pumps and fans) that extract the heat from the indoor environment and release it to the sky [92,226,228]. This way, sky radiative cooling presents the ability to restore the indoor thermal environment to its original state, making it a resilient cooling technology.

Nevertheless, as the cooling potential is influenced by air temperature, relative humidity, air speed, and clouds (e.g. the cooling potential is decreased in very hot and humid environments) [222,224–226] its restorative capacity is dependent on the outdoor climate. Thus, like other renewable energy technologies (e.g. wind, solar), its recovery speed (rapidity of the restorative capacity) can vary as well with the outdoor environmental conditions. Furthermore, the presence of solar radiation makes sky radiative cooling time dependent. As objects (e.g. other buildings) can block the radiative heat exchange with the sky while lack of space can drastically reduce the surface area facing it [220,228], their restorative and recovery capacities can be further limited in dense urban environments. Clouds, if present for a short and long period (hours to days), will reduce both its restorative and recovery capacity for the respective period. Still, even for a clear sky when the radiative heat exchange is not hindered by clouds, the convective heat exchange could counter its effect for a high outdoor temperature [221–226]. Therefore, the best sky radiative cooling solution must be chosen according to the climate and setting (high versus low building density), i.e. good planning is required for a high exploitation potential.

If used passively, sky radiative cooling cannot be adequately controlled and relies solely on favorable environmental conditions and material properties to achieve its maximum potential. However, reduced time dependency and a constant recovery speed could be achieved by employing night radiative cooling actively combined with different storage techniques (e.g. building thermal mass, storage tanks). This would allow the system to store cooling during periods with favorable conditions and use it at later times when the sky radiative cooling potential is limited. Furthermore, when using the technology actively, parameters such as the flow rate of the heat storage medium can be controlled [220,221,223,229], allowing higher exploitation (higher recovery speed), especially during periods when the potential is high, thus using the available resources in a timely manner.

After heatwaves, the sky radiative cooling's restorative capacity was rated as low to moderate, as the cooling capacity could be reduced by increased humidity and outdoor temperatures also during night time [92,225,228]. For example, an increase in relative humidity (50 to 100%) and outdoor air temperature (9 K) could reduce the cooling power of thermal solar collectors by 18% to 41%, respectively [225]. However, recent progress in solar reflective materials with high emissivity in the atmospheric window may further enhance the sky radiative cooling's restorative capacity as cooling could be achieved concurrently with the demand, i.e. during the day [92,228]. Blackouts would not pose an issue and thus the sky radiative cooling restorative capacity after blackouts was rated as moderate. The recovery speed on the other hand could vary between low and high depending on the way sky radiative technology is employed, passively or actively. If the technology is passively used, no additional auxiliary energy (e.g. pumping power) would be required to start the process. Therefore, in those situations, the recovery speed can vary from low (unfavorable environmental conditions) to high (favorable environmental conditions) during both heatwaves and blackouts. On the other hand, active use could ensure an increased recovery speed through an increased flow rate of the heat transfer medium (e.g. air, water).

Although not an issue for short-term blackouts, one challenge for active use during a long-term blackout, e.g. days, would be ensuring the circulation of the heat transfer medium. In those situations, without backup power the recovery speed would be low.

As the sky is a free cooling source, night sky radiative cooling is a renewable technology available for any consumer. Moreover, it is ready for market implementation since it can be employed through existing technologies such as solar collectors and PV/Ts [222,223,225]. However, further development and research can improve and optimise both the equipment and the systems employed, especially for daytime use [92,228]. Although it can be used directly by any consumer, the experience of design engineers and building contractors might improve its use leading to an optimum operation of the desired application.

4.2.7. High-temperature cooling system: Radiant cooling

A hydronic radiant cooling system refers to a system in which water is the heat carrier and more than half of the heat exchange with the conditioned space is by radiation [230,231]. Heat transfer from indoor spaces is by a combination of radiation and convection via cooled surfaces. The convection is usually natural, unless the air movement over the conditioned surface has been enhanced—e.g., by supplying air from a ventilation diffuser. These systems employ high-temperature cooling, where the heat-transfer medium is near room temperature. The system conditions large surfaces in indoor spaces, usually floors, ceilings, and walls, and the large conditioned surface areas make it possible to cool indoor spaces with a small temperature difference between the conditioned surfaces and the room. Supply water temperatures in radiant systems are usually 16 – 23 °C for cooling.

Radiant cooling systems can be classified as radiant cooling panels, radiant surface systems, and thermally active building systems (TABS) [230]. Radiant panel systems and radiant surface systems can be used in both new buildings and renovated buildings. However, TABS needs to be installed in the construction phase of a building, which limits the use of TABS in renovation projects. To address this limitation and to bring the benefits of TABS to renovation projects and to lightweight buildings, a particular type of radiant ceiling panels has been emerging. This technology combines PCMs with radiant ceiling panels to create a similar system to TABS—i.e., PCM radiant ceiling panels. Pipes are embedded in the PCM. Water is circulated in pipes to control the charging (melting) and discharging (freezing) behavior of PCM, which in turn controls the thermal environment in indoor spaces. This is a promising solution and has been proven to perform similar to TABS in terms of operation, energy performance, heat removal from rooms, and resulting thermal indoor environment [232–235].

Radiant cooling systems have many benefits compared to more conventional (e.g., all-air) cooling systems. The use of high-temperature cooling enables the system to couple to natural heat sources and sinks, such as ground, lake water, or seawater [236–238]. It also creates favorable operating conditions for heating and cooling plants (mainly due to operating temperature ranges and return temperatures), increasing the efficiencies of heat pumps, chillers, and boilers [81 83]. Radiant cooling systems have the possibility of transferring peak cooling loads to off-peak hours, reducing peak power demand [237]. Further benefits of radiant systems have been summarized by Kazanci [206]. One of the major characteristics of radiant systems is that they address only sensible heating and cooling loads. Therefore, they need to be coupled with ventilation systems, usually in the form of a dedicated outdoor air system (DOAS). The main function of ventilation systems is to regulate humidity (i.e., to dehumidify the air) and provide fresh air to indoor spaces [230]. There are various combinations according to the location of radiant surfaces and air distribution principles. A summary of the coupled system configurations and their performance in terms of thermal comfort and air quality have been systematically discussed in [239].

Radiant heating and cooling systems can be applied in almost all climates and building types. The main challenge for using radiant cooling systems is avoiding condensation; therefore, its applications in humid climate zones require careful design and operation considerations. Studies have shown that when properly designed, controlled, and coupled with an appropriate ventilation system, radiant cooling systems can also be applied in hot-humid climate zones without problems [240–243].

Radiant systems have similar characteristics under heatwaves and power outages. The absorptive and adaptive capacities of radiant systems under heatwaves and power outages range from low to high - low for radiant ceiling panels, high for TABS, and in between those two systems for the radiant surface systems. This is because these systems have different amounts of thermal mass, and, therefore have different operations, heat removal, and heat storage characteristics. For example, due to the available thermal mass, TABS can provide cooling even if there is no active heat removal from the TABS structure for a period (e.g., no chilled water circulation in the pipes in case of a power failure) and under a heatwave, the pre-cooled thermal mass will be able to absorb a certain amount heat from the space.

The restorative and recovery capacities of radiant systems under heatwaves and power outages are high. This is because all system types have the ability to return to normal or improved operation once the heatwave is over or power is back, and this can be done immediately.

The previously described radiant cooling systems (i.e., radiant cooling panels, radiant surface systems, and TABS) are available in the market. These systems and their components can be purchased by building owners (e.g., for a residential building) and also by building contractors. Note that, whereas the radiant ceiling panels with PCMs that were described in this chapter, are not yet available in the market, all of their individual components are market available (i.e., PCMs, piping, and metal panels).

4.3. Enhance personal comfort apart from space cooling: Personal comfort system

A personal comfort system (PCS), also known as personalized conditioning system, is a device to heat and/or cool individual occupants directly or heat and/or cool the immediate thermal environment of an individual occupant, under the control of the occupant without affecting the thermal environment of other occupants [244].

In contrast to total volume systems which condition entire indoor spaces, PCS devices condition the immediate surroundings of the occupants, creating micro-environments that can (1) extend the range of temperatures that is generally perceived as comfortable, thereby reducing the energy used by mechanical space conditioning; and (2) accommodate the interpersonal thermal differences that are inherent in any occupancy, thereby increasing the percentage of comfort in the space over that possible with uniform environmental control. The improved comfort may also increase occupants' productivity.

Cooling PCS devices may involve the following technologies:

- Vertical-axis ceiling fans and horizontal-axis wall fans (such fixed fans differ from pure PCS devices in that they may be operated under imposed central control or under group or individual control)
- Small desktop-scale fans or stand fans
- Furniture-integrated fan jets
- Devices combining fans with misting/evaporative cooling

- Cooled chairs, with convective/conductive cooled heat absorbing surfaces
- Cooled desktop surfaces
- Workstation micro-air-conditioning units including personalized ventilation, some including phase change material storage
- Radiant panels (these are currently used less for PCS than for room heat load extraction)
- Conductive wearables
- Fan-ventilated clothing ensembles
- Variable clothing insulation: flexible dress codes, variable porosity fabrics.

PCS devices offer both comfort and energy benefits. PCS devices use very small amounts of energy, making them inherently suitable for resilience applications and adaptable for use during energy emergencies. PCS devices allow occupants to personally control their thermal microenvironments and thereby satisfy their individual comfort requirements. Such comfort requirements differ due to variations in gender, age, body mass, clothing habits, and metabolic rate, and thermal adaptation [245]. The only published case of a field study of office workers reporting 100% satisfaction involved PCS installed in each workstation [246]. In a large-scale field study, Kroner and Stark-Martin [247] suggested that it is possible to increase productivity by at least 2% using PCS.

PCS devices offer an opportunity to save HVAC energy in buildings. Since it is possible to relax the room temperature range in either the hot or cold direction due to the use of personalized heating, ventilation or cooling, total HVAC energy use can be reduced at a rate of 10% per K room temperature setpoint relaxation [248,249]. Savings of this magnitude exceed those of virtually any energy-conserving technology available in the industry. Widening the temperature range for energy must continue to ensure occupants' comfort, or at least provide the same level of comfort as in current buildings. Occupants themselves require far less energy to heat and cool than does the entire indoor space that houses them. PCS offers the opportunity to accomplish this. With small amounts of energy, it can provide individual comfort within a broader range of indoor ambient temperatures (varying over both time and space).

The application of PCS enables relaxing the temperature requirements for the ambient zones in buildings. This is based on the assumption that the occupants have available to them individually controlled PCS devices at their workstations and that there is general elevated air movement provided in other zones of the building where they may spend time. Advantages for resilience include

- Flexibility in space heating and cooling temperature setpoints - the possibility of extended setpoints compared to traditional systems such as extending the room temperatures below 20 °C in the heating season and extending the room temperatures above 26 °C in the cooling season; these temperatures are based on the Category II of EN 16798–1:2019 [250]. This possibility will allow operating flexibility and will not load the cooling plant unnecessarily during an extreme event (e.g., a heatwave) or coming back to normal operation after an extreme event, and occupants can still be comfortable at high indoor temperatures, as they would have personalized cooling systems.
- Possibility of reduced-size cooling plant or a plant that is run part-time during periods beneficial to the electricity grid and supply sources.

PCS devices have no absorptive capacity under heatwaves, as absorptive capacity mainly relates to building envelope and structure. Under heatwaves, PCS devices have a high adaptive capacity as PCS or the user controlling the PCS can adjust its cooling output until its maximum capacity.

PCS devices have no absorptive capacity under power outage events, as absorptive capacity mainly relates to building envelope and structure. Assuming that there are no batteries or emergency power generators during the power outage, PCS have a low adaptive capacity as only certain PCS technologies will be able to keep on functioning (such as conductive wearables, fan-ventilated clothing ensembles or PCM assisted PCS).

PCS devices have high restorative and recovery capacities under heatwaves and power outage events, as the PCS will be functioning normally once the heatwave or power outage is over, and it will be able to recover immediately as long as the system has not been physically damaged.

PCS devices are applicable in all climate zones. The above-listed PCS devices are commercially available; however, their availability could change from country to country. Even though there are commercially available products, the technology is not as mature as some of the other technologies e.g., compression refrigeration.

4.4. Remove latent heat from indoor environments: High-performance dehumidification including desiccant dehumidification

Removing latent heat from indoor environments through dehumidification is an essential and important method, especially in hot and humid climates, to reduce cooling load and increase human comfort [251]. In high-performance buildings, the percentage of dehumidification energy consumption from the building's total energy consumption can be as high as 13–22 % [252]. There are many dehumidification methods reported in the literature and applied in practice, including desiccant dehumidification, refrigeration dehumidification, ventilation dehumidification, and thermos-electric dehumidification. Desiccant dehumidification is to utilize the humidity-absorbing material to absorb moisture. Refrigeration dehumidification uses a conventional vapor compression cycle to dehumidify the humid air through cool-reheat processes. Thermos-electric dehumidification is to utilize the thermoelectric effect (Peltier effect) to convert electricity into a temperature difference across a Peltier module. The module includes cold-side heat sink and hot-side heat source. Humid air driven by the fan flows over the cold side heat sink and the air is dehumidified. Ventilation dehumidification replaces humid indoor air with dry outdoor air.

Dehumidification technologies absorb the impacts of heatwaves by decreasing the humidity of indoor air, which improves the comfort level and relieves part of the pressure of other cooling systems. Desiccant refrigeration (see Section 4.2.4) and thermos-electric dehumidification technologies work in principle in areas with humidity higher than comfort level, while ventilation dehumidification technology works in areas with dry outdoor air. Desiccant, refrigeration, thermoelectric dehumidification, and mechanical ventilation dehumidification each require electricity and therefore are not very robust to power outages. Ventilation dehumidification through natural means could operate during a power outage, but its capacity to remove latent heat depends on building characteristics, local climate, and occupant behavior (see Section 4.2.1). Although dehumidification technologies could improve the thermal comfort level during a heatwave or recovery the thermal condition after a heatwave, their cooling capacity is limited due to the fact, they only take care of the latent heat in the indoor environment.

All these technologies have been well developed and commercial products are available in the market in the forms of either large dehumidification plants or small household dehumidifiers. Both individual consumers and building contractors are quite free to purchase dehumidification products, although the desiccant dehumidification plants are usually purchased by building contractors.

5. Assessment and comparison of resilient cooling strategies

A qualitative assessment of the resilience of cooling strategies is performed based on the criteria developed in Section 2. The resilience criteria include absorptive capacity, adaptive capacity, restorative capacity and recovery speed. Different disruptions or extreme events will have different effects on the cooling systems. 'Temperature hazard' was identified as the primary risk associated with the cooling strategies in buildings, which represents the overheating risk in buildings that threatens human health, activities and productivity [253]. Heatwave and associated power outages are identified as major disruptions because they have direct impacts on the thermal environment of buildings and they are listed as dominant threats faced by cooling systems, as stated by Attia et al.[23]. Therefore, the four resilient cooling criteria are evaluated separately for two extreme events in this study: heatwave or power outage. The resilient cooling strategies assessment framework is illustrated in Fig. 4.

We present the following approach to evaluate the resilience characteristics.

- **Absorptive capacity** can be calculated as the ratio of the absorbed heat load (or heat storage) to the change in heat load during a certain disruption.
- **Adaptive capacity** can be calculated as the ratio of the heat load reduction to the change in heat load during a certain disruption.
- **Restorative capacity** can be calculated as the ratio of the heat removed from the building to the heat stored after a certain disruption.
- **Recovery speed** can be calculated as the time required to remove the stored heat from a building until reaching a designed thermal condition.

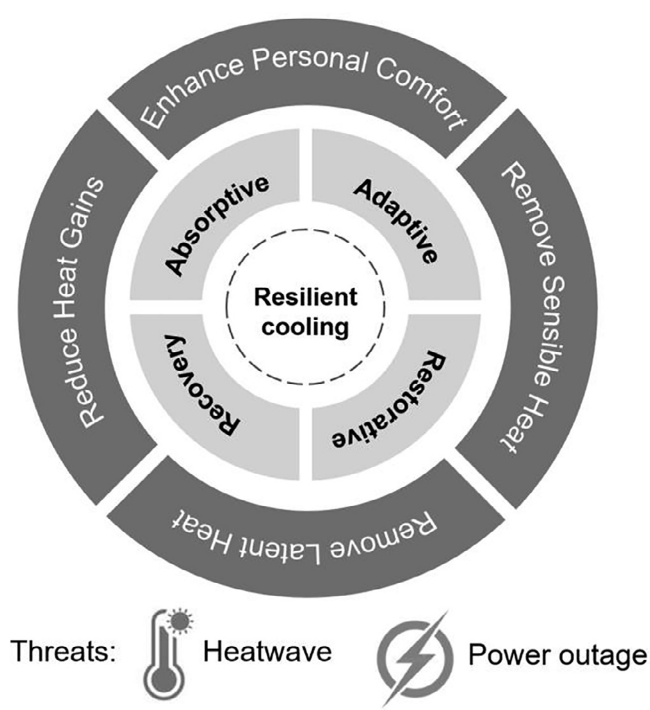

Fig. 4. Resilient cooling strategies assessment framework.

The resilience capacities can be evaluated into three categories: high, moderate and low. For recovery speed, high is within one hour, moderate is several hours, and low is one or more days. The other capacities are categorized by the following criteria:

- High: the strategy can maintain or even increase its cooling or heat-load-reduction capacity during a certain event. For example, a building's heat load might double during a heatwave or power outage due to the extreme high outdoor temperature or the failure of the mechanical cooling system. (The strategy can increase its cooling capacity to deal with a high heat load during a heatwave or power outage.)
- Moderate: the strategy can maintain its cooling or heat-load-reduction capacity most of the time during a certain event. (The strategy keeps the same cooling capacity during a heatwave or power outage.)
- Low: the strategy will experience a decrease in cooling or heat-load-reduction capacity during a certain event. (The strategy reduces cooling capacity during a heatwave or power outage.)

Besides the resilience capacities under extreme events, the cooling strategy's applicability in terms of climate zone and technology readiness level are summarized in Table 3. The climate zone classification is based on ASHRAE Standard 169 [254], as illustrated in Fig. 5.

A qualitative method is used in this study, which relies on the literature review carried out in Section 4 and focus group discussion. IEA-EBC Annex 80 participants were invited to provide evaluations of the resiliency capacities for all cooling strategies based on the categories proposed above. The participants are scientific and professional experts in the field of cooling technologies and building environments. The collected results were compared and discussed within the focus group based on the results of the literature review and their expertise and experience, to reach a final rating for each cooling strategy.

Table 3 presents assessment results of different cooling strategies where addresses the four resiliency criteria, application and technology readiness level. We obverse that cooling strategies contributing to reducing heat gains to the indoor environment generally show a moderate to high absorptive capacity under heatwaves. These strategies, such as solar shading/glazing, cool envelop materials, ventilated or evaporated envelop and thermal mass, mainly relate to the design of building structure and envelope, and should be considered in the early design phase of the buildings.

The cooling strategies with dynamic or flexible control present a high adaptive capacity under heatwaves. For example, a well-designed mechanical cooling system, such as compression refrigeration, absorption refrigeration, or active cooling with natural heat sink, could adjust its cooling capacity to fulfill the demand based on the change of the indoor and outdoor conditions or even prepare the system before the extreme event occurs if predictive control is available. However, active cooling systems strongly rely on the power supply and are not robust to the power outage. As mentioned in Section 4, an alternative approach to increase their robustness is to have local or on-site power production or connected to electrical or thermal energy storage. Another group of cooling strategies that show a high adaptive capacity under heatwaves is PCS devices, such as local fans, local cooled surfaces, or wearable systems. Instead of providing space cooling, these devices could enhance personal heat loss, and allow thermal comfort with higher ambient temperatures. In addition, PCS allow personal control of the microenvironment without affecting the thermal environment of other occupants. Even though PCS devices require a power supply, they could reduce cooling plant size or run part-time during periods beneficial to the electricity grid and supply sources.

Table 3
Assessment of cooling strategies, in term of resilience capacities, applicability, and technology readiness.

Cooling-strategy categories	Cooling strategies	Resilience under extreme events								Climate zone	Technology readiness level (TRL)
		Heatwave				Power outage					
		Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed	Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed		
A	Static solar shading/glazing	Low-Moderate	Low	N/A	N/A	Low-Moderate	Low	N/A	N/A	All	9
	Dynamic solar shading/glazing	Moderate-High	High	N/A	N/A	Low	Low	N/A	N/A	All	9
	Cool envelope materials	High	N/A (High for thermochromic CEMS)	N/A	N/A	High	N/A (High for thermochromic CEMS)	N/A	N/A	All (preferable for 0-4B)	Light-colored and cool-colored CEMs: 9; other CEMs: 4–6
	Green roofs, roof pond, and green facades	High	Moderate- High (Low for some plant species)	Moderate-High (Low for some plant species)	Moderate-High (Low for some plant species)	High	Moderate-High (Low for some plant species)	Moderate - High (Low for some plant species)	Moderate-High (Low for some plant species)	All	Green roofs and façades: 9 - roof ponds and evaporative systems: 4–8
	Ventilated roofs and facades	Low-Moderate	Moderate - High	Moderate-High	Moderate-High	Moderate-High for passive system; Low for activity system	Moderate for passive systems; N/A for active systems	Moderate - High	Moderate-High	All	4–9
	Thermal mass including PCMs	High	N/A	Low-High	Moderate	High	N/A	Low - High	Moderate	All (less effective 0–2)	4–9
B	Passive ventilative cooling	Low	Moderate	Moderate	Low - Moderate	Moderate-High	Moderate	Moderate	Low - Moderate	All (less effective in 0A, 0B, 1A, 1B)	9
	Active ventilative cooling	Moderate	High	High	Moderate - High	Low	N/A	High	Moderate - High		
	Adiabatic/ evaporative cooling	Moderate	High	High	Moderate - High	Moderate	Moderate	High	Moderate-High	All except 0A, 1A	9
	Compression refrigeration	N/A	High	High	High	N/A	N/A	High	High	All	9
	Absorption refrigeration including desiccant cooling	N/A	High	High	High	N/A	N/A	High	High	All (preferable 0A,1A, 2A)	9
	Passive ground source cooling	Moderate	Moderate	High	Moderate - High	High	Moderate	High	Moderate - High	All	9
	Active ground source cooling	High	High	High	Moderate - High	N/A	N/A	High	Moderate - High		
	Sky radiative cooling	N/A	N/A	Low-Moderate	Low-Moderate	N/A	N/A	Moderate	Low - Moderate	Increased performance in climates that are cold or with high seasonal variation (4, 5, 6) and dry (C, B) compared to hot and warm (2, 3) humid (A) climates.	7–9
	High-temperature cooling system: Radiant cooling	Low - High	Low - High	High	Moderate - High	Low - High	Low - High	High	Moderate - High	All	9

Table 3 (*continued*)

Cooling-strategy categories	Cooling strategies	Resilience under extreme events								Climate zone	Technology readiness level (TRL)
		Heatwave				Power outage					
		Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed	Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed		
C	Personal comfort systems	N/A	High	High	High	N/A	N/A or Low (e.g., fan-ventilated clothing ensembles)	High	High	All	5–9
D	Dehumidification including desiccant dehumidification	N/A	Moderate- High	Moderate	Moderate	N/A	N/A	Moderate	Moderate	All (preferable 0A,1A, 2A)	9

The cooling strategies used to remove sensible and latent heat present moderate to high restorative capacity. Mechanical cooling systems, such as compression refrigeration and absorption refrigeration can efficiently remove the surplus heat from the indoor environment in a timely manner regardless of the outdoor climate. However, the cooling systems utilizing natural heat sinks can remove the surplus heat only when there is a temperature difference between heat sinks and the indoor environment. Depending on the physical properties of natural heat sinks, ground-source cooling and evaporative cooling are more efficient than ventilative cooling under heatwaves. The recovery speed of cooling systems is influenced by the cooling potential (cooling capacity of mechanical systems, the temperature difference between natural heat sinks and indoor environment for natural or hybrid systems), design of the cooling system (for example, the window opening area and amount of thermal mass), and control or operation of the cooling system (for example, occupant behavior on window opening). In some situations, a certain cooling or building design might benefit to one resilience criteria but results in a negative impact on the other criteria. For example, a building with heavy thermal mass might have a high absorptive capacity, but have a low recovery speed due to all the stored energy that needs to be removed before the indoor environment can return to acceptable thermal conditions.

6. Discussion

6.1. Findings and recommendations

This section presents the primary findings of this study and provides recommendations to the building designers and engineers on how to address resiliency characteristics in the early design stages.

1. Resilience should be considered as an important property for cooling systems integrated with the building, together with energy efficiency, sustainability and economic affordability. Energy efficient cooling strategy does not equal to resilient cooling strategy. Sometimes, "Excessive striving for energy efficiency" could compromise a building's ability to maintain comfortable thermal conditions during extreme events.
2. The resilient characteristics of cooling strategies are summarized by four criteria – absorptive capacity, adaptive capacity, restorative capacity and recovery speed. The definition of the criteria and a qualitative approach for evaluating the resilience characteristics are proposed in this study.
3. As suggested by Attia et al. [23] and Miller et al. [253], the assessment of resilience must be based on the identification of a specific threat or disruption. 'Temperature hazard' is identified as the primary risk associated with the cooling systems in buildings, and heatwave and associated power outages are identified as major disruptions since they have direct impacts on the thermal environment of buildings.
4. Cooling strategies for reducing heat gains to the indoor environment present high absorptive capacity under heatwaves. These cooling strategies strongly relate to the design of building structure and envelope, and should be considered in the early building design phase. Cooling strategies with dynamic or flexible control present a high adaptive capacity under heatwaves. These strategies could adjust their operating mode depending on the indoor and outdoor condition or even prepare the systems or buildings before the extreme event occurs. PCS devices also present high adaptive capacity, which could allow thermal comfort with relatively higher ambient temperatures and provide personal control over the microenvironment without affecting the thermal environment of other occupants. Cooling

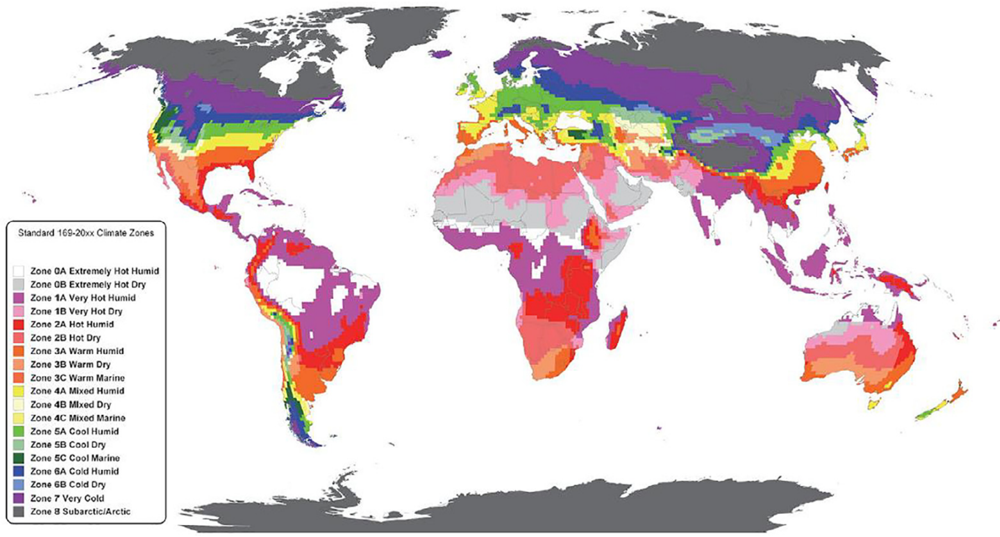

Fig. 5. Climate zone classification scheme used in ASHRAE Standard 169 [254]

strategies for removing sensible and latent heat present high restorative capacity. The mechanical cooling systems can remove surplus heat from the indoor environment efficiently without being influenced by the outdoor climate. For those cooling strategies that use natural heat sinks, such as air, water, ground and sky, the temperature difference between the heat sink and indoor environment is critical for the efficiency of these cooling strategies. The recovery speed (rapidity) of cooling strategies depends on multiply factors, such as cooling potential, design of the cooling system and control or operation of the cooling system.

5. To attain resilient cooling, the four resilience criteria should be considered from the design phase. The building and relevant cooling system characteristics should be considered simultaneously to withstand extreme events. The literature review indicates that a single cooling strategy normally does not contain all the capacities or high levels of capacities. Therefore, a combination of cooling strategies with different capacities might be needed to obtain resilient cooling, and there may not be a universally optimal solution as certain cooling strategies might perform better in certain climates.

6.2. Limitation and future directions

The study applies a qualitative approach to assess the resilience of various cooling strategies. Some limitations observed by using the qualitative approach, are explained below.

First of all, the amount of literature that discussed the resilience of cooling strategies under extreme events is limited. The literature review indicated that resilience is still a relatively new concept for the development, characterization and evaluation of cooling strategies. The current researches strongly focus on the energy efficiency and performance of the system under 'typical' operating conditions. However, the systems perform and respond to the disruptions, and the strategies for increasing the system resilience require future research. Secondly, the literature studies analyzed cooling performance under very different boundary conditions, from weather datasets, reference building, system design and operation, to performance indicators, which is difficult to conduct a direct comparison between different cooling strategies based on the results of these studies. Finally, the resiliency capacities proposed in the current study are qualitative and theoretical concepts. Even though we proposed categories for evaluation (low, moderate and high), the outcome is a rather subjective assessment of resilience than reaching an objective measure.

As a consequence, it is a challenge to provide a concrete assessment and direct comparison between different cooling strategies based on the qualitative approach. There is a strong need for a more technical or quantitative resilience assessment methodology. A numerical approach with consistent and measurable metrics for the characterization of resilience capacities will be the further direction of Annex 80.

7. Conclusions

Resilience should be considered as an important property of the cooling systems integrated with buildings, to cope with extreme events such as heatwaves and power outages. This study performs a systematic literature review on the state-of-the-art of cooling strategies, with special attention to their performance under extreme events. A definition of resilient cooling is developed and four criteria are proposed to describe resilience characteristics, including absorptive capacity, adaptive capacity, restorative capacity, and recovery speed. The developed resilience characterization scheme is used to assess the resilience of various cooling strategies qualitatively.

The literature review indicates that resilience capacities depend on many parameters: the function of cooling strategies (reducing heat gains, removing sensible/latent heat, or enhancing personal comfort), the driven forces (passive or active), design feature, and control and operation of the cooling system. A single cooling strategy normally does not contain all the resilience capacities, therefore, a combination of cooling strategies with different capacities is important to obtain resilient cooling of buildings.

The limitation of the qualitative resilience assessment approach is discussed. There is a strong need for a quantitative assessment framework with specified boundary conditions and consistent and measurable performance indicators. A numerical-based approach will be developed and discussed in further study.

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.

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