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Resilient Cooling of Buildings

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1 Introduction

The world is facing a rapid increase of air conditioning of buildings, leading the International Energy Agency (IEA) to refer to this phenomenon as the "cooling crunch". This is driven by multiple factors, such as urbanization and densification, climate change and elevated comfort expectations together with economic growth in hot and densely populated regions of the world. The trend towards cooling seems relentless therefore it is needed to guide users towards sustainable solutions. Simultaneously the importance of enhancing the built environment's ability to withstand climate change impacts and related disruptions has garnered growing interest in recent times. Against this background, it was the motivation of IEA EBC Annex 80 to develop, assess and communicate solutions of resilient cooling and overheating protection. Annex 80's main objective is to support a rapid transition to an environment where resilient low energy and low carbon cooling systems are the mainstream and preferred solutions for cooling and overheating issues in buildings [1] [2] [3].

2 What is Resilient Cooling?

The existing literature offers a variety of definitions of resilience. In the context of building cooling and with a focus on climate change and climate change adaptation, the following definition was developed as part of IEA EBC Annex 80: "*Resilient cooling is defined 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)* [1]."

2.1 *Stages of Resilience and Key Concepts*

Attia et al. [1] demonstrate that resilience in buildings is a process that involves several stages, including vulnerability, resistance, robustness, and recoverability. Figure 1 presents an overview of the definitions and their interconnections.

The first stage is **vulnerability**. This includes a design that considers future climate scenarios and prepares the building system to adapt against failures. The vulnerability assessment should examine the building's performance in the context of long-term disruptions, encompassing average, extreme, future and the most extreme future weather conditions. Additionally, the assessment should evaluate the building's resilience to short-term disruptions, including brief heat waves and power outages. It is recommended to perform a vulnerability assessment stage into the design process.

The second stage is **resistance**, which involves the ability and the depth of reaction to the disruptive event or shock.

The third stage is **robustness**, which is the most crucial stage after the buildings cooling system's failure due to a disruptive event. The robustness of a building is inherently linked to its capacity to withstand an adverse shock that would otherwise result in its complete collapse. This resilience is achieved through the building's ability to adapt its performance in response to such a shock. A robust building will initially fail, but then adapt its performance conditions to meet critical or minimum thermal requirements.

The fourth and final stage is **recovery**. The concept of recoverability encompasses the extent and nature of occupants and building services to recover, as well as the speed at which they return to their design thermal conditions.

The diagram in Figure 1 is a linear representation of the resilience process, however, the resilience cycle is in fact iterative and cyclical.

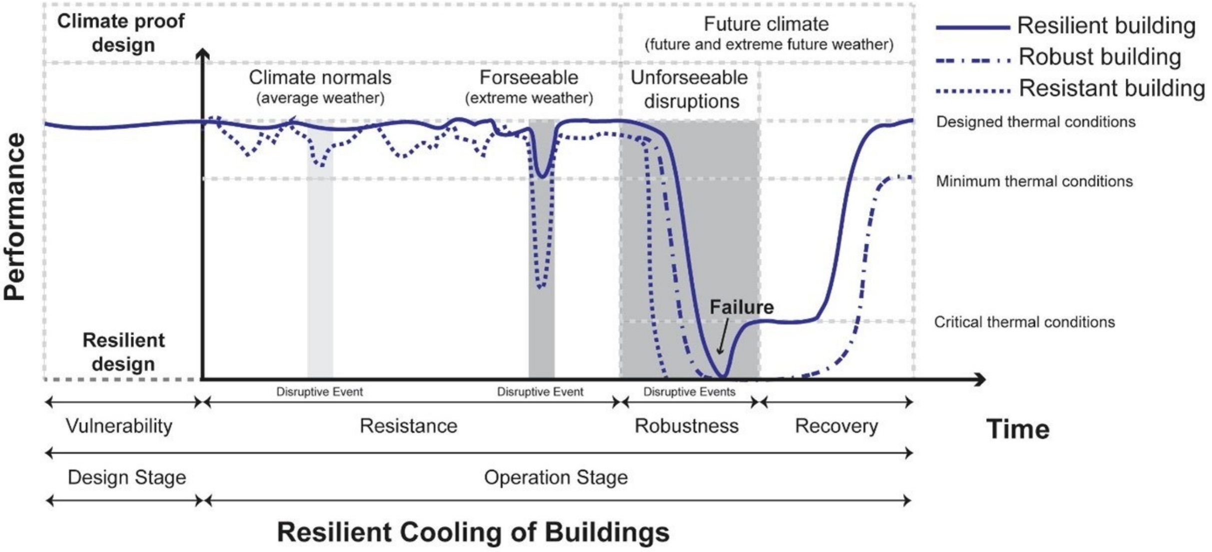

Figure 1 : The components of a resilience definition within a specific field or domain according to Attia et al. [1]

2.2 *Resilience Performance and Qualitative Technology Assessment*

While the above-described stages of resilience focus on the building scale, Zhang et al. [4] conducted a comprehensive review of the current state of cooling technologies, with a particular focus on their individual performance when heat waves and power outages occur. Based on an extensive literature research, the following four capacities to assess the resilience of cooling technologies were defined:

Absorptive capacity can be described as the ability of a technology to absorb the impacts of disruptive events and minimize their consequences with minimal effort. An example of this can be seen in the use of heavy thermal mass in a building, which 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 of a cooling technology to modify unfavourable situations through the implementation of changes. The system is able to learn from the event, evaluate its performance and modify its configurations, thereby making it more flexible in the face of future disruptions. Adaptive capacity is distinguished from absorptive capacity, in that adaptive systems undergo change in response to adverse impacts, particularly if the absorptive capacity has been exceeded. For instance, a solar shading may be deployed when the air temperature in the building begins to rise due to the storage capacity of the thermal mass being exceeded.

Restorative capacity refers to the capacity to return to a state of normal or enhanced functionality. For instance, night cooling can eliminate the accumulation of unwanted heat that occurs within the thermal mass during the day, acting as a heat sink for the following day.

Recovery time is the speed (or rapidity) with which the restorative capacity can be achieved. Recovery may potentially be accelerated if the implementation of absorption activities is well executed, and the system can mobilize and effectively utilize all the resources at its disposal. For instance, the rate at 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.

3 Resilient Cooling Technologies

IEA EBC Annex 80 has identified four distinct resilient cooling strategies, each of which is characterized by a specific approach to cooling people or the indoor environment:

A. Reducing heat gains to the indoor environment and people environments.

B. Removing sensible heat from the indoor environment.

C. Enhance personal comfort apart from space cooling.

D. Removing latent heat from the indoor environment.

3.1 *Reducing Heat Gains to the Indoor Environment and People Environments*

Solar Shading Technologies refer to a range of methods and devices designed to control the amount of solar radiation entering a building through the transparent surfaces of the building envelope. The application of shading systems serves to reduce both the peak and average cooling loads. Furthermore, the use of shading devices in buildings can serve to mitigate extreme indoor thermal conditions. In addition to these benefits, the reduction in indoor air and mean radiant temperatures that is achieved through the use of shading devices also serves to enhance the thermal comfort of building users. An additional advantage is the protection from direct sunlight that the structure provides.

Glazing Technologies are designed to limit the transmission of heat into indoor spaces while optimizing the access of natural daylight. This is achieved by the absorption, transmission, and reflection of solar radiation, which is dependent on the materials used in the glass and glazing system.

Ventilated Façades are defined by Loncour et al. [5] as *"... a traditional single facade doubled inside or outside by a second, essentially glazed facade. Each of these two facades is commonly called a skin. A ventilated cavity - having a width which can range from several centimeters at the narrowest to several meters for the widest accessible cavities – is located between these two skins"*. Façade ventilation can prevent the accumulation of heat from opaque or transparent components. They serve to mitigate the effects of external heat gains, which are mainly derived from convective heat transfer with outdoor air, longwave radiation between the envelope and the external environment (building, street, and sky), and solar heat gain during the day.

Cool Envelope Materials are a roof or exterior wall products whose elevated solar reflectance and high thermal emittance keep it cooler in the sun than a conventional roof or wall. The application of cool roofs and walls has the effect of reducing radiative heat gain at the building's opaque envelope, thereby decreasing the flow of heat into the conditioned space. This results in a reduction in cooling energy use or a lowering of the temperature inside the building.

Green Roofs and Green Façades represent cooling solutions that primarily rely on evapotranspiration from plants and substrate. The cooling potential of these solutions is contingent upon several factors, including the water retention capacity, water supply, plant species, and vegetated envelope typologies. Additionally, the plants provide solar shading, while the substrate contributes to the thermal insulation and thermal mass of the building envelope. On the external side of the building, the evaporative cooling effect prevents heat gains through the building envelope. The evaporative process absorbs the sensible heat fluxes that are derived from solar irradiance, conducted heat flux, and convective heat flux with outdoor air.

Table 1 summarizes the assessment of the technologies in this technology group in terms of qualitative resilience performance. For more information, please refer to [4] *"Resilient cooling strategies - a critical review and qualitative assessment"* by Zhang et al. (2021).

Table 1 : Assessment of cooling strategies for technology group "Reducing Heat Gains to the Indoor Environment and People Environments" in terms of resilient capacities, modified on basis of Zhang et al. [4]

Cooling strategies	**Heat wave**				**Power outage**			
	Absorptive capacity	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**	**Absorptive capacity**	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**
Solar shading technologies	Low-Moderate	Low	N/A	N/A	Low-Moderate	Low	N/A	N/A
Glazing technologies	Moderate-High	High	N/A	N/A	Low	Low	N/A	N/A
Ventilated Façades	Low-Moderate	Moderate-High	Moderate-High	Moderate-High	Moderate-High for passive systems; Low for active systems	Moderate for passive systems; N/A for active systems	Moderate-High	Moderate-High
Cool envelope materials	High	N/A	N/A	N/A	High	N/A	N/A	N/A
Green Roofs and Green Façades	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)

3.2 Removing Sensible Heat from the Indoor Environment

Ventilative Cooling is defined as the utilization of the cooling capacity of the outdoor airflow through ventilation to reduce or even eliminate the cooling loads and/or the energy consumption by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment. The driving force of the airflow can be either natural, mechanical or a combination of the two (hybrid ventilation).

Thermal Mass Utilization. Thermal mass materials, such as heavy construction materials, are frequently employed to absorb and store heat during the summer months when outdoor temperatures are higher than indoor temperatures. This stored heat is released at night when outdoor temperatures are lower than indoor temperatures, effectively functioning as a thermal battery. The implementation of thermal mass in a building can contribute to reduced peak heating and cooling loads and minimize fluctuations in indoor air temperature. This allows the heating and cooling loads to be distributed over a greater number of hours, thereby reducing the demand for peak electricity. Furthermore, it improves thermal comfort in buildings.

Evaporative Cooling is a cooling technique that employs the latent heat of vaporization of water to reduce the temperature of air drawn in from outside. Evaporative cooling systems may be an effective method to significantly reduce dry bulb temperatures in a space, which can help achieve comfort conditions without the need for additional cooling sources. Evaporative cooling systems are typically cost-effective and, when the local wet bulb temperature is sufficiently high, facilitate cooling and airflow with a limited amount of energy. However, they require significant maintenance to prevent the growth of microorganisms and associated diseases, such as legionella. It is therefore essential to regulate evaporative cooling systems in order to prevent the accumulation of high levels of relative humidity within the space.

Sky Radiative Cooling represents a phenomenon whereby 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. Radiative cooling represents a renewable technology, which harnesses the free cooling energy of the sky. The phenomenon of radiative cooling of the sky is most prevalent during nighttime, when there is no additional heat gain from the incident solar radiation. Other environmental parameters that influence the radiative cooling potential of the sky include air temperature, humidity, air speed, and clouds. An outdoor air temperature higher than the object's temperature reduces the net cooling potential, while a lower one increases it.

Natural Heat Sinks. Heat sinks are media that can be employed to directly absorb unwanted heat discharge from buildings, including ambient air, ground (water), and surface water bodies. Cooling systems utilizing natural heat sinks can be operated without mechanical cooling, whereby only pumps or fans are employed to circulate the cooling medium. Alternatively, refrigeration machines can be used to amplify the natural heat sink's cooling effect.

Compression Refrigeration appliances utilized for domestic cooling purposes operate via a thermodynamic cycle process. This cycle process makes use of the thermal energy transported within the refrigerant, which is absorbed via the process of evaporation and released via the process of condensation. To utilize the cooling effect the evaporator is situated within or coupled to the indoor environment to be cooled. In contrast, the condenser is placed within or coupled to the heat sink with which it is intended that any discarded heat from the cooling process should be absorbed. In the majority of cases, the heat sink is the outdoor air. However, other media with superior thermal transmission, such as the ground or groundwater can also be utilized.

Adsorption Chiller could be described as a thermally driven heat pump. A basic adsorption chiller comprises four main components: adsorbent beds, a condenser, an evaporator, and an expansion valve. Adsorption chillers are an efficient system that can convert heat from a heat source such as solar, geothermal, or any waste heat application into cooling or heating without the use of electricity.

Radiant Cooling operates by utilizing water as the heat transfer medium, with a minimum of half of the heat exchange with the conditioned space being conducted by radiation. The transfer of heat from indoor spaces is accomplished through a combination of radiation and convection via cooled surfaces.

Table 2 summarizes the assessment of the technologies in this technology group in terms of resilient capacities. For more information, please refer to [4] *"Resilient cooling strategies - a critical review and qualitative assessment"* by Zhang et al. (2021).

Table 2 : Assessment of cooling strategies for technology group "Removing Sensible Heat from the Indoor Environment" in terms of resilient capacities, modified on basis of Zhang et al. [4]

Cooling strategies	**Heat wave**				**Power outage**			
	Absorptive capacity	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**	**Absorptive capacity**	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**
Ventilative cooling	Moderate	High	High	Moderate-High	Low	N/A	High	Moderate-High
Thermal Mass Utilization	High	N/A	Low-High	Moderate	High	N/A	Low-High	Moderate
Evaporative Cooling	Moderate	High	High	Moderate-High	Moderate	Moderate	High	Moderate-High
Sky Radiative Cooling	N/A	N/A	Low	Low-Moderate	N/A	N/A	Moderate	Low-Moderate
Compression Refrigeration	N/A	High	High	High	N/A	N/A	High	High
Adsorption Chiller	N/A	High	High	High	N/A	N/A	High	High
Natural Heat Sinks	Moderate-High	Moderate-High	High	Low-High	High for passive systems; N/A for active systems	Moderate for passive systems; N/A for active systems	High	Moderate-High
Radiant Cooling	Low-High	Low-High	High	Low-High	Low-High	Low-High	High	Low-High

3.3 *Enhance Personal Comfort apart from Space Cooling*

Comfort Ventilation and Elevated Air Movement refers to the deliberate control and circulation of indoor or outdoor air within indoor spaces, the objective of which is to enhance thermal comfort for occupants. This technology increases the range of temperatures that are usually considered comfortable, which consequently decreases the amount of energy used by mechanical air conditioning. The lower the incoming air temperature, the more effective comfort ventilation will be. Additionally, elevated air movement systems aim to create a gentle and subtle breeze, which replicates the natural airflow experience that can be observed outdoors. Furthermore, elevated air movement helps to remove of air stratification in a given space.

Micro-Cooling and Personal Comfort Control. A personalised environmental control system (PECS) is a device under the control of the occupant that is used to condition the individual or its immediate environment (microenvironment) without affecting the environment of other occupants. PECS can be equipped with heating, cooling, and even ventilation (fresh air) functions. A variety of cooling PECS devices are available, including vertical-axis ceiling fans, horizontal-axis wall fans, small desktop-scale fans, and stand fans, among others. For more information on PECS refer to IEA EBC - Annex 87 [6].

Table 3 summarizes the assessment of "Micro-Cooling and Personal Comfort Control" in terms of resilient capacities. "Comfort Ventilation and Elevated Air Movement" was not assessed. For more information, please refer to [4] *"Resilient cooling strategies - a critical review and qualitative assessment"* by Zhang et al. (2021).

Table 3 : Assessment of "Micro-Cooling and Personal Comfort Control" in terms of resilient capacities, modified on basis of Zhang et al. [4]

Cooling strategies	**Heat wave**				**Power outage**			
	Absorptive capacity	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**	**Absorptive capacity**	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**
Micro-Cooling and Personal Comfort Control	N/A	High	High	High	N/A	N/A or Low (e.g., fan ventilative clothing ensembles)	High	High

3.4 *Removing Latent Heat from the Indoor Environment*

Dehumidification. The removal of latent heat from indoor environments through dehumidification of indoor air and of supply outdoor air is an essential and important method, especially in hot and humid climates, to reduce the cooling load and to increase thermal comfort. In hot and humid climates, conventional air conditioning systems alone might not be able to provide the desired thermal comfort conditions. In such climates, it is necessary to distinguish between the cooling requirements for sensible cooling capacity (temperature control) and latent cooling (humidity). The dehumidification process is the removal of moisture, water vapor or humidity from the air, thereby maintaining a constant dry bulb temperature.

Table 4 summarizes the assessment of "Dehumidification" in terms of resilient capacities. For more information, please refer to [4] *"Resilient cooling strategies - a critical review and qualitative assessment"* by Zhang et al. (2021).

Table 4 : Assessment of "Dehumidification" in terms of resilient capacities, modified on basis of Zhang et al. [4]

Cooling strategies	Heat wave				Power outage			
	Absorptive capacity	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**	**Absorptive capacity**	**Adaptive capacity**	**Restorative capacity**	**Recovery capacity (rapidity)**
Dehumidification	N/A	Moderate - High	Moderate	Moderate	N/A	N/A	Moderate	Moderate

4 Discussion

The ever-increasing demand for cooling in buildings, coupled with the impact of climate change and disruptive events, such as heatwaves and power outages, presents a growing global necessity for sustainable and resilient cooling. Resilient cooling is defined as a building cooling system's capacity to withstand and recover from disruptive events, such as heatwaves and power outages, and to implement post-failure strategies that maintain indoor comfort quality and effectively manage energy demand.

The application of cooling strategies to reduce heat gains to the indoor environment and people environments is particularly effective in mitigating the impact of heat waves (high **absorptive capacity**). These strategies are highly dependent on the structural and envelope design of a building, which should therefore be considered at an early stage of the design process. The application of cooling strategies to remove sensible heat from the indoor environment also demonstrates a high level of **absorptive capacity** during power outages.

The implementation of cooling strategies with dynamic or flexible controls, for example such as compression refrigeration or adsorption chillers, increases the **adaptive capacity** under heatwaves. These strategies are capable of adjusting their operating mode in accordance with the prevailing indoor and outdoor conditions, or even of preparing the systems or buildings in advance of the extreme event. Micro-Cooling and Personal Comfort Control devices also exhibit a high **adaptive capacity**, which allows thermal comfort to be maintained at relatively higher ambient temperatures and provides personal control over the microenvironment without affecting the thermal environment of other occupants.

The implementation of cooling strategies to remove sensible heat from the indoor environment and micro-cooling and personal comfort control systems present a high potential for **restorative capacity**. The utilization of mechanical cooling systems enables the efficient removal of surplus heat from an indoor environment, independent of the prevailing outdoor climate. For those cooling strategies that utilize natural heat sinks, such as air, water, ground and sky, the temperature differential between the heat sink and the indoor environment is a crucial factor in the efficacy of these cooling strategies.

The efficacy of cooling strategies in **recovery capacity** (rapidity) is influenced by a multitude of factors, including the cooling potential, the design of the cooling system and the control or operation of the cooling system. Among others, personalised environmental control systems and compression refrigeration offer a high recovery capacity.

5 Conclusion

To achieve resilient cooling, it is essential that the four resilient capacities are considered during the design phase, along with the specific characteristics of the building in question and the selected cooling strategy. This allows for the simultaneous consideration of the resilience-related characteristics of the cooling strategy itself, in addition to the resilience-related characteristics of the building and its surroundings.

It is important to note that a single cooling strategy rarely encompasses the entirety of these capacities. Therefore, it may be necessary to combine cooling strategies with different capacities in order to achieve resilient cooling. Additionally, the notion of a universally optimal solution may not exist, as certain cooling strategies may be more effective in specific building typologies and under certain climatic conditions.

6 Further reading

As part of Annex 80, numerous publications have been produced that deal with resilient cooling, offering a thorough and detailed analysis. For further details on all resilient cooling technologies, please refer to the following sources:

IEA EBC Annex 80: Resilient Cooling of Buildings - State of the Art Review summarizes an assessment of current State-of-the Art resilient cooling strategies and technologies. Accessible at https://www.building-research.at/1052776/coxk4763/.

IEA EBC Annex 80: Resilient Cooling of Buildings - Technology Profiles Report offers a collection of 16 technologies, well suited to form a part of resilient cooling solutions of Buildings. The document is intended as a comprehensive source of information for those responsible for making decisions regarding building design, encompassing both retrofitting and new construction. Accessible at https://www.building-research.at/1052776/hftr4661/.

IEA EBC Annex 80: Resilient Cooling of Buildings – Field Studies Report and the associated brochures provide examples of well-documented field studies. These field studies apply resilient cooling technologies to reduce energy demand and carbon emissions for cooling and reduce the overheating risk in different types of buildings, including newly constructed and existing buildings. The report and the brochures include examples and details on building information, energy systems, resilient cooling technologies, key performance indicators (KPIs), and performance evaluation and lessons learned. Accessible at https://www.building-research.at/1052776/jiit7246/.

Resilient Cooling Design Guidelines published as a REHVA-Guidebook addresses both free-running and mechanically cooled buildings and aims to answer the question of how to design a "resilient cooling" building. It presents the underlying concepts of resilience regarding buildings, the available technological solutions, and the methods and tools used to evaluate options. Accessible at https://www.rehva.eu/eshop/detail/resilient-cooling-design-guidelines.

IEA EBC Annex 80: Resilient Cooling of Buildings – Policy Recommendations proposes passive or low-energy cooling strategies for buildings that enhance resilience to heat waves and/or power grid failure. Each recommendation serves as a foundation for the development of a comprehensive solution. Accessible at https://www.building-research.at/1020357/b7288c/.

All publications on resilient cooling can also be accessed via the following website: https://annex80.iea-ebc.org/publications.

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