REHVA

EUROPEAN GUIDEBOOK

Resilient Cooling Design Guidelines

EBC

Energy in Buildings and
Communities Programme

IEA-EBC Annex 80 “Resilient Cooling of Buildings”

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Federation of European Heating, Ventilation and Air Conditioning Associations

REHVA

Resilient Cooling Design Guidelines

REHVA Task Force

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Executive Summary

These guidelines are a collaborative effort between the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and the Energy in Buildings and Communities (EBC) programme of the International Energy Agency; Annex 80: Resilient Cooling of Buildings project. It draws on the expertise of scientists from diverse institutions in architecture, engineering, building science, and building physics.

The global rise in energy consumption for cooling residential and non-residential buildings, coupled with increased indoor overheating, is a pressing concern. This surge is driven by various factors, including urbanization, climate change, heightened comfort expectations, economic growth, and the accessibility of air conditioning systems. Moreover, disruptive events like extreme heat and heatwaves are becoming more frequent, expected to be commonplace by mid-century. The trajectory toward increased cooling demand is undeniable, necessitating a shift toward sustainable solutions.

Resilient cooling aims to mitigate heat stress and maintain safe building conditions during externally induced disruptions, going beyond mere thermal comfort. This Guidebook focuses on designing cooling systems that are resilient to such challenges.

While a plethora of suitable technologies and solutions exist, many face practical and financial barriers hindering widespread adoption. Some technologies require further development to achieve readiness. Conventional design emphasizes optimizing performance within predetermined parameters, while resilient design prioritizes adaptability and risk mitigation. Resilient design demands a collaborative, innovative approach with a longer timeframe. Therefore, action is imperative for policymakers, stakeholders, researchers, professionals, and industry players.

This Guidebook aims to assist practitioners in implementing highly efficient, low-carbon, resilient cooling solutions, contributing to a sustainable built environment. It identifies key challenges, opportunities, and frameworks associated with building design, exploring innovative concepts to address these issues. It provides an in-depth analysis of various technologies, practices, and simulation approaches, with a focus on disruptive events such as heatwaves and power outages.

The main contents of this Guidebook include definitions of resilient cooling for buildings, metrics and key performance indicators, simulation tools and evaluation methods, inputs for performance assessment, frameworks for future weather data development, technological profiles of active and passive cooling solutions and components, and two demonstration case studies – one for new construction and one for existing building renovation.

The target audience includes practitioners in building design, architectural firms, building services sectors, consulting engineers, firms, national authorities, building owners, tenants, policymakers, government officers, and building services institutions. It is relevant for small and mid-size facilities, residential and commercial buildings, and both new construction and existing buildings in terms of operation, management, and maintenance.

Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies, processes, and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme (ECBCS).)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017, and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems, and processes. Future EBC collaborative research and innovation work should also focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority were extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives

The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings (including financing, engagement of stakeholders, and promotion of co-benefits);

- improvement of planning, construction, and management processes to reduce the performance gap between design stage assessments and real-world operations;

- the creation of 'low tech', robust, and affordable technologies;

- the further development of energy efficient cooling in hot and humid or dry climates, avoiding mechanical cooling if possible;

- the creation of holistic solution sets for district level systems considering energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means

The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analyses (LCA);

- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;

- improving smart control of building services technical installations, including occupant and operator interfaces;

- addressing data issues in buildings, including non-intrusive and secure data collection;

- the development of building information modelling (BIM) to increase building resilience opportunities, from design and construction through to operations and maintenance.

The themes in both groups may be the subjects of new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or parts thereof) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach this a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with ongoing (in May 2024) projects identified with an asterisk (*):

ANNEX 01: Load/Energy Determination of Buildings Completed

ANNEX 02: Ekistics and Advanced Community Energy Systems

ANNEX 03: Energy Conservation in Residential Buildings

ANNEX 04: Glasgow Commercial Building Monitoring

ANNEX 05: Air Infiltration and Ventilation Centre (*)

ANNEX 06: Energy Systems and Design Communities

ANNEX 07: Local Government Energy Planning

ANNEX 08: Inhabitant Behaviour with Regard to Ventilation

ANNEX 09: Minimum Ventilation Rates

ANNEX 10: Building HEVAC System Simulation

ANNEX 11: Energy Auditing

ANNEX 12: Windows and Fenestration

ANNEX 13: Energy Management in Hospitals

ANNEX 14: Condensation and Energy

ANNEX 15: Energy Efficiency in Schools

ANNEX 16: Building Energy Management Systems-User Interfaces and System Integration

ANNEX 17: Building Energy Management Systems - Evaluation and Emulation Techniques

ANNEX 18: Demand Controlled Ventilation Systems

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ANNEX 35: Control Strategies for Hybrid Ventilation in New and Retrofitted Office Buildings (HybVent)

ANNEX 36: Retrofitting in Educational Buildings - Energy Concept Adviser for Technical Retrofit Measures

ANNEX 37: Low Exergy Systems for Heating and Cooling

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ANNEX 39: High Performance Thermal Insulation Systems (HiPTI)

ANNEX 40: Commissioning of Building HVAC Systems for Improving Energy Performance

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ANNEX 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)

ANNEX 47: Cost Effective Commissioning of Existing and Low Energy Buildings

ANNEX 48: Heat Pumping and Reversible Air Conditioning

ANNEX 49: Low Exergy Systems for High Performance Buildings and Communities

ANNEX 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings

ANNEX 51: Energy Efficient Communities

ANNEX 52: Towards Net Zero Energy Solar Buildings

ANNEX 53: Total Energy Use in Buildings: Analysis & Evaluation Methods

ANNEX 54: Analysis of Micro-Generation & Related Energy Technologies in Buildings

ANNEX 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)

ANNEX 56: Cost-Effective Energy & CO_2 Emissions Optimization in Building Renovation

ANNEX 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction

ANNEX 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements

ANNEX 59: High Temperature Cooling and Low Temperature Heating in Buildings

ANNEX 60: New Generation Computational Tools for Building & Community Energy Systems

ANNEX 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings

ANNEX 62: Ventilative Cooling

ANNEX 63: Implementation of Energy Strategies in Communities

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ANNEX 77: EBC Annex 77 / SHC Task 61 Integrated Solutions for Daylighting and Electric Lighting

ANNEX 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications (*)

ANNEX 79: Occupant-Centric Building Design and Operation (*)

ANNEX 80: Resilient Cooling of Buildings (*)

ANNEX 81: Data-Driven Smart Buildings (*)

ANNEX 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems (*)

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ANNEX 86: Energy Efficient Indoor Air Quality Management in Residential Buildings (*)

ANNEX 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (*)

ANNEX 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings (*)

ANNEX 89: Ways to Implement Net-zero Whole Life Carbon Buildings (*)

ANNEX 90: EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting (*)

ANNEX 91: Open BIM for Energy Efficient Buildings (*)

ANNEX 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings (*)

Working Group on Energy Efficiency in Educational Buildings (EBC Annex 15)

Working Group on Indicators of Energy Efficiency in Cold Climate Buildings

EBC Annex 36 Extension Working Group

Working Group on HVAC Energy Calculation Methodologies for Non-residential Buildings

Working Group on Cities and Communities

Working Group on Building Energy Codes (*)

REHVA - Federation of European Heating, Ventilation and Air Conditioning Associations

REHVA was founded in 1963 and is a European professional federation that joins other national associations of building services engineers. Today, REHVA represents more than 120,000 HVAC designers, engineers, technicians, and experts from 26 European countries. REHVA is dedicated to the improvement of health, comfort, and energy efficiency in all buildings and communities. REHVA provides its members with a platform for international networking and knowledge exchange, contributes to technical and professional development, follows European Union policy developments, and represents the interests of its members in Europe and the rest of the world. REHVA's mission is to promote energy-efficient, safe, and healthy technologies for building mechanical services by disseminating knowledge among professionals and practitioners in Europe and beyond. The REHVA Guidebook series is amongst the most important tools used to diffuse knowledge on the latest developments and advanced technologies, providing practical guidance to practitioners. REHVA has published over 30 Guidebooks. REHVA would like to express its sincere gratitude to the authors of this Guidebook for their invaluable work.

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List of abbreviations

AC	Alternating Current
ACH	Air Change Rate
AHU	Air Handling Unit
AOS	Accurate Optimal Solutions
ASHRAE	American Society of Heating, Refrigeration and Airconditioning Engineers
ASTM	American Society for Testing and Materials
AWD	Ambient Warmness Degree
BACS	Building Automation and Control System
BB101	Building Bulletin
BEM	Building Energy Model
BI	Bayesian Inference
BPS	Building Performance Simulation
BS	British Standard
BSM	Building Simulation Model
CAPEX	Capital Expenditure
CCHP	Combined Cooling, Heat, and Power
CCOR	Climate Change Overheating Resistivity
CEM	Cool Envelope Material
CFC	Chlorofluorocarbon
CMIP6	World Climate Research Programme (6th phase)
CNG	Compressed Natural Gas
COP	Coefficient of Performance
CORDEX	Coordinated Regional Climate Downscaling Experiment
COSMO-CLM	Climate Limited-area Modelling Community
CR	Cool Roof
CWEC	Canadian Weather Year for Energy Calculation
DC	Direct Current
DHW	Domestic Hot Water
DOA	Dedicated Outdoor Air
DOE	Department of Energy (U.S.)
EER	Energy Efficiency Ratio
EN	European Standard

EPBD	Energy Performance of Buildings Directive
EPS	Emergency Power Supply
EPW	Energy Plus Weather File format
ES-SO	European Association for Solar Shading
FOS	Final Optimal Solution
GA	Genetic Algorithm
GCMs	Global Climate Models
GUI	Graphical User Interface
GWP	Global Warming Potential
He	Hours of Exceedance
HVAC	Heating Ventilation and Air Conditioning
HWY	Heat Wave Year
I/O	Input/Output
ID	Identification
IEA EBC	International Energy Agency: Energy in Building and Community Programme
IOD	Indoor Overheating Degree
IPCC	The Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LEED	Certification Scheme
MAD	Maximum Absolute Difference
MOGA	Multi Objective Genetic Algorithm
MVC	Mechanical Ventilative Cooling
NBR	Brazilian Regulation
NC	Night Cooling
NETCDF	Format Type
NMBE	Normalised Mean Bias Error
NVC	Natural Ventilative Cooling
ODP	Ozone Depletion Potential
OEF	Overheating Escalation Factor
OH	Overheating
PCM	Phase Change Materials
PCS	Personal Comfort System
PECS	Personalized Environmental Control Systems

PHHI	Percentage occupied Hours within Heat Index range
PHS	Predicted Heat Strain
PMV	Predicted Mean Vote
PPD	Percentage Persons Dissatisfied
PV	Photovoltaics
RCD	Resilient Cooling Design
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RH	Relative Humidity
RMSE	Root Mean Square Error
RSWY	Reference Summer Weather Year
SCOP	Seasonal Coefficient of Performance
SDGs	Sustainable Development Goals
SEER	Seasonal Energy Efficiency Rating
SET	Standard Effective Temperature
SHGC	Solar Heat Gain Coefficient
SRI	Solar Reflective Index
TABS	Thermo Active Building Systems
TBM	Technical Building Management
TES	Thermal Energy Storage
TMY	Typical Meteorological Year
TRL	Technology Readiness Level
TRT	Thermal Response Test
UN	United Nations
UPS	Uninterruptible Power Supply
VE	Virtual Environment
VRF	Variable Flow Refrigerant
WBGT	Wet Bulb Globe Temperature
WCRP	World Climate Research Programme
We	Weighted Exceedance
WRF	Weather Research and Forecasting
WUMTPO	Overall Weighted Unmet Thermal Performance
WWR	Window to Wall Ratio

1 Introduction

This chapter introduces the reader to the scope, concept, methodology, background information, and framework of this design guideline. It concludes with six practical tips for practitioners.

1.1 General Context

The world is seeing a rapid increase in the cooling of buildings (Dean et al., 2018). This is driven by multiple factors, such as urbanization and densification, climate change, elevated comfort expectations, and economic growth in hot and densely populated regions of the world. Additionally, disruptive events, such as extreme heat and heat waves, are occurring more often and are expected to become a common phenomenon by mid-century. The cooling demand is expected to increase in the coming years. It is therefore essential that this development is steered in toward sustainable solutions.

Given this context, this Guidebook is intended to support practitioners in implementing highly efficient, low-carbon, resilient cooling solutions, technologies, and strategies and contributing to a sustainable built environment. Resilient cooling aims to avoid heat stress for people and to maintain safe and operable conditions in buildings in the event of externally induced disruptions. It therefore goes beyond the upkeep of thermal comfort. This Guidebook focuses on the design of cooling that is resilient to such disruptions.

This Guidebook is an output of the international research project of the Energy in Buildings and Communities (EBC) programme, Annex 80: Resilient Cooling of Buildings. The knowledge is provided by a group of scientists from numerous institutions in various fields such as architecture, engineering, building science, and building physics. Further information on Annex 80 and its outcomes can be found at https://annex80.iea-ebc.org/.

1.2 Definitions of Resilience

The Sustainable Development Goals (SDGs) developed by the United Nations (U.N.) place resilience at the core of their objectives, which is reflected in a number of their targets (Jacob et al., 2018). The U.N. General Assembly Resolution 71/276 (Assembly, 2017) describes resilience as "the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management". ISO 15392 (ISO 15392:2019) characterizes resilience as the "ability to anticipate and adapt to, resist or quickly recover from a potentially disruptive event, whether natural or man-made." ISO 21931-1 (2022) defines resilience as the "ability to resist, adapt to, or quickly recover from potentially disruptive events or conditions, whether natural or anthropogenic, in order to maintain or restore the intended service." The above definitions are general, and there is a need to interpret them for a specific emergency affecting the built environment. In the context of buildings, these definitions promote the anticipation and counteraction of future disruptions and their effect on the building's structure, building services, technical equipment, and, most importantly, the definition depends on its users.

For the purposes of this guideline, a building's cooling system is considered resilient when it can withstand or recover from disruptions caused by heat waves and power outages and can adopt appropriate strategies to prevent degradation of the indoor environment (i.e. maintain safe and operable conditions in a building).

Consequently, based on an understanding of the hazards and their potential impacts, considerations of vulnerability, resistance, recovery, and restorations need to be facilitated in the initial design state of the building.

The processes for conventional design and RCD differ in scope, time frame, and objectives (as summarized in **Table 1.1**). While conventional design focuses on optimizing performance within set parameters, resilient design prioritizes adaptability and minimizing risk in the face of uncertainty and unexpected events. Climate change will induce an increased risk of extreme weather occurrence, duration, and intensity; therefore, special attention must be given to resilience and adaptability. The design approach to resilient cooling addresses unexpected and uncertain shocks. In the case of resilient cooling of buildings, scientists have identified two disruptive events as the main challenges for the design of resilient cooling systems: heat waves and power outages (Attia, Rahif, et al., 2021; Miller et al., 2021; Zhang et al., 2021).

The concept of RCD also incorporates reaching a further interdisciplinary and flexible design approach and considers a longer timeframe than conventional design.

***Table 1.1**. Difference between conventional and resilient design approaches.*

	Conventional Design	Resilient Design
Purpose	Solutions that are efficient, cost-effective, and easy to maintain	Flexible solutions that can withstand unexpected shocks and adapt to changing circum-stances
Goals	Optimizing performance within certain parameters, such as cost, time, and functionality	Minimizing risk and increasing adaptability
Approach	Based on established standards and best practices	More creativity and flexibility to anticipate and respond to uncertain or unexpected situations. This requires a definition of shocks which the design shall be resilient against and requires the assessment of shocks.
Scope	Focus on individual buildings or structures	Requires the consideration of the broader context and interconnectedness of systems and communities
Timeframe	Focuses on the mid-term (50 years)	Longer-term (100 years) perspective, considering potential future climate change scenarios and impacts
Interdisciplinarity	Collaboration of disciplines usually connected to building sector	Collaboration and coordination between a wider range of designers, specialists, and disciplines

1.3 A Framework for Resilient Cooling Design

Resilient Cooling Design (RCD) must consider future events and address non-predictable eventualities, especially in today's changing climate. This poses new challenges for planners and designers. To make informed design decisions, an extended knowledge base is needed. In the case of RCD, this knowledge base is enriched by disciplines not directly linked to the design of buildings and technical systems, such as climatology, physiology, and anthropology. This knowledge base is gradually expanded during the design process, following the available information at every design stage.

For example, a shadow study is carried out in the pre-design stage, when the rough design of a building is being conceived. This increases awareness of the design's impact. This knowledge then influences the orientation of the building, the arrangement of volumes, etc., and forms the basis for later stages (e.g., when fenestration is specified). This approach is appropriate for most design processes, not solely for RCD processes.

A novelty is an assessment of the design against shocks. This is the most crucial step towards RCD. Scientists in EBC Annex 80 identified heat waves, power outages, and a combination of both as major shocks for the cooling of buildings (Attia, Levinson, et al., 2021; Zhang et al., 2021). Such events are already occurring in some parts of the world and are expected to increase in frequency, duration, and intensity in mid-term and long-term future scenarios.

Heschong and Day state that building resiliency is "the ability to continue to remain safe, functional, and comfortable under extreme and unexpected conditions" (Heschong & Day, 2022). They advocate that occupants play a vital role in building operations. During disruptive events and system failures, this gains even greater significance. The dependency on external specialists to re-operate a cooling system to maintain the building in functional and safe condition can cause problems in the case of unforeseeable shocks. Alternatively, if the design of the building and its cooling system allows for occupants to intervene in an intuitive way (e.g. closing window shades or opening windows or louvres to increase air speed and prevent heat from accumulating inside the building in case of a cooling system's failure), the building could maintain relatively safe, functional, and comfortable conditions longer. Heschong and Day define this as the "operational range" of a building. They argue that it is the most important characteristic of resilient design (Heschong & Day, 2022). The extension of the operational range of a building is also the objective of RCD.

The assessment of the resilience of a building against heat waves and power outages is carried out through dynamic building simulations. This has been the subject of ongoing research. Zhang et al. (2023) developed a guideline for the performance testing of resilient cooling strategies that has been applied to numerous technologies in generic building models and in different climatic zones. Dynamic simulations for the resilience assessment should consider present, mid-term, and long-term future weather scenarios. Refer to Chapter 5 for more details.

For this purpose, a group of Annex 80 scientists has developed a method for generating future weather data files for building simulations (refer to Chapter 6 for details). Such files, representative of the mid-century (2050s) and end-of-century (2090s), have been generated for numerous cities in 12 ASHRAE climate zones. The files generated are available for application in dynamic simulation in Energy Plus weather file (EPW) format. Furthermore, the group generated heat wave data sets for the time series 2001-2020, 2041-2060, and 2081-2100. Weather data files for the longest, most intense, and most severe heat waves are available for each time series and for the selected cities for building simulation. Based on this data, the resilience of a cooling system in buildings can be thoroughly assessed.

Several Key Performance Indicators (KPIs) have been developed by Annex 80 researchers to support the quantitative evaluation of the simulation results (refer to Chapter 4 for more details). While buildings designed conventionally (from a thermal point of view), must maintain thermal comfort within defined boundary conditions. A Resilient Cooling Design must also prevent heat stress or power outages during heat waves and reduce health risks for building occupants. See Chapter 4 for further information.

The RCD framework discussed in this section is summarized in **Figure 1.1**. The figure shows how the concepts can be integrated into the various stages of the design process.

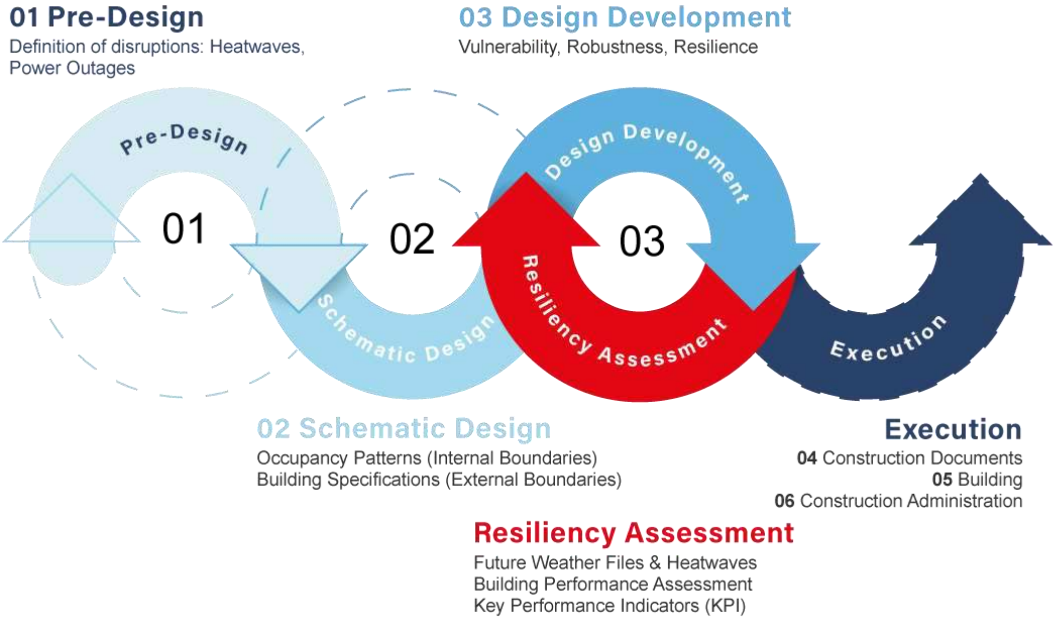


***Figure 1.1**. Design process including resiliency assessment.*

1.4 Scope of this Guideline

This Guideline addresses both free-running and mechanically cooled buildings and aims to answer the following question: How can one design a “resilient cooling” building?

As such, it is important to understand the underlying concepts of resilience regarding buildings, the available technological solutions, and the methods and tools used to evaluate options. Chapters 2-8 in this Guideline are sequenced to assist practitioners in these areas (as shown in **Table 1.2**). Chapters 9 and 10 provide practical applications of the guidelines in case-study buildings.

Table 1.2. *Chapter overview.*

Ch	Overview	Topics Addressed
2	Provides a definition of disruptions and resilient cooling and explanations of the disruptive events identified in the context of RCD	✓ How can resilience be conceptualized? ✓ How is resilient cooling defined?
3	Provides concise descriptions of resilient cooling solutions	✓ Which resilient cooling solutions exist which improve the building resilience (technology specific KPIs)? ✓ Which strategies and technologies can be implemented in building design processes to prepare for future disruptions? ✓ How can strategies be sized to consider future climate uncertainties? ✓ How can prospective performance of resilient cooling strategies be assessed?
4	Provides a selection of key performance indicators (KPIs) that can be used for the evaluation of resilient cooling in buildings	✓ How can the resilience of a building or cooling system be quantified in the cases of power outages or heat wave events?
5	Provides an overview of performance assessment methods and tools for the evaluation of operational and energy efficiency in buildings to identify potential improvements	✓ How can input and output parameters be selected for simulation and technology assessment? ✓ How can the resilience of a building be evaluated against different disruptions? ✓ How can specific resilient cooling technologies be modelled? ✓ How can a building simulation model be calibrated?
6	Introduces the climate data necessary for RCD	✓ How can future or extreme events be accounted for? ✓ How can future or extreme weather data sets be selected for building simulation? ✓ How should future weather files be prepared for building simulations?
7	Discusses parameters related to people and their use of spaces, and the incorporation of these issues into building performance simulation and analysis	✓ How do occupancy patterns impact building performance assessment? ✓ How does metabolic rate impact building performance assessment? ✓ How should internal gains be understood and assessed?
8	Addresses performance influencing factors such as the setting of a building and its form, envelope characteristics, or orientation.	✓ How do microclimate, location, landscape, and orientation affect building performance? ✓ What influence do fenestration design, shading systems, and opaque envelope characteristics have on resilient cooling?

1.5 Resilient Cooling Design in Practice

The following recommendations specifically address aspects of RCD and should be understood as supplementary to your own well-established design practice. They are consistent with the design process shown previously in **Figure 1.1**.

Define the problem: The aim of RCD is to design a building that is resilient against heat waves and power outages and that maintains safe, functional, and comfortable conditions for occupants during such events. It is advisable to discuss this with the client and end-users and to question conventional planning norms at the very beginning of the pre-design stage. Possible starting points include:

- *Comfort sufficiency*: Not all zones of the building might have to maintain the same level of functionality or thermal comfort all the time. During heat wave periods, discomfort might be tolerated for a period if it is not inside the heat-health related risk zone.
- *Occupancy patterns*: These may change during extreme heat events and are likely to be affected by power outages.
- *Building operation*: Occupants should be able to override a cooling system's control in the case of a system failure.
- *RCD brief*: The requirements for and expectations of the design should be summarized clearly.

Research and gather information: Once the problem has been discussed and defined, the next step is to gather information and conduct research that supports fulfilling the RCD brief. This involves the following:

- *Data sources*: Identify sources for future weather data for building simulation.
- *Digital tools*: Identify tools to perform first analysis already at the early design stage, such as the shadow analysis and thermal simulation of one critical room.
- *Existing passive, active, or hybrid cooling solutions*: Gather information on their implementation and analyse their suitability.
- *Key performance indicators*: Select the suitable criteria for the assessment of the RCD.

Brainstorm and explore: Based on the initial information gathered, brainstorm and conceive of potential design solutions. Exploring different approaches might lead to revisions of the definition of the design problem in

- *A variety of solutions*: Try to think of potential design solutions from different angles of perspective (simplicity, best performance, robustness of operation, occupant operability, etc.).
- *Exploration*: Explore a selection of possible solutions for different applications.
- Do not go into detail with the evaluation or testing of resilience against your solutions yet.

Conceptualize: After the identification of a range of potential resilient cooling solutions, start to develop a concept and additional alternative concepts that address all the aspects of the RCD brief.

Test and refine: Testing the developed concepts against shocks is crucial for RCD and for further developing the initial considerations.

- *Assessment framework*: Make sure to base your assessment on concise and reproducible boundary conditions. See (Attia, Rahif, et al., 2021) for further guidance on the resilience assessment of cooling technologies.
- *Building performance simulation*: Verify that digital tools identified in b) are still suitable for the testing of your RCD and providing the data for calculating the KPIs.
- *Comparison*: The KPIs support the identification of the most RCD.
- *Refinement*: Adjust your initial concept to achieve better performance in the simulations.
- *Iteration*: Several iterations might be necessary to find the best solution for RCD.

Implementation and evaluation: Prepare the refined concept of RCD for implementation. Commissioning and performance evaluation of resilient cooling systems are integral parts of RCD. Monitoring and collecting data on the system's operations and gathering user feedback support making the necessary adjustments and ensuring proper function as achieved.

2 Definition of Disruptions and Cooling Resilience

This chapter provides an overview of the definitions of disruptions and cooling resilience. It presents a framework for understanding resilient cooling and a classification for the design of resilient cooling systems. It concludes with five tips for practitioners.

2.1 Understanding disruptions

Numerous emergencies can impact the built environment in a variety of tangible and intangible ways (Tähtinen, 2022). Those impacts can affect people's health and well-being, degrade the functionality of infrastructure, and can create unliveable environments (Tähtinen, 2022). Inspired by (Castaño-Rosa et al., 2022), some emergencies affecting the built environment (specifically buildings) are listed in **Table 2.1**.

***Table 2.1**. Emergencies that can affect building performance.*

Emergency	Description
Climate Emergency	Natural imbalance due to the excessive use of natural resources and fossil fuels (Ajjur & Al-Ghamdi, 2021). This can contribute to natural hazards such as floods, heat waves, and wildfires that can cause disruptions to the essential services provided by buildings.
Pandemic Emergency	A situation triggered by a new virus or contagious illness that has significant impacts on society in terms of people's lives, work, and interactions (Saladino et al., 2020). In the case of a pandemic, it may be necessary to adjust buildings (to enable social distancing or to enhance ventilation, for example) to minimize the likelihood of transmission (Morawska et al., 2020).
Financial Emergency	A situation where the asset value or credit load drops rapidly, often due to panic or incorrect strategies in the banking system or financial markets (Claessens & Kose, 2013). The occurrence of financial crises can result in difficulty maintaining buildings, potentially affecting their quality and occupant safety (Shah Ali, 2009).
Housing Emergency	A shortage of affordable housing or a decrease in housing quality leads to the creation of low-income housing with energy poverty (Karpinska & Śmiech, 2020).
Demographic Emergency	A significant interruption in the long-term growth of the population (Ehmer, 2015). Demographic shifts (such as a growing elderly population or an abrupt surge of migrants) can increase the need for specific types of buildings and potentially strain existing infrastructure (Hummel & Lux, 2007).
Digital Emergency	The emergence of evasive phenomena due to cyberattacks or improper use of virtual and digital assets that causes danger, urgency, and unpredictability for public health and safety. As buildings increasingly depend on technology, they become more vulnerable to cyber-attacks that can significantly disrupt their operation and management (Parn & Edwards, 2019).
War Emergency	A situation in which there is a pressing danger or attack from an armed conflict. Such attacks can result in physical damage to the buildings and also put the lives of occupants at risk (Gilbert et al., 2003).
Seismic Emergency	A situation characterized by the imminent threat or occurrence of an earthquake or related seismic activity (such as aftershocks or precursor events). This scenario poses a significant risk of physical damage to infrastructure, buildings, and the natural environment, and endangers the lives and safety of individuals within the affected areas.
Aging Emergency	A condition where the buildings have exceeded their original design life, resulting in physical deterioration, obsolescence, and reduced performance. This deterioration can cause structural or functional weaknesses that pose safety risks to the occupants and can disrupt critical functions and services.
Social Unrest Emergency	A condition of widespread discontent, uncertainty, and disruption in a society, typically manifested through various forms of collective action, such as protests, demonstrations, or riots (Mason, 1994). Such actions may result in physical damage to buildings, posing a threat to the safety and welfare of the occupants.

Table 2.1 is provided to demonstrate that there are a large variety of emergencies that can affect the resilience of buildings to provide shelter and safety to occupants, including the provision of cooling. A refinement of the concept and definition of *"resilient cooling"* are provided next.

2.2 Conceptualization of Resilient Cooling

2.2.1 Resilience Against What?

In the context of building resilience, it is essential to establish a comprehensive definition and assessment framework, which includes the identification of potential threats or disruptions that could compromise the stability of the buildings under consideration. A crucial aspect of this process is to determine the specific hazards or shocks that the building and its systems should be resilient against. Therefore, the fundamental question of *"resilience against what?"* should be addressed to develop a rigorous and effective assessment methodology.

This guideline specifically focuses on defining a building's cooling resilience in response to a climate emergency, which is deemed a primary emergency that could have significant social and economic implications. From a social perspective, climate emergencies can heighten the risk of extreme weather events and other natural hazards that can lead to building and infrastructure damage and endanger public safety. In terms of economic impacts, climate emergencies can cause increased expenses related to building damage, higher energy costs, and decreased property values.

Table 2.2 lists disruptions from climate emergencies that can affect buildings. Among those disruptions, heat waves and power outages are significant disruptions that can directly affect the cooling resilience of buildings. Climate projections suggest that the frequency and severity of heat waves will continue to increase in the future (Doutreloup et al., 2022). During heat waves, the excessive use of air conditioning can put a strain on the power grid and potentially cause power outages or shortages (Stone Jr. et al., 2021). This situation can result in substantial overheating problems within buildings.

Overheating in buildings affects occupant comfort, productivity, and health (Lan et al., 2017) and can lead to illness and death in severe cases (Armstrong et al., 2011). The 2003 heat wave in Europe resulted in more than 35,000 fatalities (Brücker, 2005), with specific numbers reported in France (14,729 deaths) (Fouillet et al., 2006), England and Wales (2,139 deaths) (Johnson et al., 2005), the Netherlands (up to 2,200 deaths) (Garssen et al., 2005), and Belgium (1,175 deaths) (Robine et al., 2008). Addressing heat waves and power outages together is crucial to ensure indoor comfort and to maintain the resilience of buildings during extreme weather events.

***Table 2.2**. Different types of climate-related disruptions affecting buildings (Attia, Levinson, et al., 2021).*

Disruption	Description
Short-term Intensive Air Pollution	Air pollution pertains to the degradation of air quality, which mainly affects populations residing in or near urban areas.
Wildfire	Wildfires can cause critical damage to buildings. Even after the fires are contained, residual effects such as smoke damage, water damage, and erosion can continue to impact buildings.
Windstorms and Hurricanes	Windstorms and hurricanes (accompanied by heavy rain) are high winds or violent gusts which form cyclonic winds associated with low atmospheric pressure that can damage trees, buildings, and energy infrastructure.
Flooding	Flooding is the overflow of water into dry land caused by heavy rainfall or is when rivers overflow their banks.
Heat Waves	Heat waves are periods of hot weather with or without high humidity levels that can affect people, the built environment, and natural systems. The negative impacts of heat waves on buildings include increased demand for energy to power cooling systems, overheating, and increased stress on water supply and energy infrastructure.
Power Outages	A power outage is a period of electricity failure due to natural hazards like floods, hurricanes, and heat waves.
Water Shortages	Water shortage is the lack of sufficient water sources to meet the water demand.

2.2.2 Resilience: At which scale and for how long?

As shown in **Figure 2.1**, the definition of resilience should specify the system's ability to withstand disturbance at a particular scale and timeframe. In general, the built environment can be categorized into six major scales, ranging from a zone and system within a building, to the scale of a building, and to the scale of a neighbourhood, district, or city. In this guideline, resilient cooling in buildings is defined within specific boundaries that are limited to the building scale.

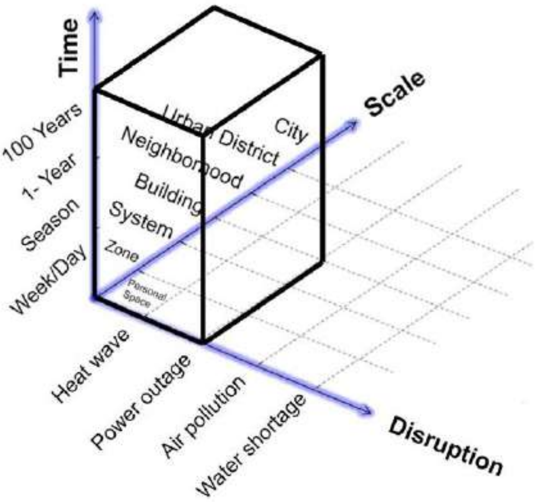


Figure 2.1. *Components of a resilience definition: timeframe, disruption, and scale (Attia, Levinson, et al., 2021).*

Understanding the different types of disruptions and their durations is crucial to designing resilient cooling systems. A building with resilient cooling is expected to withstand disruptive events, ranging from long-term climate change impacts to short-term unprecedented events. Inspired by Rahif et al. (2021), three major disruption categories challenging resilient cooling can be distinguished:

Disruption 1: Long-term weather conditions (on a yearly, seasonal, and monthly basis).

Disruption 2: Short-term extreme events, e.g. heat waves (where the duration depends on the definition of a heat wave; usually on weekly basis).

Disruption 3: Power outages (up to days or weeks).

The interconnectedness of “heat wave” intensity, frequency, and duration is shown in **Figure 2.2**, ignoring the disruption of power outages.

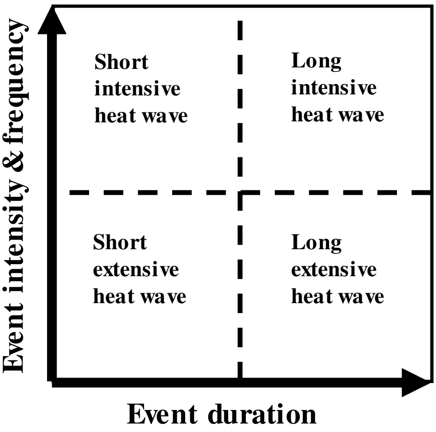


Figure 2.2. *Interconnectedness of intensity, frequency, and duration.*

2.3 Definition of Resilient Cooling

Resilient cooling refers to low-energy and low-carbon cooling concepts that help individuals and communities withstand and prevent the thermal impacts of climate change, particularly rising temperatures and heat waves (Rahif et al., 2022).

> *A building's cooling system is considered resilient when it can withstand or recover from disruptions caused by heat waves and power outages and can adopt appropriate strategies to prevent degradation of the indoor environment.*

As shown in **Figure 2.3**, this guideline includes four criteria in formulating the definition of resilient cooling, namely *vulnerability*, *resistance*, *robustness*, and *recoverability* (Attia, Levinson, et al., 2021). The design process should incorporate a *vulnerability* assessment to evaluate the long-term and short-term thermal performance of the building, and the cooling system should effectively address both aspects. For example, a building may maintain acceptable thermal comfort conditions year-round but struggle to prevent severe overheating incidents during short-term heat waves. Conversely, another building might withstand heat waves but generally provide uncomfortable thermal conditions throughout the year.

Resistance involves the building's ability to react to shocks, *robustness* requires the building to survive otherwise fatal shocks by adapting its performance, and *recoverability* involves the extent and nature of the building's services and occupants' ability to recover. Resilient cooling is a continuous process that involves commissioning and retro-commissioning building elements and systems over the building's life cycle, as well as educating occupants and preparing them for unforeseeable disruptions.

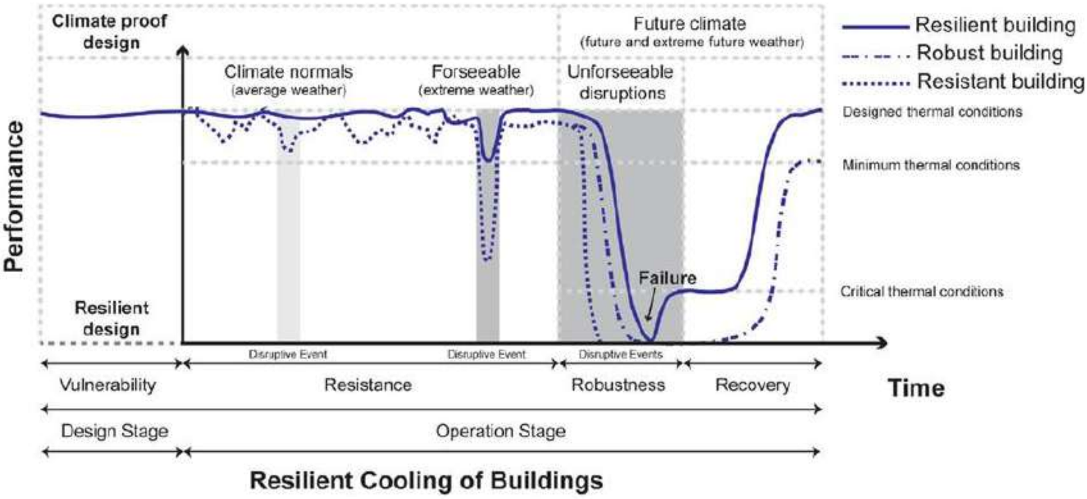
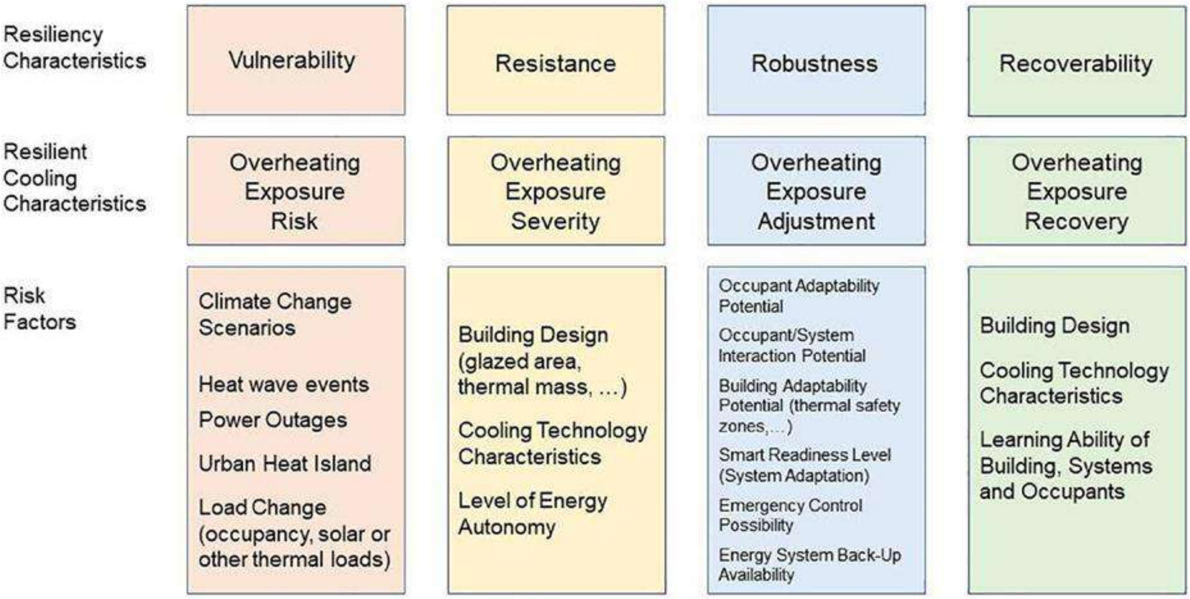


Figure 2.3. *Framework for cooling resiliency in buildings during extreme weather conditions and power outages (Attia, Levinson, et al., 2021).*

Figure 2.4 presents a complementary classification scheme for designing resilient cooling systems in buildings. It shows the risk factors to be addressed, considering the four resilience criteria. More specifically, it emphasizes the importance of identifying risk factors during the design stage to assess vulnerability, such as climate change scenarios, heat waves combined with power outages, and urban heat island effects. The resistance stage depends on the building's design features and technologies to maintain performance under severe overheating exposure until failure occurs, leading to the robustness stage. The cooling system's robustness must adapt to cover critical thermal conditions temporarily until recovery is possible, with the ability to respond and apply changes to the original thermal conditions involving occupants and system's adaptability. The presence of energy system backup and an emergency control possibility contributes to the building's robustness. This should be followed by a recovery stage to achieve the designed thermal conditions which reflect a return to normal.



Resiliency Characteristics	Vulnerability	Resistance	Robustness	Recoverability
Resilient Cooling Characteristics	Overheating Exposure Risk	Overheating Exposure Severity	Overheating Exposure Adjustment	Overheating Exposure Recovery
Risk Factors	Climate Change Scenarios Heat wave events Power Outages Urban Heat Island Load Change (occupancy, solar or other thermal loads)	Building Design (glazed area, thermal mass, ...) Cooling Technology Characteristics Level of Energy Autonomy	Occupant Adaptability Potential Occupant/System Interaction Potential Building Adaptability Potential (thermal safety zones,...) Smart Readiness Level (System Adaptation) Emergency Control Possibility Energy System Back-Up Availability	Building Design Cooling Technology Characteristics Learning Ability of Building, Systems and Occupants

***Figure 2.4**. Factors that influence resilient cooling of buildings (Attia, Levinson, et al., 2021).*

2.4 Resilient Cooling Framework in Practice

To enhance the cooling resilience of a building, the following steps can be taken:

- **Conduct a risk assessment:** To identify potential risks and hazards that a building may face during heat waves and power outages, it is crucial to conduct a risk assessment. This involves evaluating the likelihood and potential impact of various scenarios, allowing measures to be prioritized accordingly (Attia, Rahif, et al., 2021).
- **Design for cooling resilience:** To increase a building's ability to withstand heat waves and power outages, it should include features such as passive cooling and backup power. These features should ensure that the building is still liveable during extreme weather events and power outages (U.S. Department of Homeland Security, 2010).
- **Maintain the building's active cooling systems:** Regular maintenance with a professional HVAC technician should be scheduled. The professional should inspect and service the cooling system. This will aid in the prevention of breakdowns and detection of potential issues before they worsen.
- **Develop emergency plans:** Building owners and operators have a responsibility to establish emergency plans that encompass evacuation procedures, communication protocols, and additional measures to safeguard building occupants, especially vulnerable groups, during threatening events. These events should include extreme heat waves concurrent with a power outage or cooling system failure. It is crucial to review and update these plans regularly to ensure their continued efficacy (FEMA, 2018).
- **Test and improve cooling resilience:** To enhance a building's cooling resilience, it is important to recognize that it is an ongoing process that requires regular testing and reviewing to identify areas for improvement and to strengthen the abilities of the building's cooling system to withstand heat waves and power outages over time (Klein et al., 2003).

3 Resilient Cooling Solutions (Strategies, Technologies, Components)

3.1 Introduction

Resilient cooling solutions are increasingly important in the face of climate change, which has led to more frequent and intense extreme weather events such as heat waves. These events can cause significant strain on cooling systems in buildings, leading to increased energy consumption, decreased comfort, and even equipment failure. To address this challenge, researchers and practitioners have been exploring different types of cooling strategies that can withstand extreme events and maintain performance under adverse conditions.

Cooling solutions can be broadly classified into three categories: active, passive, and integrated (combining active and passive strategies). Passive cooling strategies rely on natural ventilation, shading, insulation, and other design features that minimize heat gain and maximize heat dissipation without requiring mechanical equipment or energy input. Examples of passive cooling strategies include green roofs, solar shading, and natural ventilation.

Active cooling strategies rely on mechanical equipment such as air conditioners, chillers, and fans to regulate indoor temperature and humidity. These solutions require energy input and may be more vulnerable to power outages and equipment failure under extreme conditions. However, active cooling solutions can provide more precise and consistent control over indoor conditions, which may be necessary for certain applications.

Integrated cooling systems combine passive and active components to achieve a balance between energy efficiency, performance, and resilience. These solutions can leverage the strengths of both passive and active strategies, such as using natural ventilation to pre-cool air before it enters the mechanical cooling system or using solar shading and evaporative cooling to reduce the load on air conditioners. Alongside solar shading, evaporative cooling may be used in front of the condenser units in air conditioners.

A comprehensive assessment of resilience, including absorptive capacity, adaptive capacity, restorative capacity, and recovery speed, can help evaluate the efficacy of different cooling strategies in mitigating the impact of extreme events and ensuring long-term performance.

The focus of this chapter is on cooling solutions that provide a high level of resilience against heat waves and power outages based on four criteria for resilience, which are absorptive capacity, adaptive capacity, restorative capacity, and recovery speed. In addition to resilience, this chapter focuses on cooling solutions with a high Technology Readiness Level (TRL).

3.2 Active strategies (Including technologies and components)

Active cooling strategies encompass all strategies actuating mechanical equipment following pre-defined controlled variable values (i.e., temperature and humidity set-points or thresholds in each environment).

Given the heat source (building indoor environment) and heat sink (outdoor environment) temperatures, a first distinction is made between strategies that rely on a thermodynamic cycle and those that exploit heat and mass transfers without a thermodynamic cycle.

3.2.1 Cooling by Means of a Thermodynamic Cycle-based Refrigeration System

When the outdoor sink temperature is higher than the indoor temperature set point, a refrigeration cycle must be used, yielding work or heat consumption. In electricity-driven vapor compression systems, this work is achieved with an electric motor. Cooling cycles that require heat are named heat-driven cycles. **Table 3.1** compares different examples of cooling strategies based on a thermodynamic cycle-based refrigerator. The table highlights the possibility and the means of storing energy, which can be advantageous for resilient cooling.

Table 3.1 *Examples of active cooling strategies (with a thermodynamic cycle-based refrigerator).*

		Electric Power Input	Gas Consumption	Low-Grade Heat	Energy Storage
Vapor Compression Refrigeration	Electric chillers	High*	N/A	N/A	Chilled water Ice storage
	Split air-conditioners	High	N/A	N/A	
	Solar air-conditioners (photovoltaic panels & split systems)	High (this. can work off-grid with solar DC power)	N/A	N/A	Batteries
	Engine driven chillers	Low or null	High	N/A	Gaseous or liquid fuel storage
Sorption Refrigeration	Gas driven-absorption and adsorption chillers	Low	High	N/A	Gaseous or liquid fuel storage Chilled water storage (heat sink)
	Solar-driven absorption and adsorption chillers (solar thermal panels & sorption systems).	Low	N/A	High	Hot water storage (heat source) Chilled water storage (heat sink)
	Waste heat-driven absorption and adsorption chillers (process heat & sorption systems).	Low	N/A	High	Chilled water storage (heat sink)

* High electric power means that an electric compressor is used. Low electric power input means that electrical consumption is only associated with auxiliaries, such as fans, pumps, and electronics.

3.2.1.1 Vapor Compression Refrigeration

The most common refrigerator is the vapor compression refrigerator. The success of this technology is due to its compactness, reliability, scalability (from typically 100 W to 100 MW of cooling capacity), and reliable performance. The refrigerant used is the primary determinant of the environmental impact and user safety.

The compressor within vapor compression refrigerators consumes mechanical power. Typically, an electric motor provides this power. It can also be provided by an internal combustion engine (in the case of "engine-driven chillers"), which is independent of an electricity grid and is highly resilient to power outages.

Auxiliary components also consume electricity, but to a lesser extent. These include condenser fans (in air-cooled condensers), cooling-tower fans and pumps (in water-cooled condensers), evaporator fans (in split air-conditioners), and evaporator circulating pumps (in chillers). The consumption of these auxiliary components is limited but must be taken into consideration when assessing the necessary power input of the cooling plant.

There are many types of refrigerators for air conditioning. A few of them are listed below:

- A *chiller* is a type of refrigerator that produces chilled water. Most chillers are based on a vapor compression cycle with an electricity-driven compressor (this is an "electricity-driven chiller"). Absorption chillers (or "heat-driven chillers") are discussed in the next subsection. Chillers are either air-cooled, water-cooled, or cooled by an evaporative condenser.
- A *split air-conditioner* (which is an air-to-air refrigerator) has one outdoor unit and one or several indoor units (mono-split versus multi-split systems).
- A *variable refrigerant flow (VRF)* system has one outdoor unit and several indoor units. The latter units can work either in heating or cooling modes independently of each other, ensuring that there is heat transfer between zones to be cooled down and zones to be heated.

The possibility of converting a vapor compression refrigerator into a heat pump and the potential of condenser heat recovery have yielded more integrated heating and cooling solutions. Among others, different technologies allow systems to meet simultaneous heating and cooling demands with good performance: VRF systems, water-loop heat pumps, or 4-pipe fan-coil systems.

The performance of an electricity-driven vapor compressor refrigerator is expressed in terms of the electrical coefficient of performance (COP) defined as the ratio of the heat rate extracted from the low-temperature source ($\dot{Q}_{LT}$) to the electrical power consumption ($\dot{W}_{el}$).

For vapor compression refrigerators, the electrical energy efficiency ratio (*EER*) is defined as:

$$EER_{el} = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} \tag{1}$$

The *EER* and the cooling capacity are decreasing functions of the air temperature at the condenser inlet. Furthermore, they are increasing functions of the chilled water temperature at the evaporator outlet. For each unit increase (K) in the outdoor temperature, the *EER* and the cooling capacity drop by roughly 0.1 and 1%, respectively. Heat waves therefore affect both the capacity of the machine to cover the cooling load (which increases itself) and the stress on the electricity grid or local power supply. Furthermore, working with high-temperature cooling emitters increases the cooling capacity and *EER*.

Table 3.2 shows the common ranges of performance and constraints of vapor compression chillers. For air-cooled machines, the table indicates the gain in performance when working with higher temperatures on the evaporator. This is possible with high-temperature cooling emitters, such as radiant ceilings.

Water-cooled chillers are more efficient than air-cooled chillers, despite the electric consumption of the cooling tower. However, a water-cooled chiller with a cooling tower is more expensive, and the building must be adapted to integrate the cooling tower (which is quite heavy). The cooling tower also requires maintenance, such as cleaning of components on the open water circuit because of fouling (which could be more or less severe depending on the dust content of the outdoor air) and treatment against legionella. Finally, a cooling tower consumes water, which could be scarce.

***Table 3.2**. Performance and constraints of vapor compression chillers ("electric chillers").*

	Thermal EER	Electrical EER	Constraints
Air-Cooled Vapor Compression Chiller (low-temperature cooling: A35/W12-7)	NA	2-4	
Air-Cooled Vapor Compression Chiller (high-temperature heating: A35/W25-18)	NA	3-5	High-temperature cooling emitters are required
Water-Cooled Vapor Compression Chiller (low-temperature heating: W30-35/W12-7)	NA	4-6	A cooling tower is required (with water consumption) or a dry-cooler

3.2.1.2 Adsorption and Absorption refrigeration

Sorption refrigerators are part of a large family of heat-driven cycles. Sorption refrigeration encompasses both absorption and adsorption machines. Such machines replace the compressor with a system that consists of a sorbate (the refrigerant) and a sorbent where sorption and desorption processes take place. The latter requires heat input.

Absorption machines are far more extensively commercialized than adsorption machines. They show slightly better performance but require higher heat source temperatures.

Sorption chillers are driven by a high-temperature heat source (from which they receive a heat rate $\dot{Q}_{HT}$) necessary for desorption. These are cooled down by a medium-temperature heat sink, typically a cooling water loop (into which they reject a heat rate $\dot{Q}_{MT}$) catching the heat produced during sorption and the heat at the condenser. They produce a cooling effect, transferring heat from a low-temperature heat source (at a rate $\dot{Q}_{LT}$) to the evaporator. Their auxiliary electric consumption ($\dot{W}_{el}$), circulating pump, fans, and electronics are limited.

Their performance can be described by a thermal *EER* and an electrical *EER*.

$$EER_{th} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \tag{2}$$

$$EER_{el} = \frac{\dot{Q}_{\mathrm{LT}}}{\dot{W}_{\mathrm{el}}} \tag{3}$$

Absorption chillers can describe a single effect cycle, a double effect cycle, a triple effect cycle, or even combine a single and a double effect cycle. The larger the number of effects, the better the thermal *EER*, but also the larger the necessary temperature of the heat source (**Table 3.3**). Absorption chillers cover a cooling capacity range from around 10 kW to around 10 MW. Small-scale absorption chillers (with cooling capacities lower than 50 kW) are typically of the single-stage type. **Table 3.3** also indicates the possibilities of energy storage that could be implemented to increase resilience.

***Table 3.3** Performance and constraints of sorption chillers.*

	Thermal COP	Electrical COP	Constraints	Energy Storage
Low-Temperature Absorption Chiller (single effect machine).	0.4–0.8	>30	Heat source: hot water at a temperature between 60 and 150°C (pressurized) (from waste heat, thermal solar collectors, and CCHP), low-pressure steam (turbine extraction, industrial processes), and the district heating network	Hot water tank and chilled water tank
High-Temperature Absorption Chiller (double effect machine)	1.5	>30	Heat source: hot water at a temperature between 150 and 180°C (pressurized), combustion of fossil fuels or biogas (burner and absorption machine integrated), high-pressure steam, and exhaust gases from internal combustion engines or gas turbines	Fossil fuels (CNG, propane) or biogas, and chilled water tank
Very High-Temperature Absorption Chiller (triple effect machine)	1.8	>30	Heat source: hot water at a temperature between 190 and 230°C (pressurized), high-pressure steam	Chilled water tank
Adsorption Chiller	0.4–0.6		Heat source: hot water at a temperature around 70°C.	Hot water tank, chilled water tank, and the refrigerant itself (after desorption) for longer-term storage

3.2.2 *Cooling Without a Thermodynamic Cycle-Based Refrigeration System*

Suitable environment for heat sinks to allow for heat extraction out of the building without requiring a refrigerator include outdoor air, ground, aquifers, and artificial underground energy storage. Some examples and associated constraints of cooling strategies without using a thermodynamic cycle-based refrigerator are listed in **Table 3.4**.

Table 3.4 *Active cooling strategies (without a thermodynamic cycle-based refrigerator).*

		Heat Sink	**Electric Power Input**	**Water Consumption**	**Energy Storage**	**Constraints**
Free-Chilling Systems	With wet cooling towers	Outdoor air (theoretical minimal water temperature: air wet bulb temperature)	Moderate (fan and circulating pump)	Yes	Chilled water tank	Use of high-temperature cooling emitters.
	With wet cooling towers equipped with precooling	Outdoor air (theoretical minimal water temperature: air dew point temperature)	Moderate (fan and circulating pump)	Yes	Chilled water tank	Use of high-temperature cooling emitters.
	With dry coolers	Outdoor air (theoretical minimal water temperature: air dry bulb temperature)	Moderate (fan and circulating pump)			
	No	Chilled water tank	Limited potential of free-chilling. Use of high-temperature cooling emitters.			
	Groundloop cooling	Ground Temperature depends on ground diffusivity and annual thermal loads	Moderate (circulating pump)	No	Seasonal sensible energy storage in ground (if the effective ground thermal conductivity is limited).	Use of high-temperature cooling emitters. Drilling cost. Thermal properties of the ground (its capacity to store cold). Seasonal balance between heat extraction/injection (allowing seasonal storage) if there is no natural regeneration.
	Aquifer	Ground water Aquifer can be static or dynamic (rather a constant temperature)	Moderate (circulating pump)	No	Seasonal sensible energy storage in water (if the aquifer is static)	Environmental regulation. Maximum water pumping rate. Hydraulic conductivity of the ground. Difference between injected and pumped water temperatures.
	Artificial underground thermal energy storage	Underground water reservoir (tanks, flooded mines,…)	Moderate	No	Seasonal sensible energy storage in water, with potential temperature stratification (depending on the height of the artificial reservoir)	Cost of a reservoir (if there are any local opportunities for artificial reservoirs)

		Heat Sink	Electric Power Input	Water Consumption	Energy Storage	Constraints
Mechanical Ventilation	Without adiabatic cooling	Outdoor air (theoretical minimal air temperature: air dry bulb temperature)	Low	No		Outdoor air (theoretical minimal air temperature depends on operating conditions)
	With adiabatic cooling	Outdoor air (theoretical minimal air temperature: air wet bulb temperature)	Low	Yes		Increase of indoor air humidity content if direct evaporative cooling.
Sorption Refrigeration	Desiccant cooling	Outdoor air (theoretical minimal air temperature, which depends on operating conditions)	Low	Yes		Use of low grade heat (solar energy, district heating)

3.2.2.1 Free-Chilling (Using Outdoor Air as Heat Sink)

Outdoor air can be used to produce chilled water by means of a cooling tower or dry cooler, provided it is cold and dry enough. A heat exchanger combined with 3-way valves allows it to bypass the chiller (**Figure 3.1**). The only electrical consumption associated with cooling are due to the different pumps and the cooling tower fan.

Using high-temperature cooling emitters (radiant cooling ceilings, chilled beams) increases the outdoor temperature threshold under which free-cooling operations are feasible.

The interest in free-chilling is in its low electricity consumption, which makes it suitable in cases of limited power supply. However, free chilling using wet cooling towers requires water, which is not abundantly available everywhere and in all weather conditions (for example, severe droughts). A dry cooler does not require water, but the theoretical limit on the temperature of the chilled water produced is that of an outdoor air dry bulb. Precooling the air with the chilled water leaving the cooling tower would theoretically allow it to reach the outdoor air dew point.

3.2.2.2 Ground-Loop Cooling (Using the Ground as a Heat Sink)

Ground-loop cooling (also called geo-cooling) is associated with a geothermal heat pump (i.e., a heat pump connected to a bore field, which is a set of vertical ground heat exchangers drilled at depths of typically 150 m). Horizontal-set pipes are also used in such systems at a depth of 4-5 meters. Such a system is also called a *closed system*, while a heat pump connected to an aquifer is called an *open system*. Geo-cooling bypasses the ground-source heat pump if the ground is cold enough to produce chilled water at a temperature suitable for cooling emitters in the building. The temperature of the ground depends on its characteristics (measured by means of a Thermal Response Test (TRT)) and the yearly heat profile injected into or extracted from the ground.

At the end of the heating season, the ground may be cold enough to allow for geo-cooling operations. As heat is injected into the ground, its temperature increases. When the temperature threshold over which geo-cooling is not possible is reached, the chiller must be activated. The capacity of the ground to store heat seasonally decreases with its effective thermal conductivity, which increases in the presence of groundwater flows (leading to a more dissipative ground). In the presence of ground with storage capability, the feasibility of geo-cooling will result from the amount of heat extracted during the heating season, highlighting the negative impact of a bad seasonal control on the cooling performance.

Similarly to free-chilling, the use of high-temperature cooling emitters (radiant ceilings, TABS, and chilled beams) increases the potential of geo-cooling.

In geo-cooling mode, electric consumption is associated with circulating pumps only. An *EER* of at least 12 is typically achieved.

3.2.2.3 Ground-Water Cooling (Using an Aquifer and Artificial Reservoirs)

Ground-water cooling systems (also called open systems) use water from the ground to cover the heating and cooling needs of a building. Following the temperature requirements of heating and cooling emitters, a heat pump or chiller can be associated with the water loop to further increase or decrease the temperatures. Among aquifer systems, the distinction can be made between static and dynamic ones. In a static aquifer, the underground motion of water is slow enough to allow for seasonal energy storage. Seasonal (or mid-term) energy storage can also be achieved with artificial groundwater reservoirs such as buried tanks or abandoned mines.

3.2.2.4 Desiccant Cooling Systems

Conventional desiccant cooling systems contain four major components: a desiccant wheel, a direct evaporative cooler, a sensible heat exchanger, and a regeneration heat exchanger. There is interest in desiccant cooling systems because they use low-grade thermal energy to produce cold air, and their electricity consumption is limited, meaning that they have a low load on the electricity grid. If the system is coupled with a district heating system, the desiccant cooling system allows for the use of the heat that is widely available during the cooling period.

The desiccant cooling system also requires water to feed the direct evaporative coolers, meaning that they may not be convenient for arid climates. Generally, these kinds of systems are better suited for more humid climates. The desiccant wheel dehumidifies the incoming cooling air to enhance the cooling potential of the installation through direct evaporative cooling. The activation of the desiccant wheel ensures that the air provided to the building is cold enough but not too humid, which would compromise the occupants' thermal comfort.

Desiccant cooling systems require thermal energy ($\dot{Q}_{\mathrm{reg}}$) for the regeneration of the desiccant wheel to produce cold air that can be supplied to the building ($\dot{Q}_{\mathrm{cool}}$). The system also requires an electrical input for the ventilation fans and the wheel rotor ($\dot{W}_{\mathrm{el}}$)

Thermal and electrical *EER*s can describe the performance of the desiccant cooling systems.

$$EER_{\text{th}} = \frac{\dot{Q}_{\text{cool}}}{\dot{Q}_{\text{reg}}} \tag{4}$$

$$EER_{\text{el}} = \frac{\dot{Q}_{\text{cool}}}{\dot{W}_{\text{el}}} \tag{5}$$

The thermal *EER* is rather low and is generally in the range of 0.6–1.1. It strongly depends on the regeneration temperature of the desiccant wheel. However, the electrical *EER* is close to 4–5, as the bulk of its electricity use is due to the fan. Desiccant cooling systems are generally more suitable for non-residential buildings as they require space for system installation.

3.2.3 Active Use of Cold Storage

The distinction must be made between daily and seasonal thermal energy storage.

3.2.3.1 Daily Cold Storage

The most widely commercialized solutions for daily cold storage are chilled water tanks and ice storage systems.

Chilled water storage is less compact than ice storage because it relies only on the sensible heat of water, while ice storage capacity relies on the latent heat of fusion.

Ice storage ensures a relatively constant temperature of chilled water. In a chilled water tank, the temperature depends on the state of charge or the quality of stratification. The main drawback of the ice storage system is the dependency of the overall heat transfer coefficient (between ice and chilled water or glycol water) on the state of charge. The evolution of the heat transfer coefficient with the state of charge or discharge depends on the technology of the ice storage. In ice-on-coil systems, during *charging*, ice is built up by circulating glycol water at around –5°C in a bank of tubes immersed in a water tank. Ice forms concentrically around the tube. The heat transfer coefficient decreases as the thickness of the annulus of ice increases. The performance during discharging depends on the sub-technology of ice-on-coils. In external melting systems, ice is melted from the outer periphery by circulating water at a positive temperature. This allows it to reach the water temperature at a constant temperature (close to 0°C) during the discharge process. Large cooling capacities are achieved. In internal melting systems, ice is melted from the inner periphery of the ice block by circulating glycol water at a positive temperature through the tubes (**Figure 3.1**).

In addition to the backup cooling capacity it provides, the cold storage allows for decreasing the size of the chiller and cooling tower/dry cooler. As a backup, it can be used in the case of:

- Power outage: Here, the cold storage could cover the cooling load alone, using an emergency power supply (EPS), for a time duration depending on the capacity of the storage (typically 12–24 hours with ice storage).
- Heat wave: Here, the cold storage complements the limited capacity of the chiller to cover the cooling load.

3.2.3.2 Seasonal Cold Storage

Today, seasonal cold storage in HVAC systems is primarily achieved with open and closed geothermal systems (as described above).

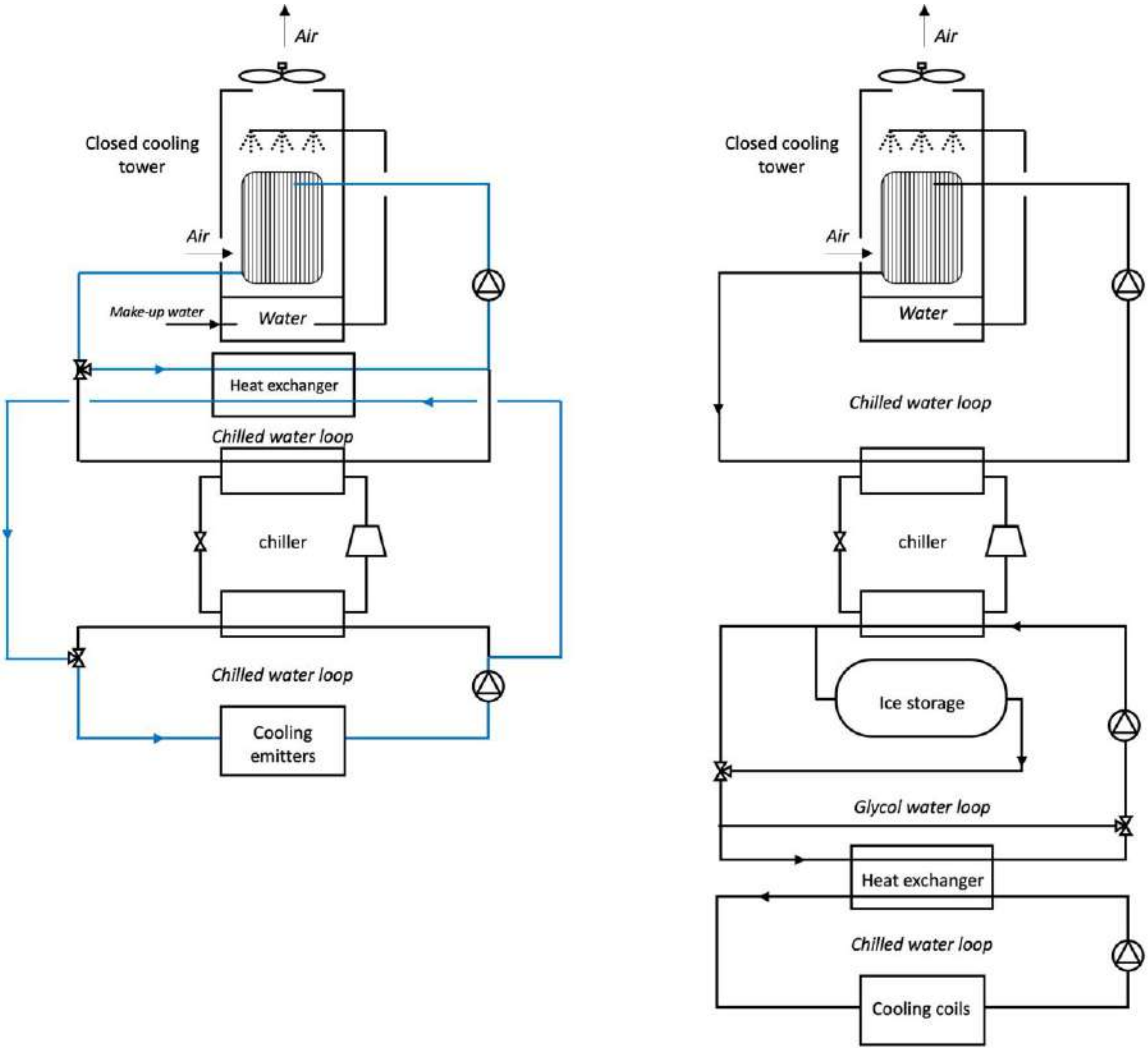


Figure 3.1. *A schematic showing typical cooling plants utilising the free-chilling operation (left) and ice storage (right).*

3.2.4 Off-Grid and Grid-Tied (with Emergency Backup Power Supply) Electricity-Driven Cooling Systems

In the case of a loss of electrical power supply, an emergency power system (EPS) can be used. Such systems provide backup electrical power by means of generators or batteries. Standby generators ("gensets") are typically diesel engine-driven generators, but other technologies can be used. Batteries can be charged from the main grid or local electricity production (using photovoltaic panels, for instance). An example of EPS configuration is shown in **Figure 3.2**.

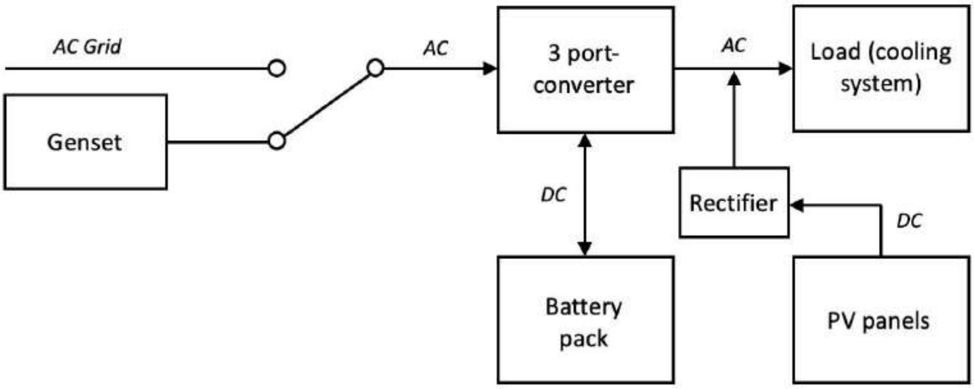


Figure 3.2. *Schematic of an emergency power system with a generator ("genset") and a battery pack. The later can be charged from the grid or PV panels.*

Such EPS systems are typically used in data centres, hospitals, telecommunication sites, or in railway signalling. Almost all cooling techniques and components described previously require electricity, but in different proportions to their cooling capacity. Systems showing low power input: either decrease the size of the "initial" system or increase the backup power supply system to guarantee the proper operation.

An alternative to AC-powered cooling systems connected to the grid (with an EPS) is the off-grid DC cooling system. Among them are solar-powered DC refrigerators, which are vapor compression systems connected to photovoltaic panels. Here too, limiting the electricity consumption of the cooling systems allows for a decrease in the size of the panels and the capacity of the batteries (if any), yielding a Capital Expenditure (CAPEX) reduction.

Sorption chillers that work with hot water heat sources are an alternative to off-grid solar air conditioning. The limited electrical energy consumption can be provided by PV panels. Absorption-based air conditioning and PV-based air conditioning should be compared in terms of performance. The overall solar-to-cooling energy conversion may be superior with PV solar air conditioning. However, absorption solar air conditioning enables one to use the hot water tank for other purposes, such as DHW (domestic hot water) production.

For buildings in which cooling is critical (for instance, a data centre), the cooling systems could be equipped with an uninterruptible power supply (UPS). This ensures that there is no cooling interruption, whereas the gensets of an EPS take a few minutes to be operational.

3.2.5 Limited Number of Temperature Pinch Points in Cooling Plants

The design of the cooling plant must limit the number and magnitude of temperature pinch points between the indoor heat source and the outdoor heat sink. Heat exchangers and mixing valves introduce irreversibility which tends to increase the chiller condensing temperature or decrease the evaporating temperature. They also tend to limit the potential of free-chilling operations. Therefore, increasing the number of pinch points and mixing points decreases the cooling resilience. For instance, ice storage with internal melting introduces one more temperature pinch point between the ice and the cooling emitter. This is because one heat exchanger is necessary to decouple the glycol water loop and the chilled water loop feeding the emitters during ice melting.

3.2.6 High-Temperature Cooling System: Radiant Cooling

A hydronic radiant cooling system refers to a system in which water is the heat carrier and at least half of the heat exchange with the conditioned space is by radiation (Babiak et al., 2009; Kazanci, 2016). Heat transfer from indoor spaces occurs through a combination of radiation and convection via cooled surfaces. These systems employ the high-temperature cooling principle, where the heat-transfer medium is close to 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. International standards such as ISO 11855 (for embedded radiant heating and cooling systems) and ISO 18566 (for hydronic radiant heating and cooling panel systems) provide detailed information on the selection, design, and dimensioning of radiant systems.

Radiant cooling systems can be classified as radiant cooling panels, radiant surface systems, and thermo active building systems (TABS) (Babiak et al., 2009).

Radiant panel systems and radiant surface systems can be used in both new buildings and renovated buildings. However, TABS must be installed in the construction phase of a building, which limits the use of TABS in renovation projects. A particular type of radiant ceiling panel emerged which enables this measure to be used in renovation projects and lightweight buildings. This technology combines Phase Change Materials (PCM) 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) behaviour of PCM, which in turn controls the thermal environment in indoor spaces. This is a promising solution and has been proven to perform similarly to TABS in terms of operation, energy performance, heat removal from rooms, and resulting thermal indoor environment (Allerhand et al., 2019a; Allerhand et al., 2019b; Bergia Boccardo et al., 2019; Bogatu et al., 2021).

Figure 3.3 shows an example of a radiant cooling system (a cooling panel).

Figure 3.3. *Example of a cooling panel (Babiak et al., 2009).*

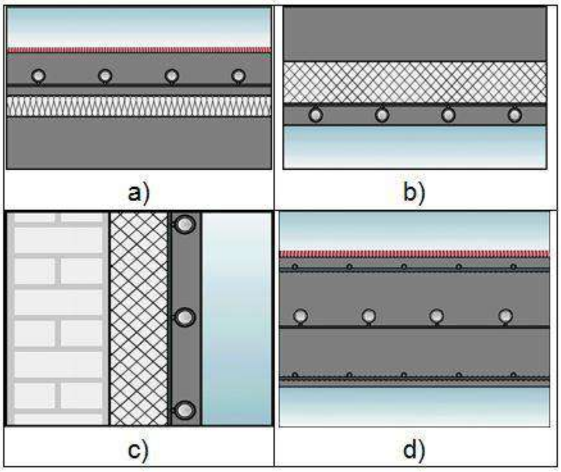


Figure 3.4. *Cross sections of embedded radiant systems: (a) floor, (b) ceiling, (c) wall, and (d) TABS (Olesen, 2000).*

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 (Feustel and Stetiu, 1995; Lehmann et al., 2007; Olesen 2008). It also creates favourable 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. Radiant cooling systems can transfer peak cooling loads to off-peak hours, which reduces peak power demand (Lehmann et al., 2007). Further benefits of radiant systems have been summarized by Kazanci (Kazanci, 2016). One of the major characteristics of radiant systems is that they address only sensible heating and cooling loads. Therefore, they must 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.

Radiant systems have similar characteristics under heat waves and power outages. The absorptive and adaptive capacities of radiant systems during heat waves and power outages range from low to high-low for radiant ceiling panels. These capacities are high for TABS, and in between the former two for the radiant surface systems. This is because these systems have different thermal masses. They therefore have different operation, 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 heat wave, the pre-cooled thermal mass will be able to absorb a certain amount of heat from the space. The restorative and recovery capacities of radiant systems under heat waves and power outages are high. This is because all system types can return to normal or improved operation once the heat wave is over or power is restored, and this can be done immediately (Zhang et al., 2021).

3.2.7 Personal Comfort Systems (Personalized Environmental Control Systems)

Personal Comfort Systems (also known as Personalized Environmental Control Systems (PECS)) serve the functions of heating, cooling, ventilation, lighting, and acoustic control. They have the advantage of controlling the localized environment in the occupant's immediate surroundings, instead of conditioning an entire space. This substantially improves the personal comfort, health of the occupants, and energy efficiency of the entire heating, ventilation, and air conditioning (HVAC) system (Zhang et al. 2010, Rawal et al. 2020, Kazanci 2022). This contrasts with conventional room-conditioning systems that aim to create mostly uniform conditions in indoor spaces.

Figure 3.5 shows an example of a PECS with possible control methods.

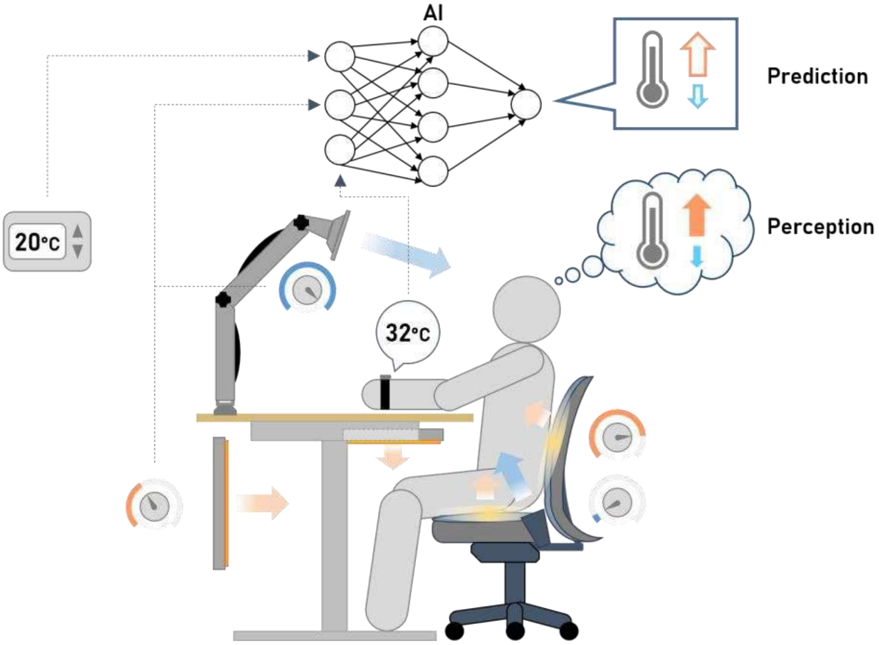


Figure 3.5 *PECS with possible controls (Jun Shinoda).*

The following are the main advantages of PECS (Kazanci 2022):

- Improved occupant comfort, health, and productivity
- Higher occupant satisfaction with the indoor environment
- Improvements to the immediate indoor environment experienced by the occupants
- Possibility of personalized control
- Potential energy and cost savings
- Possibility of addressing individual demands and preferences for the indoor environment conditions
- Resilience to extreme outdoor events (both thermal and air quality)
- Pandemic-proofing of indoor environments (such as providing clean and fresh air directly to the occupants and minimizing cross-contamination).

The main benefits of PECS for resilience include, but are not limited to (Zhang et al., 2021):

- Flexibility in space cooling (and heating) 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 Category II of EN 16798-1:2019 (2019)).
- The possibility of a smaller necessary cooling plant, or its part-time operation, or its part-load operation to decrease load on the grid.

PECS devices have no absorptive capacity under heat waves, as absorptive capacity primarily relates to the building envelope and structure. Under heat waves, PECS have high adaptive capacity, as the user controlling the PECS can adjust its cooling output to its maximum capacity. PECS have no absorptive capacity under power outage events, as absorptive capacity primarily relates to building envelope and structure. Assuming that there are no batteries or emergency power generators during power outages, PECS have low adaptive capacity, as only certain PECS will remain functional. PECS have high restorative and recovery capacities under heat waves and power outages, as PECS function normally following heat waves or power outages, and PECS recover immediately.

3.3 Passive strategies (Including technologies and components)

Passive cooling strategies include the design of building forms and materials to control the internal temperature in hot weather. The overall intent of passive cooling strategies includes blocking direct solar gain from heating up the interior environment, reducing the transmission of direct solar gain and heat through the building fabric, and using natural ventilation methods to expel unwanted heat without the use of mechanical means.

3.3.1 Static Solar Shading

Shading blocks unwanted solar gain from entering buildings. Research has shown that external shading is the most effective form of shading. Static solar shading can be provided to buildings using material additions to the façade or roof. Alternatively, it can be provided with trees or plants. The intelligent planning of the location, sizing, type of glass, and shading used for windows is indispensable for low-emission housing. These choices have a significant impact on heat loss and heat gain. These choices also impact levels of natural lighting, which have a positive impact on human health.

Types of external shading can take many forms, and in hot climates, their varied use has culminated in a cultural aesthetic. Examples of static solar shading include overhangs and vertical fins with calculated angles, jaali, awnings (venetian, hood, etc.), brise-soleil, and covered porches and verandas. Aside from windows, elements like photovoltaic panels can also beneficially shade roof surfaces. Alternatively, trees can shade pavements to reduce the heat build-up in an area's microclimate.

3.3.2 Dynamic Solar Shading

Dynamic solar shading can provide the user with more control over direct solar gain, as the desire for solar gain and levels of daylight can change on a daily and seasonal basis. Although static options can be designed to strategically minimize or maximize solar gain on a seasonal basis, there will still be a slight loss of solar gain in the shoulder seasons.

ISO 52016-3 (2022) *Energy performance of buildings - Energy needs for heating and cooling, internal temperatures, and sensible and latent heat loads - Part 3: Calculation procedures regarding adaptive building envelope elements* provides the energy performance calculation method when modifying the façade of a building using dynamic solar shading or other adaptive building elements. According to the ISO standard, a dynamic solar shading device (a blind or shutter) is a product installed to provide a modifiable level of thermal penetration, visual appeal, or security to an opening or façade. Examples include:

- Internal, external, or integrated blinds (internal/external venetian blind, roller blind, vertical blind, pleated blind, and honeycomb blind)
- Blind in a closed cavity façade (unventilated)
- Shutters (roller shutter, wing shutter, and concertina shutter)

EN 12216:2018 *Shutters, external blinds, internal blinds - Terminology, glossary and definitions* details the general terminology for internal and external blinds and shutter devices. It provides descriptions and technical drawings of different dynamic blinds and awnings based on their mechanical operation. Examples include the plantation shutter, roll-up blind, and folding arm awning (which is an awning where fabric is projected by spring-loaded arms and is retracted by rolling). The standard provides details on the type of mounting (internal and external) and operating mechanisms.

Other examples of dynamic solar shading include Bahama shutters, exterior roll blinds (sometimes made from a material to withstand projectiles from severe storms), sunscreens, awnings (e.g., roller or retractable awnings), trellis (with deciduous vines), sunscreens, and sail shades.

3.3.3 Passive Ventilative Cooling

Passive cooling is an approach to cooling a space or the individuals in a space (perceived thermal comfort) by removing heat in a building or from the individual. Passive cooling is more effective when coupled with other methods to reduce initial heat gain, such as shading or cool envelopes. Techniques to passively cool buildings through ventilation include cross-ventilation, stack ventilation, and night purging.

In existing designs, skylights in lofts can provide a stack effect to exhaust heat build-up. Opening windows to allow airflow and heat escape can be effective, especially when cross-ventilation is possible. However, the efficacy of window openings is determined by resident preference, which can be an unacceptable option where bugs, dust, smells, lights, noise, or fear of unauthorized entry are prevalent (Williams et al., 2012).

Flats may be limited in their ability to allow cross-ventilation. In this case, appropriate window placement and wingwalls may help increase the beneficial cross-airflow in single rooms.

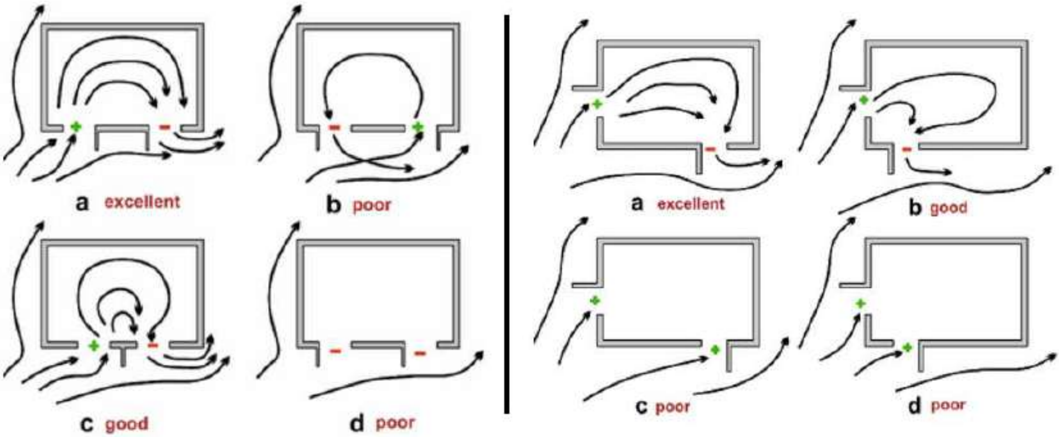


Figure 3.6*. Use of wing walls to capture airflow (Rizk et al., 2018).*

Additionally, though not a passive measure, fans can be an extremely helpful, low-cost, and low-energy solution to provide a cooling effect to individuals and to assist passive measures.

3.3.4 Cool Envelope Materials

Solar reflective walls and roofs (the application of solar reflective white or silver paint to walls and roofs) are common cool treatments for envelope materials. External insulation with solar reflective paint has been shown to be most effective in reducing the impact of solar gain on buildings. Exterior coatings are measured by Solar Reflective Index (SRI; ASTM, 2019) where the higher the SRI the more reflective the coating. SRI is measured on a scale from 0 to 100, where 100 has the highest solar reflectance. White roof coatings, for example, are listed as having a range from a cool white SRI of 71, to a warm white SRI of 82. White roof cooling energy reduction is reported to range from 7–15%, calculations of savings are highly location-dependent (Mellott et al., 2013).

Green roofs are also effective roof cooling solutions. Like white or reflective roof materials, green roofs also have a high albedo. This reflects unwanted solar radiation, while the higher insulative properties of the green roof slow the transmission of heat (Li and Yeung, 2014). However, green roofs are primarily cooled by the evaporation of water from plant surfaces. The soil layer provides additional insulation as well as thermal mass.

Green roofs are broadly categorized into three types. These are extensive, semi-intensive, and intensive. Extensive green roofs have a thin growing medium, require minimal maintenance, and generally do not require irrigation. Intensive green roofs have a deep growing medium that is sufficient to grow trees and shrubs in. Intensive green roofs that can act as parks generally require irrigation. All types serve to provide a level of stormwater management and reduce the urban heat island effect. **Table 3.5** details some differences between these types.

Table 3.5 *Green roof types and characteristics (greenrooftechnology.com).*

Green Roof Type	Extensive	Semi-Intensive	Intensive
Vegetation	Moss, herbs, grasses	Grasses, herbs, shrubs	Lawn, perennials, shrubs, trees
Overall Depth	100-200 mm	150-250 mm	200-750+ mm
Weight Range	100-200 kg/m²	120-300 kg/m²	220-800+ kg/m²
Irrigation System	Not recommended	Partial	Required

Like green roofs, green walls provide a barrier to solar radiation and heat transmission and provide localized cooling through evapotranspiration. Monitoring research (Djedjig et al., 2017) has shown that a constructed green wall can reduce the mean radiant and indoor air temperatures of a building. Furthermore, a green facade can cool the air near it within a street canyon, contributing to the reduction of the urban heat island effect.

Both white or light-coloured surfaces and green roof or walls require maintenance. For white or light-coloured surfaces, it is important to keep them clean, as sediment build-up will cause their albedo to decrease. Green roof and walls require as much care as any garden that contains living plants.

3.4 Overall recommendations

In conclusion, the following active cooling strategies are recommended:

- To improve resilience to heat waves:
  - Increase the capacity of the cooling production system by using cold storage (latent or sensible). The cooling load is covered by both the chiller and the storage, with optimized charging and discharging strategies accounting for weather forecasts.
  - Use a cooling production system whose cooling capacity is independent of weather conditions: including heat-driven chillers, and geo-cooling.
- To improve resilience to power outages:
  - Use heat-driven chillers (converting renewable energies or waste heat and not fossil fuels).
  - Valorise solar air conditioning.
  - Implement backup thermal energy storage.
  - Use cooling systems with low electricity consumption to increase the autonomy of EPS. Therefore, free-chilling, free-cooling, or geo-cooling should be implemented. Furthermore, the number and amplitude of temperature pinch points must be limited to decrease the temperature lift of the chiller and increase its COP.
  - Limit the power consumption of circulating pumps and fans.
  - For buildings with critical cooling (data centres), implement a UPS on chilled water circulating pumps and cooling emitter fans.

Additionally, the following passive cooling strategies are recommended:

- To improve resilience to heat waves:
  - Explore using shading strategies that are secure and avoid solar gains in the summer while allowing the winter sun in.
  - Deploy natural ventilation strategies that allow indoor and outdoor exchange for optimal use of thermal mass.
  - Integrate solar reflective walls and roofs to help reduce the impact of solar gain on buildings.
- To improve resilience to power outages:
  - Use natural ventilation strategies that allow for cross-ventilation with no dependence on energy use.
  - Use external shading that is designed to function without any input of energy.
  - For buildings with critical cooling (data centres), implement cool roofs and green roofs where applicable.

4 Key Performance Indicators for Evaluation of Resilience in Buildings

This chapter summarizes widely used key performance indicators (KPIs) that are suitable for undertaking a resilient cooling analysis of buildings.

The objective of this study is not to comprehensively address all resilience-related KPIs currently in use. A list of useful examples is provided, which is divided into three categories that reflect possible motivations for a resilience analysis: evaluating the overheating and climate resistance of buildings; assessing the thermal comfort and heat stress of occupants; and evaluating related effects on energy performance and emissions.

4.1 Introduction

Key performance indicators represent a quantifiable measure of performance over time for a given objective. Thermal and energy performance are primary concerns in the context of the resilient cooling of buildings. They should be measures of how well a building and its systems are able to provide a healthy indoor thermal environment to its occupants with efficient energy use. Thus, KPIs can be applied to evaluate overheating risk, climate resistance, thermal comfort, and heat stress in buildings. KPIs may also be used to assess different cooling strategies, technologies, and solutions in terms of energy performance and emissions, in combination with other competitive systems and technologies.

It is recommended to select KPIs that communicate whether the building design fosters expected resilience characteristics, such as absorptive capacity, adaptive capacity, restorative capacity, and recovery capacity. For quality resilience assessment criteria, refer to Zhang et al. (Zhang et al., 2021). Multiple KPIs may be necessary to quantify and understand resilience comprehensively.

Table 4.1 shows thirty-two of the most widely used KPIs in their respective categories. The structure of the table is consistent, containing the name and unit of the KPI, the formula and terms, the definition-description, and the source.

4.2 KPIs for Resilient Cooling

KPIs can be clustered into 3 categories:

Category 1: Overheating and climate resistance

Category 2: Thermal comfort and heat stress

Category 3: Energy performance and emissions

Measurements or simulations can be used for the calculation of the KPIs. In this Guidebook, no specific limits or benchmarks are proposed. The energy and emissions KPIs have been developed to be consistent with International Standards.

In this Guidebook, all listed KPIs are only calculated during occupied hours. It is suggested that the values of time-integrated indicators be normalized (e.g. weighted exceedance hours, indoor overheating degree, ambient warmness degree, and others) to the number of days in the episode when comparing them between different timeframes (e.g. heat wave events). The same normalization approach should also be used to calculate energy usage (e.g. summer months or cooling seasons of variable durations).

4.3 KPIs in Practice

The following recommendations are provided to assist in the selection of a suite of KPIs that are relevant to the specific building(s) under assessment:

- Select multiple KPIs to comprehensively quantify and understand resilience. The KPIs should be consistent with the RCD brief for the building.
- Select KPIs from different categories to ensure that overheating risk/climate resistance, occupant thermal comfort/heat stress, and energy performance/emissions impacts are being assessed.
- Determine the benchmarks or minimum performance standards to be reached given all stakeholders associated with a specific building.
- Devise an ‘emergency management plan’ (refer to Chapter 2) if building performance (in terms of thermal comfort and safety) is breached by unexpected extreme weather (beyond the resilience design parameters) or energy outage events. It is important that each building has a plan for keeping building occupants safe in such circumstances and that this plan is communicated to occupants. This resembles common emergency management plans in buildings in the event of fires or other emergencies (e.g. occupants need to know when it is suitable to ‘shelter in place’ and when it is advisable to evacuate the building).

***Table 4.1**. Key performance indicators.*

1. Indoor Overheating Degree (*IOD*), (°C) [Category 1]

$$IOD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}}\left[\left(T_{fr,i,z} - TL_{comf,i,z}\right)^{+}\bullet t\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}} t_{i,z}}$$

z: the building zone counter; *i*: the occupied hour counter; *t*: the time step (typically it is 1 h) [h]; *Z*: the total number of zones in a building; $N_{occ}(z)$: the total occupied hours in a given calculation period; T_{fr}: the free-running indoor operative temperature at the time step *i* in the zone *z* [°C]; TL_{comf}: the comfort temperature limits at the time step *i* in the zone *z* [°C].

It is the summation of positive values of the difference between zonal indoor operative temperatures and the thermal comfort limit (operative temperature or *PMV/PPD*), averaged over the sum of the total number of zonal occupied hours. Both fixed and adaptive temperature limits can be assumed as comfort thresholds. Applied to both single zones and multi zones (controlled, hybrid, and free-running mode). *(Source: Hamdy et al., 2017)*

2. Ambient Warmness Degree (*AWD*), (°C) [Category 1]

$$AWD_{18°\mathrm{C}} \equiv \frac{\sum_{i=1}^{N}\left[\left(T_{a,i} - T_b\right)^{+}\bullet t_i\right]}{\sum_{i=1}^{N} t_i}$$

T_a: the outdoor dry-bulb air temperature [°C]; T_b is base temperature (set at 18°C) [°C]; *N*: the number of occupied hours such that $T_{a,i} > T_b$ in the summer season; *t*: the time step [h].

Indication of the severity of outdoor thermal conditions. Only positive values. The selection of base temperature is context-specific based on the building typology and climate. *(Source: Hamdy et al., 2017)*

3. Overheating Escalation Factor (*αIOD* or *OEF*) [Category 1]

The slope of the regression line between *IOD* and *AWD*.

It is used to assess the resistivity of a building to climate change and associated overheating risks. An overheating escalation factor greater than the unit ($\alpha IOD > 1$) means that indoor thermal conditions get worse when compared to outdoor thermal stress. On the contrary, an overheating escalation factor lower than the unit ($\alpha IOD < 1$) means that a dwelling can suppress some of the outdoor thermal stress. *(Source: Hamdy et al., 2017)*

4. Climate Change Overheating Resistivity (*CCOR*) [Category 1]

$$\frac{1}{CCOR} \equiv \frac{\sum_{Sc=1}^{Sc=M}(IOD_{Sc} - \overline{IOD}) \times (AWD_{Sc} - \overline{AWD})}{\sum_{Sc=1}^{Sc=M}(AWD_{Sc} - \overline{AWD})^2}$$

Sc: weather scenario counter [-]; M total number of weather scenarios [-]; $\overline{IOD}$ and $\overline{AWD}$): average of total *IODs* and *AWDs*.

The *CCOR* shows the rate of change in the *IOD* with an increasing *AWD* due to the impact of climate change. It can be calculated using linear regression assuming linearity between the *IOD* and *AWD*. It is introduced to couple the outdoor and indoor environments, quantifying the climate change overheating resistivity of cooling strategies in buildings. Where CCOR>1 the building can suppress the increasing outdoor thermal stress due to climate change, and where *CCOR* < 1 the building is unable to suppress increasing outdoor thermal stress due to climate change. *(Source: Rahif et al., 2022)*

5. Unmet Hours or Exceedance hours, (h or %) [Category 2]

The number of occupied hours within a defined period in which the environmental conditions in a zone exceed a defined comfort criterion. It can be applied to a wide range of comfort criteria, such as operative temperature, *PMV*, *PPD*, *SET*, and others (per year, per month, per week or per day). It may also be applied using weighing factors. *(Source: Psomas et al., 2015; 2016; ASHRAE, 2021; EN, 2019)*

6. Exceedance Degree Hours, (degree h) [Category 2]

The number of occupied degree hours within a defined period in which the environmental conditions in a zone exceed a defined comfort criterion. It can be applied to a wide range of comfort criteria, such as operative temperature, *PMV*, *PPD*, *SET*, and others (per year, per month, per week or per day). *(Source: Psomas et al., 2015; 2016; ASHRAE, 2021; EN, 2019)*

7. Hours of Exceedance (*He*), (h) [Category 2]

The number of hours (*He*) during which ΔT is greater than or equal to one degree (K). ΔT the difference between the actual operative temperature in the room at any time (T_{op}) and T_{max} the limiting maximum acceptable temperature. ΔT is rounded to the nearest whole degree. Inclusive shall not be more than 3 per cent of occupied hours. *(Source: CIBSE, 2013)*

8. Daily Weighted Exceedance (*We*), (°C.h/d) [Category 2]

We = Σ(he)×WF

> *he*: time [h] when $WF = y$; *WF*: weighting factor [-]; $WF = 0$ if $\Delta T \leq 0$, otherwise $WF = \Delta T$; ΔT: temperature above the comfort threshold temperature [°C].

This indicator sets an acceptable level for the severity of overheating in a single day. To allow for the severity of overheating the weighted exceedance (*We*) shall be less than or equal to 6 in any one day. *(Source: CIBSE, 2013)*

9. Upper Limit Temperature, (°C) [Category 2]

The difference between the actual operative temperature in the room at any time (T_{op}) and the limiting maximum acceptable temperature (T_{max}). An absolute maximum value for the indoor operative temperature the value of ΔT shall not exceed 4 K. *(Source: CIBSE, 2013)*

10. Averaged PPD (*AvgPPD*), (%) [Category 2]

The average predicted percentage of dissatisfied occupants over time, during occupied hours. *(Source: ISO, 2005)*

11. Unmet Load Hour, (h) [Category 2]

An hour in which one or more zones is outside of the thermostat setpoint, plus or minus one half of the temperature control throttling range. Any hour with one or more zones with an unmet cooling load or unmet heating load is defined as an unmet load hour. If unmet load hours for multiple spaces coincide (occur in the same hour), they are counted as only one unmet load hour for the building. Unmet load hours for the proposed design or baseline building designs shall not exceed 300 (of the 8 760 hours simulated), and unmet load hours for the proposed design shall not exceed the number of unmet load hours for the baseline building design by more than 50. *(Source: ASHRAE, 2022)*

12. Overall Weighted Unmet Thermal Performance ($WUMTP_{overall}$), (degree h/m^2) [Category 2]

$$WUMTP = \sum_{i=1}^{12} S_i W_{P,i} W_{H,i} W_{E,i}$$

$$WUMTP_{\text{overall}} = \frac{\sum_{z=1}^{Z} WUMTP_z}{\sum_{z=1}^{Z} A_z}$$

i: 12 segments [-]; S_i: area of segment i during the occupancy hours, calculated based on the hourly indoor operative temperature [°C.h]; $W_{P,i}$: phase penalty [-]; $W_{H,i}$: hazard penalty [-]; $W_{E,i}$: exposure time penalty [-]; z: building zone counter [-]; Z: total number of zones [-]; A_z area of each zone [m^2]

The deviation from the thermal targets for the whole building and penalizes them based on three factors: the phase, the hazard level, and the exposure time of the event. It is calculated from a multi-phase thermal resilience curve associated with a specific event (e.g. power outage during a heat wave). It can quantify resilience during and after the disturbance. *(Source: Homaei et al., 2021)*

13. Maximum Annual Operative Temperature ($T_{o,max}$), (°C) [Category 2]

$T_{o,max}$ = max($T_{o,occ,n}$)

$T_{o,occ,n}$: hourly operative temperature when the room is occupied at hour "n" [°C]

The maximum annual operative temperature inside a room when it is occupied. It describes the intensity of overheating (between all rooms). *(Source: Krelling et al., 2023)*

14. Passive Survivability [Category 2]

The ability to maintain safe indoor thermal conditions in the absence of active cooling (air conditioning). The output is a yes or no within a chosen timestep. It is based upon a definition of survivable indoor conditions. *(Source: Sun et al., 2021)*

15. Thermal Autonomy, (%) [Category 2]

The fraction of time a building can passively maintain comfort conditions without active systems. *(Source: Kesik et al., 2019)*

16. Standard effective temperature (SET), (°C) [Category 2]

The temperature of an imaginary environment at 50 percent relative humidity, less than 0.1 meters per second air speed, and where the mean radiant temperature equals the air temperature, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level. Furthermore, they have the same heat stress (skin temperature) and thermoregulatory strain (skin wettedness) as in the actual test environment. *(Source: ASHRAE, 2021)*

17. Wet Bulb Globe Temperature ($WBGT$), (°C) [Category 2]

$WBGT = 0.7 \times T_w + 0.2 \times T_g + 0.1 \times T_d$

T_w: natural wet-bulb temperature; T_g: globe thermometer temperature; T_d: dry-bulb temperature.

It is a type of apparent temperature used to estimate the effect of temperature, humidity, wind speed (wind chill), and visible and infrared radiation (usually sunlight) on humans. Compliance with passive survivability (thermal safety). *(Source: Holzer, 2022)*

18. Percentage of Occupied Hours Within a Heat Index Range (*PHHI*), (%) [Category 2]

The heat index (*HI*) represents what the temperature feels like to the human body when relative humidity is combined with the air temperature. For a single zone, the *PHHI* is calculated as the proportion of occupied hours that a space is occupied, and its heat index is within each of the different ranges. For multi-zones: average values for each range considering all zones. An *HI* between 26.7°C and 32.2°C is classified with "Caution" (fatigue possible with prolonged exposure and/or physical activity). An HI between 32.2°C and 39.4°C is classified with "Extreme Caution" (heat stroke, heat cramps, or heat exhaustion are possible). An *HI* between 39.4°C and 51.1°C is classified with "Danger" (heat cramps or heat exhaustion are likely, and heat stroke is possible). An *HI* of 51.7°C and beyond is classified with "Extreme Danger" (heat stroke highly likely). Compliance with passive survivability indicator (thermal safety). *(Source: Steadman, 1979)*

19. Predicted Heat Strain (*PHS*) [Category 2]

The thermal balance of the body, influenced by the parameters of the thermal environment (air temperature, mean radiant temperature, partial vapor pressure, and air velocity) and the mean characteristics of the subjects exposed to the working situation (metabolic rate and clothing insulation). It is connected with body dehydration and core temperature. *(Source: ISO, 2004)*

20. Recovery Time, (h) [Category 2]

Amount of time between the moment of maximum annual operative temperature ($T_{o,max}$) and the time when the space reaches an acceptable operative temperature threshold. For multi-zones, it is the amount of time the zone with highest Tomax takes to recover. *(Source: Homaei et al., 2021)*

21. Cooling Load per Conditioned Floor Area, (W/m^2) [Category 3]

Heat (energy) to be extracted from a thermally conditioned space to maintain the intended space temperature conditions during a given period. Divided by the conditioned floor area. Alternatively, peak load (max) during a period is used. *(Source: Zhang et al., 2023)*

22. Annual Cooling Source Energy Saving Intensity, (kWh/m^{2}a) [Category 3]

The annual reduction of source energy for cooling, per conditioned floor area, that can be achieved by a specific (resilient) cooling measure, against a conventional cooling solution without this specific (resilient) cooling measure. It is the cooling for a year divided by the conditioned floor area. *(Source: Zhang et al., 2023)*

23. Annual Cooling Site Energy Use per Conditioned Floor Area, (kWh/m^{2}a) [Category 3]

The cooling site energy use over a year divided by the conditioned floor area. Indicate gas, electricity, or other energy. *(Source: Zhang et al., 2021)*

24. Annual Cooling Primary Energy Use per Conditioned Floor Area, (kWh/m^{2}a) [Category 3]

The cooling primary energy use for a year divided by the conditioned floor area. Indicate gas, electricity, or other energy and national or regional primary energy factors. *(Source: Zhang et al., 2021)*

25. Annual HVAC System Total Primary Energy Use per Conditioned Floor Area, (kWh/m^{2}a) [Category 3]

HVAC refers to heating, cooling, ventilation, and air conditioning. The HVAC usage for a year divided by the conditioned floor area. Indicate national or regional primary energy factors. *(Source: Zhang et al., 2023)*

26. Reduction in Peak Source Power Demand Intensity, (W/m^2) [Category 3]

The annual reduction of source peak power demand (relative to the floor area) that can be achieved by a specific (resilient) cooling measure, against a conventional cooling solution without this specific (resilient) cooling measure. The reduction in source peak power demand may be extended to the number of annual hours during which grid power demand exceeds grid power supply. *(Source: Holzer, 2022)*

27. Reduction in Peak Site Power Demand Intensity, (W/m^2) [Category 3]

The annual reduction of site peak power demand (relative to the floor area) that can be achieved by a specific (resilient) cooling measure, against a conventional cooling solution without this specific (resilient) cooling measure. *(Source: Zhang et al., 2021)*

28. Seasonal Energy Efficiency Ratio (*SEER*) [Category 3]

The coefficient of performance (*COP*) (identical to the energy efficiency ratio (*EER*) of a refrigerator, chiller, or air conditioning system) is the ratio between useful cooling output and power input, at a given state of operation. The seasonal coefficient of performance (*SCOP*) (which is identical to the seasonal energy efficiency ratio (*SEER*)) is the same ratio over a full cooling period. *COP* and *EER* shall include not only a compressor's energy need but all auxiliary energy needs, too. *COP* and *EER* can be applied not only to active cooling technologies but also to automated passive ones. In this case, the power input is limited to auxiliary energy inputs (such as fans, circulation pumps, actuators, or controls). *(Source: Zhang et al., 2023)*

29. Seasonal Coefficient of Performance (*SCOP*) [Category 3]

See above. *(Source: Zhang et al., 2023)*

30. Annual CO_2-equivalent Emission per Conditioned Floor Area from HVAC Energy Use, ($KgCO_2/m^2a$) [Category 3]

Greenhouse gas emissions associated with the HVAC energy use during a given period. For a year divided by the conditioned floor area. Indicate national or regional carbon emission factors. *(Source: Zhang et al., 2023)*

31. Ozone Depletion Potential (*ODP*), (gCFC11eq) [Category 3]

The ozone depletion potential of a refrigerant. It is a measure of how much damage a chemical can cause to the ozone layer compared with a similar mass of trichlorofluoromethane (CFC-11). (*Source: DCCEEW*)

32. Global Warming Potential (*GWP*) [Category 3]

The global warming potential of a refrigerant. It describes the relative potency (molecule for molecule) of a greenhouse gas, taking account of how long it remains active in the atmosphere. (*Source: EC*)

5 Building Performance Assessment Methods and Tools

5.1 Introduction

The objective of this chapter is to provide a brief review of the various methods and tools used for building performance assessments. Performance assessment methods and tools are used to evaluate the operational and energy efficiency of buildings and to identify potential improvements and areas for further investigation. Emphasis is given to the modelling of resilient cooling technologies and strategies. The chapter also provides a framework for the selection of input and output parameters used in the simulation and assessment.

5.2 Approaches to Energy Modelling of Buildings

5.2.1 General Modelling Approaches

Two general modelling approaches can be applied to the energy performance assessment of buildings:

> **Forward (direct) approach**, which allows one to predict the output variables of a system with known structure and known parameters, subject to specified input variables.
>
> **Data-driven (inverse) approach**, in which inputs and outputs are known and measured, and the objective is to derive a mathematical model of the system and estimate its parameters.

The forward approach presupposes in-depth knowledge not only of the various physical phenomena that affect the behaviour of the system but also of the magnitude of the various interactions and therefore of the parameters that characterize the system (such as heat and mass exchange coefficients and thermal capacities). The main advantage of this approach is that the system does not necessarily have to be real (as in the case of the data-driven approach). Therefore, this approach is used in the initial design stage and during the analysis stage. Direct modelling of building energy requires the physical description of the building system or component being considered. For example, the geometry of the building, the geographic location, the thermal characteristics (e.g., properties of the materials and thicknesses of the layers forming the walls), the type of equipment and their operating time profiles, the type of air conditioning system, the hours of use of the building, and the equipment of the plant are specified.

Unlike the direct approach, the data-driven approach is appropriate when the system under investigation is already built, and actual performance data are available for model development and/or identification (ID). The ID allows mathematical models of a dynamic system to be built based on measured data, essentially by adjusting parameters within a given model until its output coincides as well as possible with the measured output. Data-driven modelling often enables the ID of system models that are not only easier to use but also enable more accurate forecasting of system performance than direct models.

The data-driven approach emerges in many fields (such as physics, biology, engineering, and the economy) but the approach has not been widely adopted in energy and building models.

This chapter focuses on the direct approach; it presents several advantages given that it is based in engineering principles, and it is therefore recognized and accepted by the professional world. Furthermore, the primary building thermal energy simulation tools are based on direct simulation models.

5.2.2 Flowchart of the Energy Simulation Process

The procedures for energy analysis of buildings are generally split into the following items:

(1) Calculation of the thermal loads of the built environment, which are the heat flows that need to be added or removed from an internal environment to maintain pre-set temperature and relative humidity conditions.
(2) Calculation of the thermal and electrical loads of the secondary equipment, which includes the appliances that distribute heating fluid, cooling, or ventilation to air-conditioned environments.
(3) Calculation of the energy use of primary equipment, which includes the generation plant equipment converting fuel, electricity, or on-site renewable sources into heating and cooling energy used by secondary equipment.
(4) Performance of an economic and environmental analysis that allows the cost-effectiveness and environmental performance of energy-saving measures to be established.

The previous four items are often analysed in series to define the flowchart of the energy simulation process. However, in more complex models, it is possible to follow a holistic approach and to have interactions between the analyses referred to in items (1), (2), and (3).

Item (1) is linked to the performance of the building as such (fabric), while items (2) and (3) consider HVAC systems, and item (4) introduces specific metrics (even multi-domain metrics) to assess the building performance.

5.2.3 Classification of Forward Models

As regards the application context and boundary conditions, the forward energy models can be classified according to:

- Considered the physical system (e.g., the fabric alone or the building, including its technical systems).
- Level of spatial detail of the assessed object (e.g., a single space, a thermal zone, or the whole building).
- Time variation and time interval of the boundary conditions for which the main differentiation is between steady-state and dynamic regimes.

In the steady-state regime, boundary variables are integrated over time by adopting average values either on monthly or seasonal time steps. In the dynamic regime (which can be differentiated into periodic and non-periodic regimes), boundary variables are either time-stamped or integrated over hourly or sub-hourly time steps.

5.2.4 I/O Data for Energy Calculations

The input data for energy calculations can be classified into four main categories: climate, building, HVAC systems, and users:

- Climate data include time schedules of air temperature and humidity, solar irradiance, wind speed and direction, and cloud coverage.
- Building data include thermal parameters of building components (layers, thermal/solar properties), thermal bridge characteristics, and external solar shading.
- HVAC systems data include the characteristics of different components categorized by type of system (heating, cooling, ventilation) and sub-system (emission, control, distribution, storage, generation).
- User data include time schedules of occupancy rate, internal heat gains, management of shading devices, shutters, natural and mechanical ventilation, and thermostats.

The primary instantaneous results of dynamic thermal simulations of a building are the hourly or sub-hourly values of the following quantities:

- Air temperature and relative humidity operating temperature
- The temperature of the surfaces of the enclosure
- Cooling and heating loads in the space
- Thermal energy gains or losses of building elements
- Supply and extraction airflow rates
- Temperature and relative humidity of the supplied air
- Capacities of the various components of the air conditioning system
- Airflow rates and temperatures at each node of the air conditioning system.

5.3 Modelling of Specific Resilient Cooling Technologies and Strategies

5.3.1 Framework of the Resilient Cooling Technologies and Related Assessment Methods

Four cooling-strategy categories have been developed based on their approaches to cooling people or the indoor environment (Zhang et al., 2021):

- Reducing heat gains to indoor environments and people indoors
- Removing sensible heat from indoor environments
- Removing latent heat from indoor environments
- Enhancing personal comfort, apart from cooling whole spaces

Resilient cooling technologies can also be classified according to the system to which they belong:

- Envelope technologies (such as solar shading and advanced shading), cool roofs, ventilated façades, PCM, and advanced glazing
- Technical building systems (such as active ventilative cooling, dehumidification, and high-efficiency cooling)
- Building Automation and Control Systems (BACS)

Table 5.1 *International standards applicable to the performance of different resilient cooling technologies.*

Strategy	Technology	Standard(s)
Reducing heat gains to indoor environments and people indoors	Advanced solar shading or glazing technologies	ISO 52016-3
	Cool envelope materials	ASTM E1980-11 ISO 22969
	Green roofs, roof pond, and green facades	BS 8616 (2019) ASTM E2777 (2020)
	Ventilated roofs and ventilated facades	ISO 52016-3
	Thermal mass utilization	ISO 13786 EN 16798–15
Removing sensible heat from indoor environments	Ventilative cooling	EN 16798-7 CIBSE AM10
	Evaporative cooling	EN 16798-5-1
	Compression refrigeration	EN 16798-13 ISO 13612
	Absorption refrigeration including desiccant cooling	EN 16798-13 ISO 13612
	Ground source cooling	EN 16798-13 ISO 13612
	Sky radiative cooling	ISO 52017-1 / ISO 52016-1
	High temperature cooling systems	ISO 52031 ISO 11855-7
Removing latent heat from indoor environments	Dehumidification	EN 810
Personal comfort system (PCS)	Vertical-axis ceiling fans and horizontal-axis wall fans	ISO 7730 EN 16798-1 ASHRAE 55
	Small desktop-scale fans or stand fans	
	Furniture-integrated fan jets	
	Devices combining fans with misting or evaporative cooling	
	Cooled chairs, with convective or conductive cooled heat absorbing surfaces	
	Cooled desktop surfaces	
	Workstation micro air conditioning units including personalized ventilation	
	Personalized radiant panels	
	Conductive wearables Fan-ventilated clothing ensembles Variable clothing insulation	

5.3.2 *Adaptive Building Envelope Elements*

ISO 52016-3 specifies procedures for the hourly calculation of internal temperatures and sensible and latent heat loads of a building by considering the following adaptive building envelope elements:

- Those with dynamic solar shading
- Those with chromogenic glazing
- Those with an actively ventilated cavity

For each type of adaptive envelope element, the method can apply to different control scenarios and control types. For example, either an environmentally activated or an actively controlled (manual, motorized, or automated) element can be considered.

5.3.3 *Green Roof*

No standardized model is currently available. In EnergyPlus, a model of the heat transfer processes involved on a vegetated roof has been developed. This accounts for:

- Long-wave and short-wave radiative exchange within the plant canopy
- Plant canopy impacts on convective heat transfer
- Evapotranspiration from the soil and plants
- Heat conduction (and storage) in the soil layer

5.3.4 *Thermal Mass Utilization*

Thermal energy can be stored (as a change in the internal energy) in 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).

ISO 13786:2017 specifies the characteristics related to the dynamic thermal behaviour of a complete building component and provides methods for their calculation. The calculation method uses complex numbers representing a sinusoidal variation of temperature and heat flow to calculate the dynamic thermal properties of a building component. These functions approximate daily variations on an hourly basis and annual variations monthly.

The EN 16798-15 European Standard specifies a calculation method for the energy performance of storage systems used for ventilation systems. It considers the energy performance of storage systems using water from phase change material (PCM) to store cooling energy. This standard presents a general method applicable to the different technologies of water-based storage systems or PCM-related control systems.

The standard EN 16798-15 covers the calculation of the energy use for the following technologies:

- Storage of energy without phase change (use of the sensible thermal capacity of water)
- Storage of energy using the latent thermal capacity of liquid and solid water: the ice is formed outside (most frequently) of a tube where the primary refrigerant is circulating. The set of tubes is installed inside an insulated reservoir, which is connected to the refrigerating unit and to the distribution system. As an alternative, the ice could be stored inside a tubing system
- Storage of energy using the latent capacity of PCM other than water. In this scenario, we condition the PCM in nodules installed inside an insulated reservoir

5.3.5 Ventilative Cooling

The EN 16798-15 European Standard describes the methods to calculate the ventilation air flow rates for buildings to be used for energy calculations, evaluation, heating, and cooling loads. It is applicable to hybrid systems combining mechanical and passive duct ventilation systems in residential and low-rise non-residential buildings. The results provided by the standard include the air flow rates entering or leaving a ventilation zone and the airflow rates required to be distributed by the mechanical ventilation system, if present. Air flow rate may be calculated using two methods:

- **Method 1** estimates the air flow rates based on detailed building characteristics
- **Method 2** specifies rules to fulfil to apply a statistical approach to be defined at the national level for the determination of air flow rates (including infiltration) that may be based on calculations with Method 1 or on measurements

5.3.6 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 coils).

5.3.7 High-Temperature Cooling Systems

ISO 52031:2020 presents an overall calculation method for the additional heat losses and energy efficiency of heat emitters based on temperature differences (temperature variations). The determination of input parameters for embedded surface cooling systems is specified in ISO 11855-7:2019.

5.3.8 Building Automation and Control System (BACS)

ISO 52120-1:2021 specifies a structured list of Building Automation and Control System (BACS) and Technical Building Management (TBM) functions that have an impact on the energy performance of buildings. Moreover, methods to assess the impact of these functions in the calculations of energy performance are also specified.

BAC functions related to space cooling include emission control, emission control for TABS, control of distribution network cold water temperature (supply or return), control of distribution pumps in networks, intermittent control of emission and distribution, interlocking heating and cooling control of emission and distribution, generator control for cooling, sequencing of different chillers, and control of thermal energy storage (TES) charging.

BAC functions related to ventilation and air conditioning include supply airflow control at the room level, room air temperature control by the ventilation system, coordination of room air temperature control by ventilation and by the static system, outside air (OA) flow control, air flow or pressure control at the air handler level, heat recovery control to prevent overheating, free mechanical cooling, supply air temperature control at the Air Handling Unit (AHU) level, and humidity control. BAC functions related to blind control are aimed at avoiding overheating and glaring.

5.4 Available Simulation Tools and Future Improvements

5.4.1 Comparison of Tools for Whole Building Simulation

Building performance simulation (BPS) tools have been widely used over the past 50 years for developing whole-building energy models. They allow architects, engineers, and building owners to analyse and simulate the energy performance of a building, identifying opportunities to save energy, reduce costs, and improve occupant comfort. These tools vary in aspects such as their accuracy, flexibility, user-friendliness, and graphical capabilities. Overall, choosing a suitable BPS tool depends on several factors, such as the type of building and the complexity of the model. Therefore, it is essential to conduct a thorough investigation and comparison of available BPS tools before selecting the most suitable one for a particular project.

In this section, we will compare seven popular BPS tools: EnergyPlus, DesignBuilder, IES VE, TRNSYS, eQUEST, Modelica, and IDA-ICE.

- EnergyPlus: EnergyPlus is a free and open-source BPS tool developed by the U.S. Department of Energy (DOE). It is designed to simulate the energy use of buildings, including heating, cooling, ventilation, lighting, and plug loads. It includes a graphical user interface (GUI) and supports several file formats, including gbXML, IDF, and OpenStudio. EnergyPlus also includes a large library of predefined building components, weather data sets, and design day data sets.
- DesignBuilder: DesignBuilder is a BPS tool that integrates 3D building design with energy simulation capabilities. It is known for its user-friendliness and ability to generate models quickly. DesignBuilder supports several file formats, including gbXML, DXF, and IFC. DesignBuilder also offers advanced features, such as a daylighting module, parametric analysis, and HVAC optimization.
- IES VE: IES Virtual Environment (VE) is a BPS tool that includes energy simulation, daylighting analysis, and CFD analysis. It is known for its accuracy and flexibility, allowing users to model complex building systems and configurations.

ISE VE supports several file formats, including gbXML, IFC, and OpenStudio. ISE VE also offers advanced features, such as BIM integration.

- TRNSYS: TRNSYS is a BPS tool that specializes in simulating energy systems, such as solar thermal, photovoltaic, and geothermal systems. TRNSYS supports several file formats, including TRNSYS Type, IDF, and CSV. TRNSYS also offers advanced features, such as Monte Carlo simulation.
- eQUEST: eQUEST is a BPS tool that focuses on energy-efficient building design. It is known for its user-friendliness and ability to generate models quickly. eQUEST supports several file formats, including DOE-2, EnergyPlus, and gbXML components. eQUEST also offers advanced features, such as a daylighting module, parametric analysis, and HVAC optimization.
- IDA-ICE: IDA-ICE is a BPS tool that specializes in indoor climate and energy performance. It is known for its accuracy and ability to model complex indoor environments.

Table 5.2 *Comparison of tools for modelling of specific technologies including some design parameters.*

Technicality	**Building Performance Simulation Tools**					
	Energy-Plus	**Design-Builder**	**IES VE**	**TRNSYS**	**eQUEST**	**IDA-ICE**
Hourly Energy Simulations	✓	✓	✓	✓	✓	✓
Sub-Hourly Energy Simulations	✓	×	✓	✓	×	×
Multi-Zone Calculations	✓	✓	✓	✓	✓	✓
Configuration of HVAC Systems	✓	✓	✓	✓	✓	✓
Modelling of Carbon Dioxide	✓	×	✓	✓	×	✓
Selections of Systems in Simulations	×	✓	✓	✓	✓	✓
Importing from CAD	✓	✓	✓	×	✓	✓
Exporting to CAD	✓	✓	×	×	×	✓
Natural Ventilation Modelling	✓	✓	×	✓	×	×
Window Airflow	✓	✓	✓	✓	×	✓

5.5 Calibration and Optimisation

Building Energy Models (BEMs) are essential tools for understanding different building performance metrics for new and existing buildings. BEM calibration is an important step in ensuring the accuracy of the model [24]. Specifically, it is the process of adjusting the model inputs and assumptions to more accurately reflect the real-world conditions of the building, such as actual construction details, occupancy patterns, and equipment performance. The process may include, but is not limited to:

- **Validation of Design Assumptions:** During the design phase, building simulation models are often used to predict energy performance, thermal comfort, and other aspects of a building before it is constructed. Calibrating the model involves comparing its predictions to actual data from existing buildings with similar characteristics. This helps validate the design assumptions and ensures that the model accurately represents the real-world behaviour of the proposed new building.
- **Commissioning:** Verifying that the building systems are operating as intended and meeting design goals;
- **Operation:** After construction, calibration can be used to verify that the actual building is performing as expected based on the design. Any discrepancies between the model's predictions and real-world data can be investigated and addressed.
- **Retrofits:** Analysing the potential impact of different retrofit options on energy use and identifying the most cost-effective measures.

The process of calibration or adjustment can be achieved either by manual or automatic approaches when the BEM simulation results are different from the measurements. However, both approaches are known to be mostly deterministic and ignore the inherent uncertainties of the BEMs. Comparatively, the recent development of stochastic automatic BEM calibration (e.g., based on Genetic Algorithm (GA) [25] and Bayesian Inference (BI) [24]) has gained wide attention. This section focuses on the automatic calibration of Genetic Algorithm (GA) and the associated software tools. With validated BEMs, building owners, operators, and designers can make more informed decisions about how to optimize building performance.

5.5.1 Calibration Procedure by Genetic Algorithm

The genetic algorithm has been shown to be effective for automatic calibration based on building performance data, such as energy consumption or thermal data. For example, it has recently been used for BEM calibration based on indoor temperature data measured from multiple buildings and rooms [25, 26, 27]. The auto-calibration methodology consists of nine steps, as explained below, and illustrated in **Figure 5.1**:

- *Collect information about an existing building* that can be obtained by building managers or through field measurements. The minimum required information for BEM includes the geometry of the building (exterior and interior dimensions), orientation (e.g., from GIS tools such as Google Map/Earth), the activity type within the building, and the mechanical HVAC system.
- *Create a building simulation model* in an energy simulation tool (e.g., EnergyPlus (E+)) using the collected data as inputs.

- *Determine the uncertainty in input building parameters and their distribution ranges*. In the absence of information about the renovation, it is recommended to create two calibration ranges, one based on the original construction of the building, and the other on proposed renovations.
- *Use global or local sensitivity analysis* (if necessary) to reduce the number of uncertain parameters by selecting sensitive, uncertain parameters. SimLab, Sobol Indices Toolbox, jEplus-EA, or DesignBuilder can be used.
- Remove any insensitive parameters from the calibration process and assign a specific value to these parameters in E+ initial model by setting the average value of their range.
- *Define Multi-Objective Genetic Algorithm MOGA simulation settings,* defining objective functions, decision variables, population size, genetic operations, generation count, and termination criteria.
- *Determine the Pareto optimal solutions* in each iteration based on the evaluation criteria (objective functions) established for each room (as shown in Section 5.5.3).
- *Stop the iteration and select the final Pareto optimal solutions* if the Pareto solutions have not changed in the last ten generations.
- *Determine the final optimal solution* from the Pareto optimal solutions list based on the new selection criteria (as shown in Section 5.5.4).

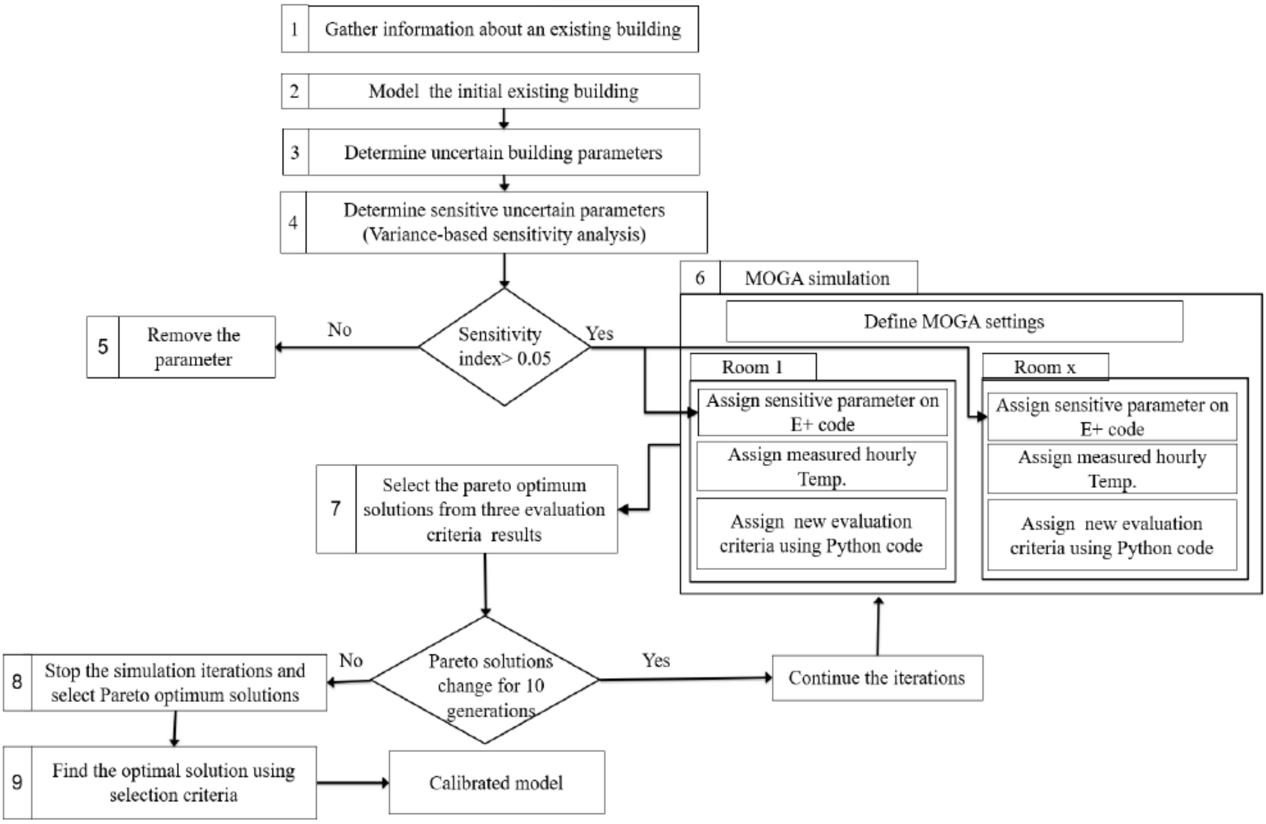


***Figure 5.1** Flowchart of the genetic algorithm automatic calibration based on hourly indoor air temperature of multi-rooms.*

5.5.2 Calibration Tool – jEPlus and jEPlus+EA

jEPlus is a Java-based graphical user interface for EnergyPlus. The jEPlus tool allows users to create and run EnergyPlus simulations easily with a variety of different input parameters. jEPlus+EA is a software tool that combines EnergyPlus simulation software with evolutionary algorithms. JEPlus+EA uses NSGA-II genetic algorithm (Non-dominated Sorting Genetic Algorithm II) to solve problems with multiple objectives, where the goal is to find a set of solutions that are not dominated by any other solution in the problem space (such as optimization tasks and calibration studies). jEPlus is a component of the jEPlus+EA software package. The key advantage of this software is that it allows for parametric analysis for building optimization.

5.5.3 Evaluation Criteria

In the calibration process, the objective functions are typically measures of the disparity between the simulated model outputs and the observed real-world data, aiming to minimize this disparity to achieve a close match between the model and reality. Previous studies that calibrated buildings using energy meter data typically used evaluation criteria (objective functions) like RMSE (Root Mean Square Error) and NMBE (Normalized Mean Bias Error) to determine the error between measured and predicted energy consumption of buildings. However, these criteria can be achieved even though there is a significant discrepancy between prediction and measurement temperature data distribution. Therefore, these three evaluation criteria (objective functions) are required for each room:

- Maximum Absolute Difference (MAD) finds the maximum absolute difference between the simulated and measured hourly indoor temperature during the calibration period.
- RMSE shows how close the simulated values are to the measured values and how similar the distribution is.
- NMBE captures the average bias between them.

$$MAD\ (°\mathrm{C}) = \mathrm{Max}\ (\mathrm{abs}(T_{\mathrm{s}j} - T_{\mathrm{m}j})), j = 1 \dots n \tag{6}$$

$$RMSE\ (°\mathrm{C}) = \left[\frac{1}{n-1} \cdot \sum_{j=1}^{n} (T_{\mathrm{s}j} - T_{\mathrm{m}j})^2\right]^{0.5} \tag{7}$$

$$NMBE\ (\%) = \frac{100}{\bar{T}_m} \cdot \frac{\sum_{j=1}^{n} (T_{\mathrm{s}j} - T_{\mathrm{m}j})}{n-1} \tag{8}$$

Where j is a specific hour during the calibration period, T_s is the simulated data, and T_m is the measured data, n is the number of observations, and $\bar{T}_m$ is the average of the number of n observations.

To facilitate the calibration, the codes for the three evaluation criteria can be accessed in the following repository: https://github.com/fuadbaba/Calibration-BEM.git

5.5.4 Selection Criteria

To find the Final Optimal Solution (FOS), the following points shall be considered:

First, five Accurate Optimal Solutions (AOS) shall be found. AOSs are the model solutions that achieve:

- MAD criterion for each room lower than 1.5°C, 2.0°C (if there are models values lower than 1.5°C) or 3.0°C (if there are still limited models)
- If MAD for a room is higher than 1.5°C, RMSE for the room shall be lower than 0.8

Second, use a new metric, called the "PE: 1°C Percentage Error (%)" criterion, that was developed to find FOS among the top AOS. The 1°C Percentage Error criterion calculates the percentage of the number of hours (hr) over the calibration period having the difference (ΔC) between simulated (S) and measured (M) indoor air temperatures higher than 1°C.

$$PE\ (\%) = \frac{\sum hr\ \forall\ \Delta C\ \geq 1°C}{\sum hr} \cdot 100 \tag{9}$$

$$\Delta C = S - M \tag{10}$$

The reason for the Percentage Error (PE) criterion is that the lowest MAD may not necessarily be the best solution. According to adaptive criteria for overheating assessment (such as ASHRAE 55 or EN15251) the difference between the acceptable limits is 1°C. This indicates that the 1°C PE difference can lead to a significant difference in the calculation of overheating hours. Therefore, the 1°C criterion is important to reduce the discrepancy in assessing the overheating risk using the simulation and the measured data. A 0.5°C PE criterion can also be used as an indicator to demonstrate the level of accuracy.

6 Future Weather Data for Resilient Cooling in Building Design

This chapter provides an overview of weather data for RCD. It details existing data bases for historic and future climate data and explains the processes involved in developing future climate data, the selection of data sets for applications, and the preparation of data sets for building simulations. It concludes with three suggestions for practitioners.

6.1 Introduction

Buildings around the globe are exposed to systemic climate change and more frequent, longer, and more intense episodes of natural hazards due to global warming. The IPCC (2023) reports that global surface temperatures in 2011-2020 were 1.1°C higher than 1850-1900, with strong regional differences and consequences of extreme events (such as heat spells, wildfires, and floods) being several magnitudes larger than before. Therefore, to ensure the safety and comfort of the global population, the built environment should be designed and planned to anticipate current and potential future changes in climate and extreme events.

Building simulations are important tools that allow for the evaluation of building performance under current and future projected climates. Dynamic energy simulation requires robust and reliable meteorological datasets to specify the exterior boundary conditions a building will experience over its lifetime.

A variety of climatological data is utilized to determine the nature and extent of external conditions. These data include air temperature, solar radiation, atmospheric humidity, wind, rain, and snow (ISO 6243:1997). Different methods are specified for building simulation calculations and climatic data: a typical year of hourly values (8760 hours) of appropriate meteorological data is suitable for evaluating the average annual energy for heating and cooling (EN ISO 15927-4:2005), hourly data can be used to determine the design heat load for space heating in buildings (ISO 15927-5:2011), and hourly data can be used in determining the design cooling load of buildings and the design of air conditioning systems (ISO 15927-2:2009).

To perform effective climate change impact assessments on buildings, both multi-year historical climate data recorded near the buildings as well as projected future changes in climate using climate models for areas surrounding the buildings are necessary. The heterogeneous nature of urban environments means that a dense network of sensors recording the different climate variables is required to adequately resolve the local climate near buildings.

The future projected building simulation climate data is usually prepared from global or regional climate model simulation results. These climate outputs are not tailored for the needs of building practitioners as much as they are for the climate science community, and additional steps should be performed to transform them into ready-to-use future weather files for building simulations. Although several databases of such climate simulations exist, a limited number of climate model simulations provide data at the required hourly (or faster) temporal frequency necessary for building simulations. The simulation results are also usually available at spatial resolutions much coarser than the building scale. To bridge this gap in spatio-temporal resolutions, several spatial downscaling and temporal disaggregation techniques have been developed (these are discussed in detail in Section 6.3.1).

Finally, future climate projections have uncertainties built into them, which are heightened by several factors. One source of uncertainty is the existence of multiple climate models in the literature. For example, there are over 30 global climate models discussed in the 6th Assessment Report of the Intergovernmental Panel for Climate Change (IPCC). All 30 are considered equally reliable, and their projections are considered equally plausible in the future. Such sources of uncertainty need to be accounted for when conducting climate change impact assessments on buildings, considering that these large uncertainties in input climate data greatly affect the building simulation outputs, such as summer thermal discomfort, peak cooling loads, or annual cooling demands. Many approaches have been developed to account for uncertainties in a computationally efficient manner (Zou et al., 2022). However, guidance on their use in building design and related risks is still unclear for building designers.

This chapter discusses the prominent climate databases that are useful for building performance assessment under the changing climate. It also highlights their limitations and provides guidance on how to select climate datasets for building performance assessment.

6.2 Climate Data for Building Design

6.2.1 Existing Databases for Contemporary Building Design Climate Data

Buildings must maintain acceptable levels of performance against the cycles of day-to-day weather over their design lives. Given that the design lifespans of buildings can range from 60 to 100 years, systemic climatic changes due to sources of change (such as global warming) must be accounted for in their design. Buildings must maintain structural integrity against extreme events such as wildfires, floods, thunderstorms, extreme wind, and earthquakes, and must ensure safe indoor environments for building occupants during heat waves. Climate databases that are relevant to the design of buildings are summarized in **Table 6.1**. These databases can be used for obtaining both typical and extreme climate data for contemporary building design.

6.2.2 Existing Databases for Future Climate Building Design Data

While the numerical climate model's robustness has considerably increased in recent decades, the different climate models worldwide do not provide the same projections, even though they converge on similar trends (especially temperature). There is no consensus within the scientific community on which climate model, which socio-economic scenario, or which climate sequence is best to use, even though there are many initiatives to generate reliable future weather datasets in the literature (Ramon et al., 2019). No harmonized standards exist, neither worldwide nor for individual countries. Different approaches are used to produce these future datasets, such as methods which use observations from recent heatwaves (data can be obtained from **Table 6.1**) or which generate future typical years (TMY) or future heat waves (HWY) (see **Table 6.2**).

***Table 6.1**. Databases for historical climate data.*

Name of the Database	Details	Data Type and Format	License
Integrated Surface Database	Global database consisting of hourly and synoptic surface observations of numerous climate parameters such as wind, temperature, and dew point compiled from numerous sources at more than 14,000 locations around the globe	Multi-year time series of individual climate data in ASCII format	Open access
Canadian Weather Year for Energy Calculation (CWEC)	Canadian database of hourly surface observations of climate parameters needed for building energy simulations for typical building energy years for 564 locations in Canada	Historical time-series in EPW format	Open access
European aggregated surface weather data for energy system modelling	European level hourly dataset of 2 m temperature, 10m wind speed, 100 m wind speed, surface solar irradiance, wind power capacity factor, solar power factor, and degree days spanning over 30 European countries	Historical time-series in netcdf format	Open access
Climate.OneBuilding.Org	Climate.OneBuilding.Org contains climate data designed specifically to support building simulations. As such, the files are Typical Meteorological Years (TMY) and are published by a variety of organizations.	Historical time-series of typical years in EPW format	Open access
Meteonorm software	Meteonorm allows access to historical time series of irradiation, temperature, humidity, precipitation, and wind for locations around the globe. The new archive contains hourly data since 2010 and is constantly updated. The database consists of more than 8 000 weather stations, five geostationary satellites and a globally calibrated aerosol climatology.	Historical timeseries of typical years in EPW format	Fee

Uncertainties in climate data emerge from different sources, including the climate models themselves and the socio-economic emissions scenarios. For instance, comparing 11 climate model projections, the mean summer temperature in Paris differs by up to 7°C by the 2050s (Marchard, 2021). These uncertainties are then propagated in the modelling chain all the way toward the building performance evaluation. When using future climate data projections for building thermal or energy simulations, it is good practice to evaluate several climate scenarios to account for uncertainties. In the near-term future (2050s), the highest uncertainty comes from climate models, while in the long-term future (2100s), the highest uncertainty comes from socio-economic scenarios (Giorgi, 2019).

Table 6.2. *Databases for future weather data.*

Name of the database	Details	Data type and format	License	Comments
Coupled Model Intercomparison Project – Phase 6 (CMIP6) Climate Database	The Coupled Model Intercomparison Project, which began in 1995 under the auspices of the World Climate Research Programme (WCRP), is now in its sixth phase (CMIP6). The CMIP6 provides climate simulation results of over 30 different global climate models performing common sets of simulation experiments.	Hourly time-series of projected climate data from global climate models in NETCDF format	Open-source data	Data that can be used to assemble future TMY or HWY
Coordinated Regional Climate Downscaling Experiment (CORDEX) Database	CORDEX is a WCRP framework to evaluate regional climate model performance through a set of experiments aiming at producing regional climate projections.	Projected future regional climate model database, in NETCDF format	Open-source data	Data that can be used to assemble future TMY or HWY
Canada's Building and Infrastructure Climatic Design Data	The dataset developed by the National Research Council Canada in partnership with Environment and Climate Change Canada provides buildings design indices for more than 600 reference locations as part of the National Building Code of Canada.	Projected future buildings design indices in CSV format	Open-source data	Data can be used to design building components
Meteonorm	Meteonorm provides future typical weather files based on an average of different climate model and socio-economic scenario outputs.	Projected future building simulation weather files: TMY format	License needed	Future TMY
Weathershift	Weathershift provides future weather files for a variety of future climate models and socio-economic scenarios considering the 10th, 50th, and 90th percentiles of warming from the ensemble.	Projected future building simulation weather files: TMY3 format	License needed	Future TMY weather files with 10th, 50th, and 90th percentiles of projected warming
Climate Change World Weather File Generator (CCWorld-WeatherGen)	The CCWorldWeatherGen tool allows one to generate climate change weather files using morphing technique for world-wide locations ready for use in building performance simulation programs. It requires an EPW file as an input. Climate data are based on A2 scenario and climate model HadCM3.	Projected future building simulation weather files: EPW format	Open-source data	Future TMY
ANNEX 80 Project Database	Annex80 future weather database provides both contemporary and future TMY and HW files for 14 ASHRAE locations worldwide. Climate data are based on RCP 8.5 scenario and climate model MPI-REMO.	Projected future building simulation weather files: EPW format	Open-source data	Future TMY and HWY

Several researchers compared building performance using different climate models and socioeconomic scenarios and found that the yearly cooling demand can differ by up to 500% (Nik, 2013). Heat stress evaluation results can also largely differ between using a future TMY or a future HW weather file. A difference of more than 5°C in indoor effective temperature was found by Machard (2021), which is a critical difference during hot weather. Furthermore, Machard et al. (2023) found that the primary building envelope parameters and control strategies impacting indoor heat stress were different when using TMY and HW files, which must be identified in the early stages of building design. For these reasons, it is crucial to use several climatic projections and to use both typical and extreme weather files to proceed with a holistic building performance evaluation.

Different databases of future climate projections exist (such as the CMIP6 and CORDEX databases) that are climatological outputs for a wide range of climate models and socioeconomic scenarios. These must be downscaled and reformatted before they can be used as inputs for building thermal simulations, for both building energy and overheating assessments. Future weather generators available in the literature provide future climate data in the appropriate format for building performance simulations (such as EPW). However, the methodology used is more suitable for developing TMY datasets than HWYs.

Detailed explanations of these different future weather data sources and considerations for selecting the appropriate ones are outlined in the next section.

6.3 Future Climate Datasets for Building Simulations

6.3.1 From Global to Local Spatial Scale for Building Performance Evaluation

Future emission scenarios and global climate models (GCMs) that simulate the historical and future climate of the earth system as a response to the greenhouse gas emissions are the foundation for future climate analysis. The GCM outputs have spatial resolutions ranging from 150 to 600 km (Flato et al., 2013). Due to their coarse spatial resolution, they are not appropriate for building-level simulations, as the local-level effects surrounding buildings are not accounted for in their simulations. In this case, the GCMs must be downscaled to the required spatial and temporal resolution (less than 100 km and at least hourly values, respectively). Dynamic and statistical downscaling are two main approaches to spatially downscaling GCM projections. On the one hand, in statistical downscaling methods, local environmental conditions are estimated from GCM-based atmospheric conditions using statistical functions. On the other hand, in dynamic downscaling methods, the atmospheric conditions from GCMs inform a higher-resolution physics-based climate model, set up around a smaller area of interest, to obtain higher-resolution climatic estimates (Schoof, 2013).

6.3.1.1 Statistical Downscaling

Statistical downscaling uses deterministic or stochastic methods to build and apply statistical links between local or regional climate variables and large-scale climate data from GCMs (Moazami et al., 2019). Time series adjustment (morphing) is the most widely used approach for applying statistical downscaling. The current weather data is used as a baseline for morphing. A global or regional climate model's monthly climate change signals convert this baseline into a future time series (Belcher et al., 2005). Several online tools can be used to generate future weather data using this method, including CCWorldWeatherGen and WeatherShift (both of which are listed in **Table 6.2**).

6.3.1.2 Dynamic Downscaling

The dynamic downscaling technique "simulates atmospheric and land surface processes while accounting for high-resolution topographical data, land-sea contrasts, surface characteristics, and other components of the Earth system" (AMS, 2022). Given that the dynamically downscaled outputs are generated from a climate model, they are physically consistent and better represent the local climate's geographical and temporal variability than their statistically downscaled counterparts (Soares et al., 2012). One of the limitations of this approach is that creating data requires more computer power and data storage capabilities than statistical downscaling. A summary of the strengths and limitations of the statistical and dynamical downscaling methods is provided in **Table 6.3.**

Table 6.3*. Downscaling methods: strengths and limitations.*

Downscaling	Strengths	Limitations
Statistical	1) Fast and computationally inexpensive. 2) Possible to encompass uncertainty from different GCMs and emission scenarios, as it can be quickly implemented. 3) Widely used in literature and outputs are available from many online tools. 4) Future projected datasets are usually available in formats conducive for building simulations such as EPW.	1) Built around a strong assumption that statistical functions linking large scale climatology from GCMs with local climate will remain stationary between historical and future time-periods. 2) The downscaling can only be performed at locations where observational climate records are available in the required temporal scale and are of sufficient quality and length. Therefore, their application is limited over data sparse areas and climate variables which are not frequently recorded at many locations (such as solar radiation). 3) The length of the downscaled future projections is usually the same as the length of the observational climate records and are usually a linearly modified version of the observations. Therefore, they are not physically consistent. 4) These methods are not able to represent future extreme events.
Dynamic	1) Downscaled projections are physics based and consistent with the geophysical context of the location of interest. 2) Downscaling can be performed for any location and climate variable regardless of the availability of the observations at that location. 3) With the constantly improving capabilities of high-performance computing and data storage, dynamic downscaling has become increasingly more accessible to users in recent years. 4) Extremes in climate data are well represented.	1) Due to high computational costs, uncertainty in climate projections necessitates the use of multiple downscaled datasets. 2) The biases in the lateral boundary conditions from the GCMs are usually transferred to the dynamically downscaled outputs unless they are corrected. 3) Usually, the dynamically downscaled outputs are not tailor made for ready usage as building simulation inputs. Several steps (such as downloading datasets, sub-setting them over the areas of interest, and converting them to appropriate formats) must be performed by the end user.

6.3.2 Selection of Future Weather Files (Depending on the Application)

Most frequently, building performance assessments are performed over a “typical year” to calculate building energy profiles. However, while conventional building design aims to optimize energy performance, resilient building design needs to minimize the risk of extreme weather events and optimize the building's performance against the extreme events. In that sense, weather files need to be created that are specific to these extreme weather events, using a selection of the climatic sequence based on the weather parameter driving the extreme event. In **Table 6.4**, the weather parameter(s) that must be used in the climate selection are identified.

While typical weather files made to calculate building energy needs are based on an equivalent weight given to the temperature, humidity, and solar radiation parameters, heat waves must be identified based on hot temperature identification and must also account for humidity in hot-humid climates. Cold spells must be identified based on extreme cold temperatures. Droughts and floods must consider precipitation as the main parameter in climate sequence identification (extreme low rain or extreme high rain), and the storm should account for the wind to construct extreme storm weather files.

In the context of this REHVA guideline focused on “Resilient Cooling Design”, the focus has been put on assembling extreme heat wave weather files. However, RBD from a more holistic perspective, must consider all types of extreme weather events.

6.3.3 Preparation of Future Weather Datasets for Building Simulations

The frequency distribution of each meteorological parameter and the cross-correlation between them, besides the proper values of the meteorological data, are all necessary to simulate building performance accurately. In this case, long periods (at least ten years, preferably thirty) must be used (EN ISO 15927-4, 2005).

Table 6.4. *Typical and extreme weather events linked to weather parameters.*

a/a	***“Typical”***	***“Extreme”***						
	Energy Needs	**Heat Wave**	**Wild-fire**	**Cold Spell**	**Drought**	**Flood**	**Moisture**	**Storm**
Temperature	×	×	×	×	×		×	
Humidity	×	×	×				×	
Solar Irradiance	×	×						
Precipitation			×		×	×	×	
Wind Speed	×		×				×	
Wind Direction			×			×	×	×
Atmospheric Pressure								×

To prepare future long-term datasets, the first necessary step is to collect climate data from the CORDEX (Coordinated Regional Downscaling Experiment) platform. CORDEX, which is the main reference framework for regional downscaling research, includes a large Regional Climate Model (RCM) database for the historical period from 1976 to 2005 and for the future period from 2006 to 2100. Depending on the model, the data are available for representative concentration pathway (RCP) 4.5 and 8.5 (W/m²), which are scenarios that were introduced by the fifth assessment report of the Intergovernmental Panel on Climate Change (Flato et al., 2013). The platform is updated with new climate data from available domains all over the globe (WCRP). Several conditions must be met to narrow down the available climate model options: the availability of weather variables for re-assembling weather datasets as inputs for building energy simulations; a minimum temporal frequency of 1 record per hour must be available; and there must be a minimum of spatial frequency of 25 km.

After storing the collection of regional climate models (in NETCDF format), different weather variables for the desired time periods (present and future) are extracted from the closest grid to the pertinent city location and then gathered in a single dataset. NETCDF is a file format for storing multidimensional scientific data. Using an ensemble of RCM models assists in reducing the uncertainty of single models and increases the reliability of the results (Feng et al., 2011). Because of the coarse spatial resolution at which global or regional climate simulations are conducted, climate model simulations are known to contain bias. For this reason, the weather data set created within IEA Annex 80 from climate models is bias-adjusted using long-term observational data (with a minimum of ten consecutive years). Numerous bias-correction approaches are addressed in the literature (Maraum, 2016). Multivariate bias-correction approaches have been proven to be the most efficient in correcting bias while conserving the interrelationships across variables. They are suggested for accurately presenting risks reliant on multiple climate variables (Cannon, 2018).

Weather files covering current and future typical and extreme weather conditions are prepared to lower the computing costs of building simulations for long periods of time. The Typical Meteorological Year (TMY) is generated according to the international standard EN ISO 15927-4, which uses hourly climatic data to assess the annual energy use for heating and cooling in buildings. This method is suitable for analysing the long-term energy loads of buildings considering climate change but is not suitable for creating extreme or semi-extreme meteorological data. To create a TMY, a statistical analysis is conducted to identify the 12 most representative months based on multiyear records (at least ten years). These 12 months are used to construct a fictitious year that is composed of 8760 hourly records, which are then converted into EnergyPlus weather files (.EPW) for use in building energy simulations.

To assemble extreme hot files, it is possible to select heat waves from multiyear datasets. Many heat wave selection methods exist worldwide. In IEA Annex 80, the method proposed by Ouzeau et al. (2016) is used for a multiyear historical temperature period (i.e. 1990-2019). Three temperature thresholds are calculated. The 99.5 threshold (99.5th percentile) is utilized to identify a temperature peak and a potential heat wave. The 97.5 threshold (97.5th percentile) is employed to determine the duration (in days) and severity (in °C above the threshold) of the heat wave. The heat wave ends if the temperature drops below this threshold for more than three consecutive days. If the temperature falls below the 95 threshold (95th percentile) the heat wave is declared to have ended. The research expands on the methods to create future weather files, such as heat waves for building energy and thermal performance simulations using CORDEX climate data (Marchard et al., 2020).

Three criteria define each heat wave in the suggested approach: intensity (the highest daily mean temperature °C obtained during the heat wave), duration (days), and severity (aggregated temperature above the 97.5 threshold in °C). Several heat waves are likely to be found and it is the choice of the building designer to decide which heat wave will be used to size the building's resilience to heat. During the Annex 80 project "Resilient Cooling for Buildings" one of the approached used was a risk-based analysis and the three most extreme heat waves were selected for building performance resilience assessments (i.e., the most intense, the most severe, and the longest heat waves of each multi-year period).

6.4 Integrating urban Effects into Climate Model Simulations

Only a small fraction of climate change impact assessment studies on buildings have accounted for urban effects. The climate projections with urban effects have been developed using statistical, dynamic, or statistical-dynamic approaches.

Among the statistical downscaling methods used is the empirical transfer function method, which links large-scale variables (predictors) to local variables (predictands) by statistical regression. The functions are established for a past reference period for which large-scale re-analyses and local observations are available. The functions are then applied to climate projections. For example, Hatchett et al. (2016) show that the global climate model simulations over Reno, Nevada, USA, show a cold temperature bias in urban areas, which is effectively corrected when a quantile mapping bias-correction of temperature simulations from global climate models is performed.

Statistical methods have limitations. Future projections are built from a statistical analysis of past data under a strong assumption of stationarity in time. The representation of future extreme events may also be questionable, and the interactions between urban climate and regional climate are not always considered. Some studies have therefore performed a complete dynamic downscaling of global climate model projections to a high-resolution climate modelling configuration, integrating a specific urban climate model online. Many studies were performed with the weather research and forecasting (WRF) model at resolutions of 1-4 km by focusing on specific periods of the year. Other models, such as the climate limited-area modelling community (COSMO-CLM) regional model for the downscaling urban climate of the 2060s in Brussels, Belgium, have also been used (Lauwaet et al. 2016).

Finally, several statistical-dynamic methods have also been used. A city's signature is integrated into atmospheric fields (temperature, humidity, wind, and radiation) from the long-term RCM series by performing two joint high-resolution simulations of local climate, one with urban parametrization and the other without urban parametrization. The anomaly fields resulting from urban influence were calculated as the difference and superimposed on climate projection data to spatially disaggregate them while correcting for urban effects (Duchere et al., 2020).

6.5 Summary of Climate Data for Resilient Cooling Building Design

There exist different approaches to using weather data for the design of a resilient cooling building. These are summarized in **Table 6.5**.

Table 6.5*. Weather data for resilient cooling building design.*

	Comments	Usage	Difficulty
Future TMY (typical)	These are easily found in existing databases. These datasets can be used to estimate future yearly heating and cooling demand but might underestimate the cooling demand, especially cooling peaks.	Yearly heating demand Yearling cooling demand	*
Observational HW (heat waves)	These data can be found on existing databases. These are the most accurate type of data; however, it is difficult to use them to assess future building performance. These data can be used for thermal comfort / heat stress evaluation	Summer thermal comfort and heat stress assessment, cooling loads and system sizing	**
Future HW (heat waves)	These data are harder to find as only a few researchers have begun publishing them. One can either use weather files from existing databases such as (https://annex80.iea-ebc.org/weather-data) or assemble future heat waves weather files (for which a climatological background is necessary).	Summer thermal comfort and heat stress assessment, cooling loads and system sizing	***

6.6 Resilient Cooling Weather Files in Practice

These recommendations are provided to assist in determining which weather files are most suited for specific applications:

- Investigate what weather files are available for the location. This may include daily and historical weather observations from the nearest national weather station and derived TMY files for the location. What historical data set are the TMY files based on? To what extent do the actual current weather data (on a daily, monthly, or seasonal basis) and observational heat wave data differ from the TMY files? Are any future weather files (TMY or heat wave) available for the area, or do they need to be created?
- Investigate the site location to determine to what extent the nearest weather station data pertains to the site. Are there local features that may impact the climatic conditions of the building in question (e.g., urban heat island effect and natural or man-made obstacles to cooling breezes)?
- Liaise with the building stakeholders to determine the benchmarks to be met (e.g., the thermal comfort thresholds under heat events of various durations and intensity parameters).
- For a robust assessment of resilient cooling solutions, use future TMY and observational and future HW files, in addition to the usual historically based TMY and HW files.

7 Occupancy Patterns Variations and Consequences

Resilient cooling in buildings is provided for the comfort and safety of occupants. This chapter highlights the importance of understanding occupancy patterns in building performance modelling. It concludes with four suggestions for practitioners.

7.1 Introduction

This chapter provides an overview of occupancy patterns in building performance simulations and their impacts on resilient cooling solution analyses. Occupancy patterns are one of the leading causes of the gap between real and simulated results (Hong et al., 2017). Therefore, this chapter discusses parameters related to how people use spaces, such as occupancy schedules, metabolic rates, and internal gains, focusing on their impacts on building performance assessment.

The content is divided into the main topics designers must consider for modelling occupancy patterns in building simulation. It describes some important aspects to be considered when developing building simulations for resilient cooling assessments.

7.2 Impact of Occupancy Patterns on Building Thermal Performance

Defining occupancy patterns are crucial when modelling a building for thermal performance analyses, as are solutions which focus on resilience. Occupants generate significant heat which impacts a building’s thermal balance. Some heat originates from occupant bodies and some heat irradiates from equipment and lighting. Most of this radiation is directly dependent on occupancy patterns. Furthermore, in some building types, building operation is controlled by the occupants, therefore some cooling strategies depend on the presence of occupants and their behaviour. The times of the day when occupancy occurs also affect the building's thermal balance (i.e., if people use rooms during the daytime, the building will likely experience heat gain from the external environment in addition to internal heat loads from occupancy). This may be somewhat counterbalanced during the day if occupants take action to limit overheating (e.g., by using activate shading devices and closing external doors or windows). If occupancy occurs during the night, solar radiation does not directly affect the building, and outdoor temperatures will likely be lower than daytime temperatures (although this might not be the case for periods of heat waves). In these times, when the building is losing heat to the outdoors, internal heat gains may be the primary reason for rising indoor temperatures. Therefore, occupancy patterns can be decisive when choosing the most appropriate solutions for resilient cooling and building performance. Indoor environment requirements in terms of temperature, humidity, airflow rate, lighting, and others depend on the building typology and associated occupant activities undertaken within the building. As a result, occupancy should be modelled carefully according to building categories and space categories within the building (ISO 52000-1:2017).

7.2.1 Examples of the Impact of Occupancy Patterns on Simulations

The impact of modelling occupancy in building thermal performance simulation is relevant for both passively and actively cooled buildings (as exemplified below, for a typical detached dwelling in São Paulo, Brazil). **Figure 7.1** shows the operative temperatures of a naturally ventilated living room on a typical summer day for different occupation patterns. The range of temperatures is narrower when no occupation and no natural ventilation are modelled. On the one hand, outdoor temperatures are lower during the night and there is no air exchange through the windows. On the other hand, daytime internal loads generated by occupants raise internal temperatures. If natural ventilation is included in the simulation but no occupancy is modelled, internal temperatures follow the oscillations of the outdoor temperatures more directly. When both occupation and natural ventilation are modelled, internal temperatures vary significantly, depending on the hours of the day when the building is occupied, when windows could be open.

Figure 7.2 presents cooling thermal loads for the same living room from the same example as **Figure 7.1**. However, in this figure air conditioning is used instead of natural ventilation. This shows how cooling loads are higher when occupancy is modelled and how the occupation period significantly impacts cooling loads, especially if air conditioning is activated only during occupancy.

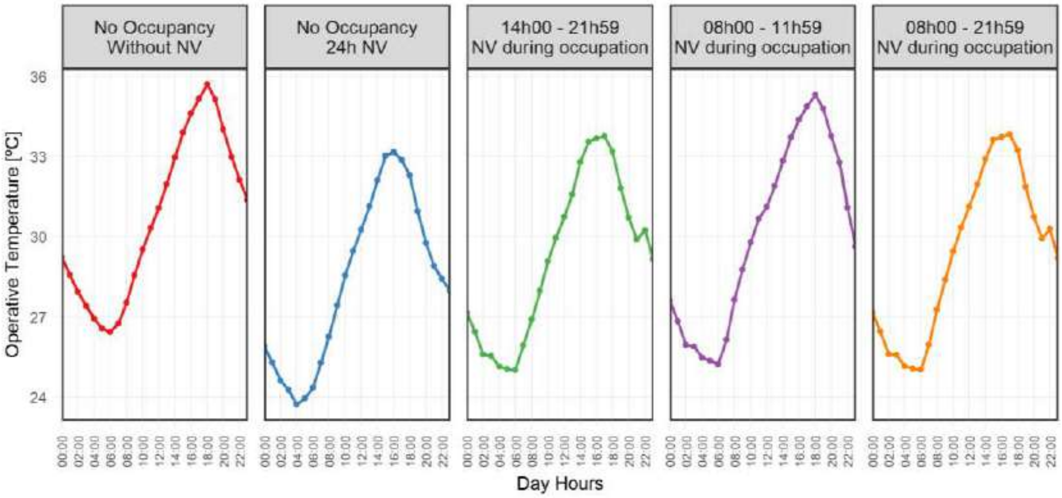


Figure 7.1. Operative temperatures for a living room on a typical summer day for different occupation patterns.

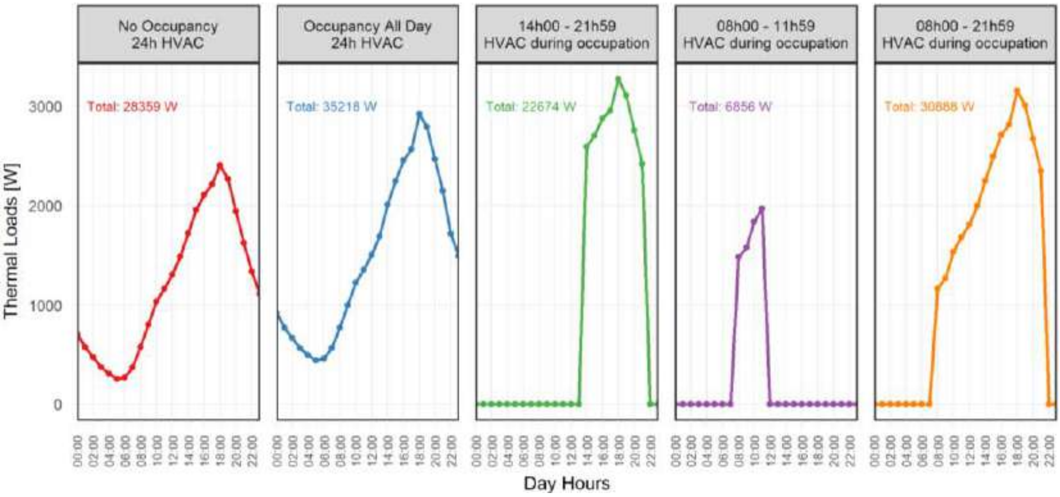


***Figure 7.2**. Thermal cooling loads for a living room on a typical summer day for different occupation patterns.*

To standardize occupancy patterns for building performance simulations, the codes, labelling programs, and standards that determine usage schedules must be understood and factored in. Furthermore, the models should consider which times people typically use spaces, occupant density, lighting, equipment usage density, and other aspects related to occupancy. Some examples of international standards with usage schedules are ISO 17772-1:2017 (for different buildings categories), ISO 18523-1:2016 (for non-residential buildings), and ISO 18523-2:2018 (for residential buildings). For regional standards, some examples are the European Standard EN 16798-1:2019 (with usage schedules for different building categories) and the Brazilian NBR 15575-1:2021 (for residential buildings). In the scope of Annex 79 (2023), O'Brien et al. (2020) reviewed occupant-related aspects for codes and standards. In all these references, it was possible to obtain a complete occupancy pattern for each analysis purpose. However, the assumptions which relate to occupancy in performance simulation for building resiliency analysis are not covered within regulations, as of yet. This chapter discusses them.

7.3 Occupancy Hourly Schedules

Occupancy hours are the periods when building spaces are used, and, consequently, when some building systems may be operational (e.g. lighting, equipment, HVAC, and windows). Depending on the type of building and the type of space within the building, occupation occurs at different hours. Furthermore, the number of people in a building varies according to the time of day, the day of the week, and the seasons of the year. Different solutions may be adopted depending on the occupancy hours to avoid overheating.

In building simulation, a building's occupancy hours vary according to building and space categories, calculation methods, and the time step length. For instance, if the building simulation has a daily approach, the occupancy pattern must consider 365 divisions (i.e., one daily schedule). For an annual approach, ISO 18523-1:2016 provides one schedule representative of the entire year for non-residential buildings and ISO 18523-2:2018 provides the same but for residential buildings. These describe each critical part of a schedule related to occupancy and the time intervals (i.e. annual, daily, monthly, and seasonal), as well as examples of schedules for different building categories and periods.

Standards such as ISO 17772-1:2017 and BS EN 16798-1:2019 specify usage schedules for different building typologies related to commercial and residential activities. These schedules are divided into weekdays and weekends. For example, in ISO 17772-1:2017 (which is for commercial buildings), occupancy hours usually occur during the day on weekdays, and there is no occupancy during weekends. In residential buildings, occupancy occurs all day on weekdays and on weekends. **Figure 7.3** shows an example of occupancy in an office landscape and a residential apartment.

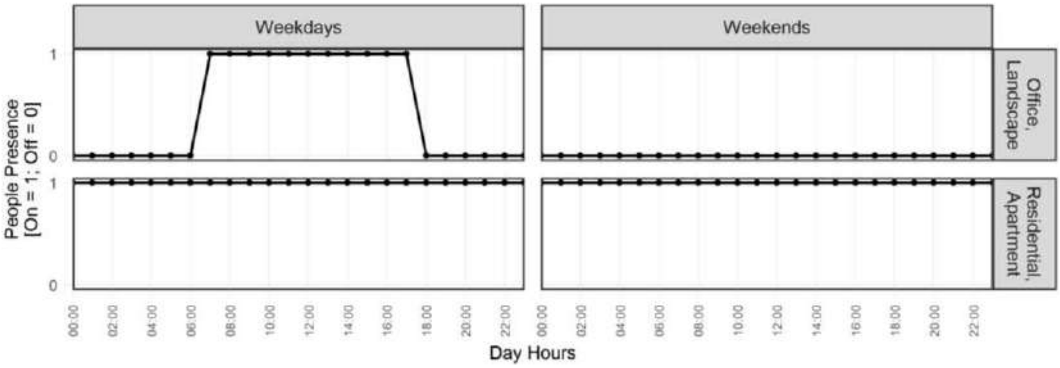


***Figure 7.3**. Occupant presence for an office landscape and a residential apartment according to ISO 17772-1:2017.*

However, it is necessary to verify if those schedules are compatible with the real usage of the analysed building and for building space categories (e.g. bedrooms and living rooms). Some people work away from home all day and their homes are occupied only during the night, but there are cases when people work from home, occupying living rooms during the day and bedrooms at night. There are other cases (e.g. shift workers, the elderly, babies or young children, or work-from-home workers) where bedrooms may be occupied during the day. In all cases, the simulation model must consider these particularities in usage schedules. It is also essential to consider aspects related to regional characteristics and adaptation to users: international and regional codes and standards have different usage schedules for modelling occupancy patterns on building performance simulation, which are primarily based on local field studies. For residential buildings, the regional standard NBR 15575-1:2021 from Brazil is an example of a building simulation procedure with usage schedules based on Brazilian field studies (Ramos et al., 2020). For non-residential buildings, a review of occupant-related aspects of building energy codes and standards was conducted by O'Brien et al. (2020) and this appears in Annex 79. Thus, field studies regarding occupant behaviour could improve resilient cooling analysis if these studies focus on different populations with varying habits and social and economic aspects relating to how they use specific buildings. However, when assessing worst-case scenarios related to overheating, it may be relevant to consider atypical occupancy patterns. For instance, during a power outage event, people may not go to work and may instead stay in their homes in the hottest hours of the day. Another atypical instance may be during an extreme heat wave, when workers are advised not to go to work and hence stay at home.

Whether simulating for resilience against power outages or heat waves, it may be helpful to consider full occupancy to account for higher internal gains, despite hourly values defined by building simulation standards. Given that it is impossible to accurately predict what occupants will do in the case of an extreme event, the simulation should consider the scenarios that will stress the building the most.

7.4 Occupant density

Occupant density relates to the number of people occupying a specific building space. It can be described as a ratio between the total number of occupants (or similar value) and the building area, such as "people per square meter" or "square meters per person". In most cases, the number of occupants varies at different times of the day. In building performance simulation, occupancy density is usually described as a fraction of the maximum value for occupancy and varies according to the hour of the day. The standards and codes mentioned above have examples of occupant density. One example is ISO 17772-1:2017, which has values for occupant density and the fraction to be considered each time. **Figure 7.4** shows an example of the fraction that must be considered relative to time for the same building categories as shown in **Figure 7.3**. ISO 17772-1:2017 presents typical occupant densities of 17.0 m²/person for office landscapes and 28.3 m²/person for residential apartments.

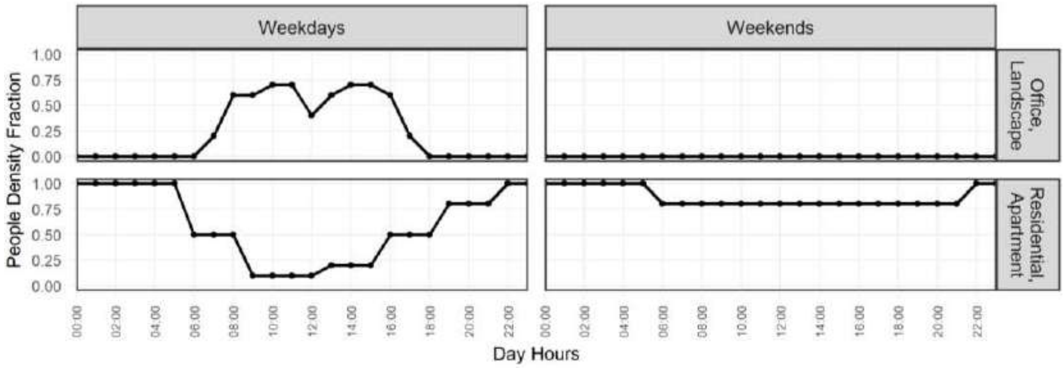


__Figure 7.4__. Occupant density fraction for an office landscape and a residential apartment according to ISO 17772-1:2017.

It is essential to verify that values are appropriate in each case. For example, heat gain from the envelope is often more significant in residential buildings than internal sources but in commercial buildings this may not be the case. Therefore, if a modeller overestimates internal gains, simulation results could underestimate the applicability of strategies related to the envelope, and vice-versa. Furthermore, as mentioned when addressing occupancy hours, it may be relevant to consider higher occupant densities when assessing worst-case scenarios related to overheating.

7.5 Metabolic Levels

Metabolic levels represent the activities performed in a building space. This is important to consider because the heat generated by occupants depends on their activities. For example, if people are resting or working while sitting at a desk, they produce less heat than people doing domestic work or some form of physical activity. The proportions of sensible (radiation plus convection) and latent (evaporation) heat also vary according to the metabolic rate and the environmental conditions.

The international standard ISO 8996:2021 presents metabolic rates for different activities. In general, the metabolic rates should correspond to the main activity performed in specific building spaces. However, the metabolic rate could also increase during extreme events, when internal temperatures exceed the threshold of the thermoneutral zone. In the case of performance assessment for extreme events (such as heat waves and power outages) a higher metabolic rate could be considered the baseline, although occupants might stop doing their typical activities for health concerns, effectively slowing down their metabolic rates.

In building typologies with components of residential activities, the metabolic rate of different occupants may require consideration. For example, in elderly homes or residential aged care facilities, the metabolic rate for occupants may be lower than for healthy younger adults. However, the ability to shed heat is typically lower for elderly people. Another example is in hospitals where patients are typically inactive (and have a lower metabolic rate) while nursing staff are active (with higher metabolic rates). The differing metabolic rates of occupants of such buildings make it complex to determine internal heat gains and methods for managing thermal comfort and safety for all occupants.

7.6 Internal Gains from Lighting and Equipment

Lighting and equipment are significant sources of heat inside a building. In a similar way to occupant density, internal gains are commonly described as the total power generated in a building space (in Watts), or can be related to the area (such as “Watts per square meter” or “square meters per Watt”). Furthermore, power density values are usually expressed as a fraction of the maximum value throughout the day. Lighting and equipment power density tend to have higher values when people use the building. However, this might not always be the case, such as in bedrooms (where people sleep with the lights off) or in data centres (which typically have high thermal loads, even if no people occupy the space).

Beyond the occupant density, the previously mentioned standards and codes propose values for internal gains from lighting and equipment. ISO 17772-1:2017 defines the power density of appliances (i.e. equipment) and lighting values as lux. Therefore, the power density depends on the lighting system's efficiency. Another example is ASHRAE's Standard 90.1, which indicates lighting and equipment power densities expected for efficient buildings. Following previous examples, **Figure 7.5** shows the density fraction for appliances present on ISO 17772-1:2017 in which the appliance density value standard is considered 12 W/m² for office landscape and 3 W/m² for residential apartment. Total heat gain by appliances in a building performance simulation is generally calculated by multiplying the density values with the room's area and the density fraction.

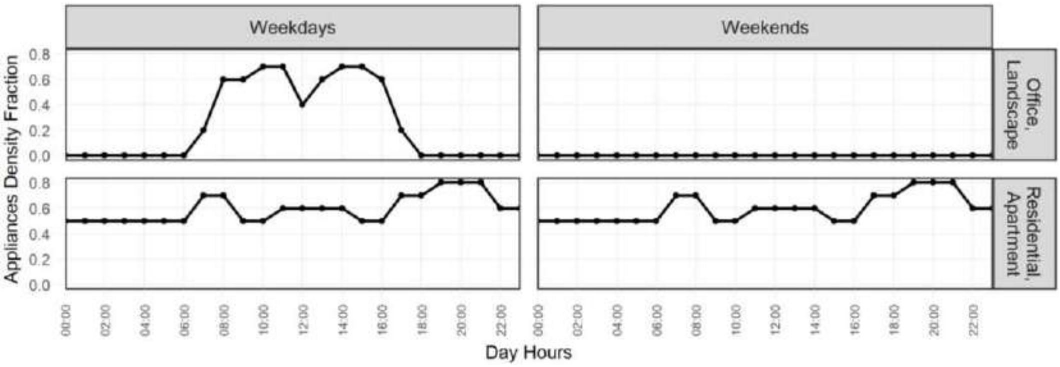


Figure 7.5 *Appliance density fraction for an office landscape and a residential apartment according to ISO 17772-1:2017.*

When analysing building resilience to adverse events, there may be changes in how power density is modelled. For instance, in the case of power outages, lighting and equipment stop working and these heat sources should be disregarded. In the case of heat waves, the operation schedule of cooling devices like refrigeration and air conditioners may increase and their efficiency may decrease, leading to increased heat gain that may need to be considered.

7.7 Systems Operation Schedule

Building operation depends on the building systems installed and user behaviour. One building could have many systems, such as operable windows for natural ventilation and lighting, shading devices (i.e. shutters and blinds), and HVAC systems for cooling and heating spaces. Each of these systems must be represented with an operation schedule in the building performance simulation. Studies related to modelling occupant behaviour in buildings have been conducted by IEA EBC Annex 66, and such modelling is currently being further developed in Annex 79. In general, if the operation of such systems is not automated, different temperature setpoints and patterns for controlling windows, shading devices, shutters, or HVAC systems may be considered, depending on occupant preferences.

Some operation strategies are related to passive cooling measures, and others are related to the HVAC system's operations. Different schedules may be used to describe each of these strategies. Some are synchronous (e.g., opening the window to allow outdoor air in while blocking the sun with some shading device), and some are asynchronous (e.g., turning the AC on and shutting the windows). Furthermore, building systems could be driven by existing building automation or by each occupant. All oof this information must be considered when setting up system operation schedules in building simulation models.

For example, the cooling setpoint varies in an office where the HVAC system is triggered by a room air temperature and there is no automated operation. If the cooling setpoint was assumed to be 21°C or 23°C in the building performance simulation, the cooling thermal load could be overestimated. This is illustrated in **Figure 7.6** which shows an office room in a warm climate. In this case, it is recommended that variable schedules be defined. These would consider what the real triggers are for activating the HVAC system.

Figure 7.6 shows the impact of different cooling setpoints on the cooling thermal load. In a heat wave situation where power supply may be limited (e.g., a building is running off grid or the network is constrained), it may be advisable that a higher cooling set point be established. This would need to be determined in consultation with building stakeholders (including occupants) and should be well documented and communicated.

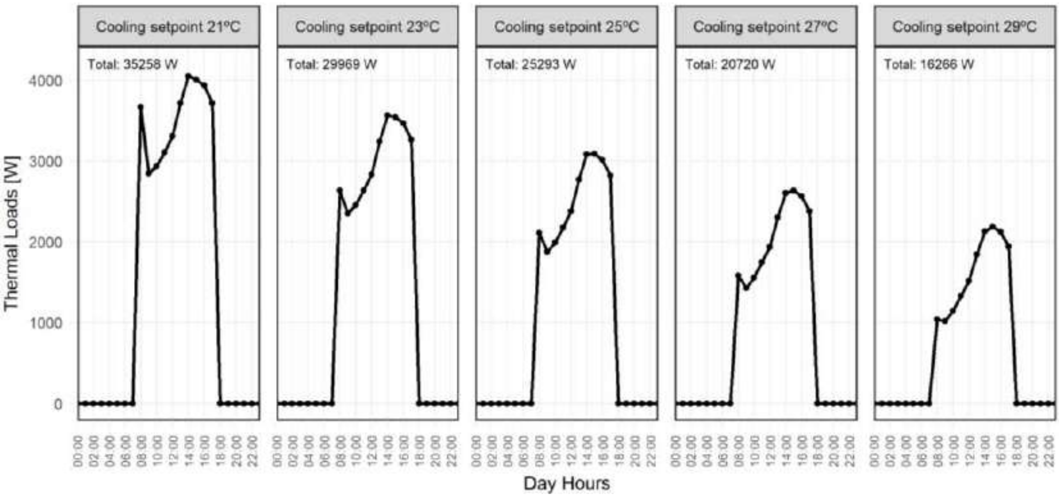


***Figure 7.6** Thermal cooling loads for an office with variations in cooling setpoint.*

For building resilience analysis, different approaches could be adopted regarding system operation. On the one hand, the analysis could be related to the consequences of the failure of the air conditioning system (e.g., air conditioning is broken or a power outage occurs). On the other hand, the analysis could evaluate the performance of the building in the case of passive cooling systems not working as expected (e.g., when windows do not open or shading devices are not used correctly to reduce solar radiation). The behaviour of occupants is also relevant to consider as users do not always know how to use passive cooling systems most effectively. For instance, opening windows during a heat wave could bring in hot air from outdoors and increase internal temperatures (this may even be true at night). Therefore, this situation should be considered in the worst-case scenario. For longer heat waves, natural ventilation may not be effective, so building simulation would be used only to verify whether the internal temperatures increase to a point where the health of occupants is at risk.

It is essential to consider that for some building types no building operation happens during unoccupied hours. Therefore, if the building is left closed for a whole weekend when a heat wave occurs, the heat stored inside the building could be significant, and the building could take a long time to return to acceptable internal temperatures once systems are adequately operated.

In building performance simulation, if building operation does not represent its actual use, it could increase the gap between simulation results and reality, even when occupancy is modelled according to standards. As mentioned in **Figure 7.1** and **7.2**, it is important to consider operations as close as possible to how people use buildings as this could significantly modify the operative temperatures in models with natural ventilation and the requisite thermal loads in models with air conditioners.

7.8 Final Remarks

Although it is well understood that occupancy patterns vary depending on the type of building, these patterns are not predictable in a deterministic way. For instance, it is expected that a school classroom would have a higher occupant density, and this occupancy would depend on the schedule of the classes. However, it is impossible to know exactly how many people will be in a specific room, for how long they will remain, the exact metabolic rate of each occupant, and what equipment or lights will be used. These aspects are especially complex when we model occupant behaviour concerning HVAC, windows, and shading controls. Therefore, the modeller should assume occupancy schedules, considering all the above variables.

As occupancy patterns are complex phenomena to predict and model, some assumptions and simplifications are inevitable. Nevertheless, their impact on building thermal performance simulation is significant and may result in either higher or lower performance. Some use patterns result in lower and higher building performance according to the time of the day or the season of the year. Therefore, modellers must create a consistent purpose for their simulations, considering all the aspects related to occupancy patterns and their impacts on simulation results.

7.9 Resilient Cooling Occupancy Considerations in practice

The following recommendations are provided to assist you in determining what occupancy schedules and considerations to apply to your specific building context:

- Understand the purpose of the building simulation. Assessing cooling resilience may be the overall purpose, but the specific purpose will vary depending on whether the cooling load is being assessed (for resilience against power outages or for the efficacy of onsite energy generation and storage) or thermal comfort and/or safety for occupants is being assessed for heat wave events. The KPIs mentioned in Chapter 4 will assist in this regard.
- If modelling a new building, begin with the occupancy patterns designated by a Standard for that type of building. If building specific occupancy patterns are known, use these (and document them). Consider changes in occupancy patterns that may result from heat waves (e.g. increased, or decreased occupant density). Vulnerable populations are important to consider when simulating extreme events in residential buildings, nursing homes, and hospitals. In these cases, people may not be able to leave the building, and they might be more vulnerable to higher temperatures or humidity. A possible solution to mitigate extreme temperature events is moving occupants of the building from the hotter spaces of the building to a cooler, resilient space (e.g., the basement, or a ‘cool retreat’). During heat waves, auditoriums or basketball arenas may host elderly people. In this case, the occupant

density in the cooler space should account for all the occupants moving from the hotter spaces of the building.

- A resilient cooling assessment may include performance evaluation in atypical occasions, and there might be no standards with specific values for occupancy patterns modelling in these cases. If it is the case that the worst-case scenario is evaluated, the modeller should consider occupancy patterns which result in the greatest stress related to the building overheating. However sometimes the worst-case scenario is not necessarily realistic. For instance, in the case of a power outage, the HVAC system would not be working, and there would be no thermal load for lighting and equipment. Furthermore, in such cases if the simulation represents an office building, the occupants would likely leave the building. This will depend on whether the building has energy autonomy in terms of backup generation and/or energy storage as part of a resilience strategy.

8 Building Information in Relation to Climate Resilience

This chapter gives valuable insights and an overview of the influence of the properties and forms of buildings on their ability to withstand and adapt to rising temperatures. It explores essential design parameters, including building orientation, fenestration, shading systems, insulation, ventilation, and material selection.

Specifically, this chapter focuses on parameters that can minimize heat gain within buildings, which is the first step in resilient cooling. Readers can expect to learn about the practical strategies (listed below) for promoting energy efficiency, maintaining thermal comfort, and ensuring the well-being of occupants in the face of increasing heat waves and climate change. It concludes with six tips for practitioners.

- Building orientation and form
- Fenestration optimization
- Solar shading implementation
- Effective insulation
- Proper ventilation strategies
- Thoughtful material selection

8.1 Introduction

The design of buildings plays a critical role in their response to external climatic conditions, particularly when it comes to the issue of overheating risk and thermal resilience to overheating in buildings. As global temperatures continue to rise due to climate change, the frequency, duration, and intensity of heat waves are increasing, posing significant challenges to the maintenance of comfortable indoor environments. The objective of this chapter is to explore the specific design parameters that can enhance the thermal resilience of buildings to overheating. By understanding and implementing these parameters, architects and designers can create energy-efficient, comfortable, and sustainable buildings that can better withstand the challenges of increasing heat.

8.2 Building Setting and Form

8.2.1 Microclimate and Geographic Location

The building's microclimate and its surrounding environment affect the amount of heat that is absorbed and retained by the building (Hwang et al., 2020). A building's microclimate is highly site-specific and can deviate from the macroclimate of the location due to factors such as its elevation above sea level, proximity of water bodies, and soil types. Apart from these factors, a building's location and surrounding structures, orientation, form, size, shape, surrounding landscape and vegetation also impact the overheating risk and the thermal resilience of the building.

The thermal resilience of a building is impacted by the site elevation, latitude, proximity to water, and surrounding land use. For example, outdoor temperature drops increase with the elevation of the land. The vertical ascent produces a cooling rate of 2°C per 300 m of elevation. Furthermore, in the northern hemisphere, south-facing sites are much warmer than north-facing sites because they receive much more solar radiation. The inverse is true of sites in the southern hemisphere. Sites close to the equator can receive solar radiation from both the north and the south. This means that latitude is an important consideration in the site context. The presence of large water bodies in the vicinity of a building will significantly affect temperature, as these generate daily alternating land and sea breezes and increase humidity. The heat capacity, colour, and water content of soil also have a significant effect on microclimate.

8.2.2 Location and Surrounding Structures

A building's location determines its solar gains, prevalent wind speed and direction, and the effect of surrounding buildings on shading and urban canyon effects. More information about the urban heat island (UHI) effect and the way it is simulated in software appear in Chapters 5 and 6.

The urban or rural setting of a building impacts the microclimate and, in turn, the internal thermal conditions in these buildings. In dense urban spaces, the combined effect of all the man-made structures (buildings, streets, and parking lots) due to their size, form, and colour, differentiates the micro-climate significantly from the surrounding rural area. This is known as the urban heat island effect. Large areas of pavement (especially dark-coloured asphalt) can generate temperatures as high as 60°C. The heated air then migrates to overheat adjacent areas as well. In summer, urban areas can be 4°C warmer than rural areas. Solar radiation can be 20% lower because of air pollution, and the relative humidity can be 6% lower due to a reduced amount of evapotranspiration (Santamouris et al., 2017). Even though wind speeds can be about 25% lower, very high local wind speeds often occur in urban canyons (Lechner, 2014). However, urban canyons can become very hot due to the presence of many air conditioners which pump heat from indoors to outdoors (contributing to the UHI). In future climate scenarios, an increase in cooling demand and widespread use of air conditioning will likely aggravate urban heat island scenarios (Salvati et al., 2017).

In urban areas, the positioning of the surrounding buildings can be leveraged to provide effective shading and minimize unwanted solar gains. By incorporating this shading concept into the building design, architects can mitigate heat gain and reduce reliance on artificial cooling systems. Additionally, by carefully considering the site layout and harnessing natural elements (such as prevailing wind patterns) designers can identify opportunities for maximizing natural ventilation. By aligning building openings (such as windows and vents) with the prevalent winds, they can facilitate the inflow of fresh air and promote natural airflow (which is generally desirable if the outdoor temperatures are not above the desired internal temperature).

8.2.3 Landscaping and Vegetation

Some research shows that efficient landscaping and selection of plants can reduce the heating and cooling costs of a building by 25% (Lechner, 2014). Vegetation can help to offset the effects of direct sunlight, wind, and can reduce overheating risks in buildings.

Trees and greenery provide natural shading, minimizing direct sunlight, and lowering heat absorption by the building envelope. By means of shading and transpiration, plants can significantly reduce air and ground temperatures. However, they can also increase humidity. Evapotranspiration is the combined effect of evaporation from the soil and transpiration from plants. In a hot, humid climate, the ideal cooling scenario is to have a high canopy of trees for shade but no low plants that could block the breeze. The stagnant air created by low trees and shrubs will cause the humidity to build up to undesirably high levels. By incorporating green spaces, rooftop gardens, or vertical gardens, designers can create a sustainable urban environment that mitigates the urban heat island effect and enhances overall thermal performance.

8.2.4 Green Roofs, Roof Ponds, and Green Façades

Evaporation on the outside of the building envelope is an efficient cooling technique that can be managed with vegetated surfaces, water films, ponds, and sprays. These strategies demonstrate high thermal resilience to overheating (Sun et al., 2021). The primary difference between façades (green or watered) and roofs (green roof or roof pond) is the presence or absence of vertical water runoff, which amplifies the thermal transfer due to the increased sensible and convective heat transfer in the water stream. Innovative evaporative envelopes include combinations of increased albedo, the development of porous materials, or movable claddings. However, for hot, temperate, and even cold climates, evaporative envelope surfaces have demonstrated strong cooling effects for roofs and façades in summer conditions. These cooling techniques are also widely recommended for their stormwater retention potential. However, these evaporative façades require continuous water spray or water supply to permanently irrigate the upper areas, while roof ponds and green roofs may adapt more easily to various climate conditions without water supply.

8.2.5 Orientation of the Building

Building orientation is one of the most crucial parameters to be considered in design to reduce overheating risks in buildings. The ideal orientation for a building will depend on a range of factors, including the location (latitude and longitude, which determine the solar path), climate and micro-climate (which determine the prevalent wind speed and direction), site topography, and building design (Gaitani et al., 2007). Building orientation can be leveraged to reduce solar gains and heat transfer through the building envelope and to enhance the building’s thermal resilience. In Europe (northern hemisphere), buildings are typically designed to be south (equatorial) oriented (ISO 9050:2003). If all windows face south and north, solar energy collection, shading, and daylighting can all be maximized, saving both energy and money. Given that orienting the building to the south is not always applicable due to site limitations, solar glazing will perform fairly if oriented up to 20° east or west of the true south and even 45° to the true south. The orientation of the building can also be used as an advantage to increase wind movement through the building and improve natural ventilation. In the southern hemisphere, a northerly (equatorial) orientation provides the best opportunity for limiting excessive heat gain from solar radiation. Again, orientation should be guided by the solar path for the specific latitude as well as the prevailing cooling breezes. The orientation of buildings close to the equator is of less importance, as solar radiation can be an issue for all orientations (and all orientations will require consideration of shading).

8.2.6 Compactness, Exposed Area, and Thermal Planning of the Building

Heat gain and heat loss through the building envelope are directly proportional to its surface area. The compactness of a building is the ratio between its surface area and its volume. Compact buildings also have less exposed surface area, which means less heat loss or gain through walls, floors, and roofs. This can help to maintain a more stable internal temperature. When exposed areas are increased in buildings, the solar heat gains are increased, leading to higher indoor temperatures. Thus, compact buildings have higher thermal resilience compared to buildings with more exposed areas.

Solar thermal planning of the spaces inside a building can aid in preventing heat stress on the occupants. The concept of thermal zoning or heat buffering creates intermediate, semi-controlled outdoor zones that serve as an active double skin. These outdoor zones serve to block the heat in the mass of spaces. They include courtyards, deep verandas, corridors, porches, and earth-sheltered partitions of buildings (Agostino et al., 2017). The judicious placement of photovoltaic panels and roof coverings can reduce the amount of heat that enters the building through the roof.

8.3 Fenestration Design

8.3.1 Window to Wall Ratio (WWR)

Window orientation and window to wall ratio (WWR) have a significant impact on thermal resilience to overheating (Psomas et al., 2016). Increasing WWR can increase the amount of solar radiation in a building and, in turn, increase overheating risks (Phillips et al., 2017). Good designs will manage WWR (to between 10% and 45%) to reduce solar loads to the extent permitted by non-energy considerations such as access to the outdoors, aesthetics, and space utilization. These considerations are less important for high-performance windows that are highly insulating or which can dynamically adjust solar-optical properties (e.g., electrochromic and thermochromic glazing). Overheating risk in buildings with higher WWR can still be reduced by using advanced glazing and solar shading (ISO/FDIS 52016-3). In Europe, north-facing windows receive low solar radiation (in the southern hemisphere this is true of south-facing windows), while East windows receive solar radiation in the morning and west windows do in the evening. For west and south-west-oriented windows in both hemispheres, high solar loads can coincide with high outside air temperatures, contributing to peak cooling loads and overheating risks. Designing windows on the east and west façades to be smaller than those on the north and south façades will help to improve the thermal resilience to overheating. Alternatively (or additionally), providing vertical shading on eastern and western windows can limit solar radiation ingress.

8.3.2 Glazing and Window Frames

Windows account for about 30% of the heating and cooling load of a building, and they have a large impact on thermal comfort (Lechner, 2014). 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. Glazing with fixed solar optical and thermal properties does not have the flexibility to respond dynamically to changing environmental conditions or to grid demands. Buildings with low *U*-value glazing or with advanced glazing can reduce solar gains (ISO 9050:2003). Total solar energy transmittance (*g*-value) is a coefficient used to measure the transmittance of solar gain through glazing. Higher *g*-values are associated with high solar energy transmittance, which in turn increases overheating risk in buildings. The shading coefficient (SC) of glazing measures how much solar radiation is transmitted through the glazing compared to a standard clear glass. A lower SC indicates that the glazing is more effective at blocking solar radiation and reducing overheating. 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 glazing layers. For example, in an insulated glazing unit with two or more glazing layers, these layers provide a wide range of thermal management capabilities. The most effective and widely used glazing products incorporate low thermal-infrared emittance (“low-E”) coatings, which can serve two purposes. It reduces 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 (with visible transmittance (Tv) > 60%) while effectively reducing solar gain (with solar heat gain coefficient (*SHGC*) less than 0.30). Buildings with a higher glazing ratio and high WWR should implement low-E coatings or tinted glazing to compensate for the solar gains and improve thermal resilience to overheating. Tinted coatings may reduce the natural daylight within spaces and increase the usage of artificial lighting, which in turn increases the internal gains. The optimal glazing and frame ratio can vary depending on several factors, including climate, building orientation, WWR, energy efficiency goals, and architectural design (EPBD, 2018). Frame materials with low thermal conductivity are used to reduce heat transfer. Framing materials should be carefully selected based on insulation, durability, and maintenance requirements.

8.4 Shading Systems

In addition to window orientation, WWR, and fenestration design, shading systems are crucial in preventing excessive solar radiation from entering buildings. This can include elements like exterior shading devices such as overhangs, fins, or louvers, as well as interior shading options such as blinds or curtains. These systems help to block direct sunlight, reduce glare, and minimize heat build-up, allowing for more efficient cooling strategies and reducing reliance on mechanical cooling systems (ISO 52016-1:2017).

Shading systems can be static or dynamic and are mounted either to the exterior (external screens, blinds, overhangs, and fins) or to the interior (screens, drapes, curtains, and blinds) of the glazing. The combined ability of window and shading technologies to provide resilient cooling depends on the intrinsic properties of the window or glazing package as modified by any shading technologies. The newest generation of exterior solar shading can incorporate power generation (i.e., PV arrays) into the shading elements. Given that the solar loads are dependent on the ever-changing position of the sun, fixed shading solutions will have an annual performance that varies with latitude, orientation, and geometry. When mounted on the building exterior, shading devices are more effective at managing solar loads. An interior operable shading system will always be less efficient than a similar exterior system as the solar radiation absorbed by the shading system is trapped within the building (Sengupta et al., 2020; Zhang et al., 2021). Shading elements are commonly relied upon to manage solar gain in the event of a heat wave or power outage. The solar shading's response in terms of thermal resilience depends on whether the shading is a static or dynamic technology. The resilience also depends on the control strategy (manually operated or automatically operated). Operable systems have limited efficacy and resilience if they are not triggered and operated appropriately in response to climatic stress. Improved controls, wireless sensors, and better integration with building control systems have promise in reducing costs and improving the reliability of automated systems. Improved building documentation and occupant education in the design and operation of the building can improve the efficacy of manually operated systems.

ES-SO is a European association that focuses on solar shading and daylighting solutions. It represents the interests of the solar shading industry in Europe, promoting the benefits of solar shading in buildings and the contribution of this system to energy savings and comfort.

8.5 Opaque Building Envelope Characteristics

The building envelope serves as the interface between the indoor and outdoor environments, playing a crucial role in determining the heat gains and losses of a building. Apart from building envelope characteristics (such as level of insulation, airtightness, and thermal mass) the selection of suitable building materials can significantly impact thermal resilience to overheating. Certain materials, such as those with high thermal mass (e.g., concrete or masonry), can absorb and store heat during the day and release it gradually at night, thereby reducing temperature fluctuations. Additionally, materials with high reflectivity or emissivity properties can minimize solar heat gain and reduce the energy required for cooling.

8.5.1 Envelope Insulation

Insulation is another vital parameter that affects a building's thermal resilience to overheating. Thick insulation reduces the heat flux into the house during the day but may retain the heat within the house more at night. Proper insulation minimizes heat transfer through the building envelope, reducing the impact of external temperature fluctuations on the indoor environment. It helps maintain a stable and comfortable temperature inside, preventing excessive heat gain during hot weather and heat loss during colder periods. Energy-efficient year-round solutions include having highly insulated envelopes (Sengupta et al., 2023). Highly insulated envelopes have lower U-values (thermal transmittance), which affect the flow of heat to the conditioned space. Thermal resistance and thermal transmittance calculation methods can be found in ISO 6946:2017. The U-values of external walls, floor slabs, and roof areas of Passive Houses range from 0.10 to 0.15 W/(m²K) (for the Central European climate; these values may be slightly higher or lower depending on the climate).

Highly insulated buildings are still designed under expected (historical) weather and operational conditions (i.e., occupancy loads and solar heat gains), which are not always the actual conditions.

Highly insulated buildings can retain heat, and during an overheating event (such as longer warm periods and heat waves) highly insulated buildings tend to overheat compared to buildings with lower insulation (unless other design measures are utilized to enable the building to shed its excessive heat). Instead of a static calculation, a dynamic approach must be taken to find the optimum insulation and outer envelope thickness.

There are many different types of insulation materials available, and choosing the right one for a particular application can be challenging. Some insulation materials may be more effective than others at reducing overheating. To reduce the risk of overheating, the insulation materials and their thickness should be carefully designed and selected to balance the trade-off between energy efficiency, cost, embodied energy, and thermal resilience to overheating.

Thermal bridges can be defined as areas of a building where there is a higher rate of heat transfer than the surrounding areas (ISO 14683:2017). They can be caused by a range of factors, such as gaps in insulation, poorly designed or constructed joints, and the use of materials with high thermal conductivity. Thermal bridges can help to transfer heat from a warmer area to a cooler area, helping to reduce overheating in certain spaces within the buildings or, conversely, contributing to overheating.

8.5.2 Airtightness

One of the key measures used to quantify the air tightness of the envelope is the air permeability of a building, which is expressed as the air changes per hour at a specified pressure difference (ACH at 50Pa). Extremely airtight buildings (0.6 ACH at 50 Pa) with reduced infiltration are energy efficient but are more prone to overheating (ISO 13786:2017) as they retain warm air inside the spaces. In the event of a failure of a mechanical ventilation system during power outages resulting from heat waves, the airtight buildings cannot flush out the stored heat, significantly reducing thermal resilience to overheating. The relationship between air tightness and natural ventilation is a delicate balance. On the one hand, while air tightness is important for energy efficiency and reducing uncontrolled air infiltration, too much air tightness can lead to heat build-up during heat waves and power outages, resulting in buildings prone to overheating risks. On the other hand, an overly heavy reliance on natural ventilation in a poorly sealed building may result in inconsistent indoor temperatures and reduced energy efficiency.

The best approach is to design buildings with a focus on both air tightness and natural ventilation. This involves using appropriate materials and construction techniques to achieve good air tightness while also incorporating well-planned natural ventilation strategies to ensure a healthy and comfortable indoor environment. By striking the right balance between these two concepts, architects and engineers can create sustainable, energy-efficient, and thermally resilient buildings that promote occupant well-being.

8.5.3 Thermal Mass

The thermal mass and thermal capacity of any building can be calculated according to ISO 52016-1 (ISO 52016-1:2017) and ISO 13786 (ISO 13786:2017). Heavy thermal mass performs well in short-term shocks like short heat waves when the building takes a longer time to absorb the heat (Sengupta et al., 2023). Heavy thermal mass coupled with an effective ventilation strategy can provide the best results for improving thermal resilience to overheating in some climatic contexts. Parameters such as specific heat capacity and thermal conductivity are used to characterize TES systems. TES systems absorb, store, and release thermal energy on a cyclical basis (usually daily) to regulate internal temperature and improve thermal comfort in buildings. Thermal energy can be stored as a change in the internal energy of a material as sensible heat (e.g., ground, water tanks, and aquifer energy storage), latent heat (e.g., PCM, including organic and inorganic substances and ice storage), or chemical energy (e.g., thermochemical storage). TES systems also increase the cooling system's reliability and can easily be integrated with other functions, such as on-site fire protection and water storage. The use of thermal mass may not be as effective in hot and humid climates in reducing overheating, as the humidity can reduce the effectiveness of the cooling effect. Incorporating heavy thermal mass into a building's envelope also increases the overheating risk. Once the heat enters the building, without proper ventilation, the heat is retained in the building for longer periods and negatively impacts the building's thermal resilience to overheating (Sengupta et al., 2023). The thermal mass of a building also takes a long time to heat up or cool down, which means that it may not be effective at dealing with sudden changes in temperature.

Installing phase-change materials (PCMs) can reduce indoor air temperature variations. The effectiveness of PCMs in reducing overheating in buildings depends on PCM properties and the specific climate. The use of PCMs is beneficial in some periods during the year but may not be effective in providing cooling on very hot days because they remain liquid throughout the day.

8.5.4 Colours, Albedo, Reflectors, and Cool Envelope Materials

When it comes to reducing overheating in buildings, the choice of colours for building elements (such as roofs, walls, and window treatments) can play a significant role in managing heat gain. Light-coloured surfaces, such as white or light shades of grey, beige, or pastel colours, have higher reflectivity and lower absorption of solar radiation than darker colours of the same material. They reflect a significant portion of the sunlight that strikes them, reducing the amount of heat transferred to the building. Light-coloured roofs, walls, and window frames can help to minimize heat absorption and keep interior spaces cooler. The heat gain through a white roof will be about 50% that of a black roof. Both white and cool-coloured roof materials (materials with properties that specifically enhance their solar reflectance) are mature technologies that are widely available to both building owners and building contractors. They are identifiable via mature product rating systems provided by the Cool Roof Rating Council (Home Cool Roof Rating Council) and the European Cool Roofs Council.

The measure of a surface's reflectivity to solar radiation is called albedo. It varies from 0 to 100%. Thermal resilience can be enhanced, and cooling energy needs can be reduced by increasing the albedo of the roof and external envelope. Although polished metal surfaces have high reflectivity (albedo), they have low emissivity and, therefore, get much warmer than surfaces which are light in colours (which have high emissivity). In dense urban areas, light colours should be used to increase the albedo of the paving and other surfaces. A 15% increase in albedo can result in a 3°C temperature drop in cities (Lechner, 2014).

Exterior specular reflectors are applied in building design, redirecting sunlight for several purposes. These reflectors are utilized on various parts of buildings, including rooftops, walls, windows, and architectural elements like sun shades, awnings, and canopies. These surfaces are chosen strategically to redirect sunlight. Reflectors on roofs enhance solar energy collection, while those on walls and windows improve interior daylighting and regulate heat gain. Additionally, they help manage heat gain during warmer months by deflecting sunlight away from windows, which in turn supports temperature regulation and indoor comfort. The reflectors can be adjusted seasonally, redirecting sunlight to either minimize heat gain in the summer or enhance warmth in the winter. Architectural elements with integrated reflectors contribute to both aesthetics and energy efficiency. Their placement depends on the building's design, orientation, and the desired impact on solar gain and lighting.

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) to decrease heat gains. CEMs help to lower indoor temperatures and the risk of overheating. 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. CEMs must be coupled with heat-modulating strategies to provide the best results. Cool wall materials (such as light-coloured paints, claddings, and sidings) and some cool-coloured wall products, are similarly mature and available, but their product rating system is still under development. 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. As passive solar-control measures, CEMs help whenever the sun shines. They continue to mitigate unwanted solar heat gain during a power outage or heat wave. However, their absorptive capacities diminish when cloudy, hazy, or smoky skies reduce incident sunlight.

9 Developed Case Study I

9.1 Introduction

The design process presented in Chapter 1 of this guideline was applied in this case study, which includes the pre-design, schematic design, design development, resiliency assessment, and building performance assessment steps (Qi et al., 2023). Field measurements and simulations were performed to evaluate the performance of resilient cooling technologies under current, mid-term, and long-term climate conditions. Suggestions and lessons learned are also provided.

9.2 Case Study

The case study building is a primary school built in 1958, located in Montreal, Canada. It is in a climate zone of 6A according to ASHRAE 90.1 (2022). It offers space for classrooms, meeting rooms, and gyms. The key information about the building is listed in **Table 9.1**. The building was constructed according to building code requirements in the 1950s (NRC, 2012). **Figure 9.1** shows the exterior view of the school.

Figure 9.1. *Exterior view of the school. (Google maps)*

Table 9.1. *Key information about the building.*

Location	Montreal, Canada
Building Type	School
Occupants in Each Classroom	25
Surroundings (Urban/Rural)	Urban
Year of Construction	1958
Floor Area (m²)	1 152
Window Area to floor Area Ratio (−)	25%
Window-to-Wall Ratio (−)	60%
Climate Zone	6A (ASHRAE 90.1)

9.3 Design Process

9.3.1 Pre-Design

The following basic information about the building was ascertained:

- The building envelope consists of a reinforced concrete skeleton with a brick façade, but it lacks high insulation properties.
- The windows consist of two layers of single-glazed windows.
- 25% of the total window area is openable (as shown in **Figure 9.2**).
- The windows are shaded using interior blind roll shading.
- No exterior solar protection was installed.
- No cooling system or mechanical ventilation was installed.
- The building is cooled mainly via natural ventilation.
- The occupants are children aged 5-10 years.
- The occupancy schedule for the children is 40 hours per week, Monday to Friday, from 9am to 4pm, from January to December, except July and August.
- Specific details regarding the thermal properties of the building envelope, such as the *U*-value, the *SHGC* of the windows, the thermal characteristics of the shading system, as well as information regarding internal loads and natural ventilation rates, are not available. Therefore, the calibration methodology presented in Chapter 5 was used (as shown in Section 9.3.2.2).

Climate change has led to increased temperatures in Canada during the summer, which can have negative impacts on the well-being of Canadian people. This is especially true of vulnerable people, such as children. Furthermore, the negative impact of heat waves on the built environment includes increased energy demand to cooling systems and increased stress on water supplies.

Therefore, the major objective of this case study is to evaluate the effect of climate change on indoor thermal comfort (especially during heat wave periods) and to find passive mitigation measures that can reduce overheating hours without adding cooling energy demand.

Figure 9.2 *Classroom with exterior windows and interior shading (left), interior window and door (right).*

9.3.2 Schematic Design

9.3.2.1 Field Measurement

Four classrooms (shown in **Figure 9.3**) located on the second floor (i.e., Rm. 200, 203, 208, and 212) were selected according to their different orientations, to measure and compare the indoor thermal conditions, including internal temperature. Classrooms 200 and 203 are southeast-oriented, while classrooms 208 and 212 are northwest oriented. All the classrooms have a floor area of about 70 m². A weather station was installed on the roof of the building, and the parameters measured included temperature, relative humidity (RH), solar radiation, wind speed and direction, and rainfall intensity. The measured data indicated that the occupants open windows when the indoor temperature reached 23°C in the southeast classrooms and 24°C in the northwest classrooms.

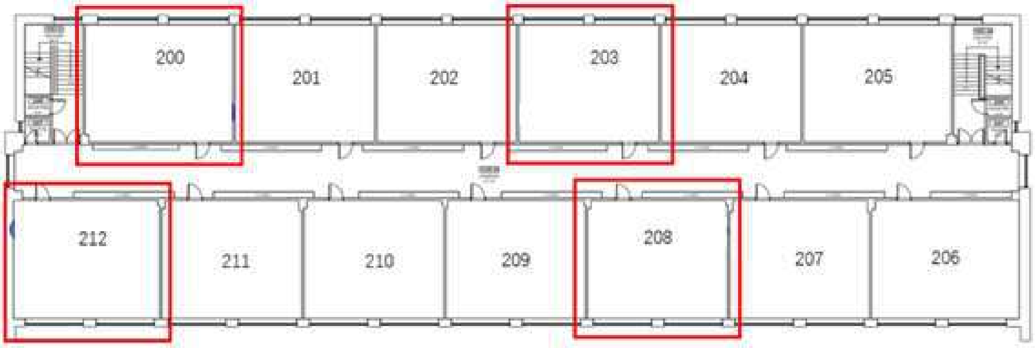


***Figure 9.3** Four classrooms located on the second floor.*

9.3.2.2 Validated Building Simulation Model

To assess and address the risk of overheating in various scenarios and weather conditions, it was crucial to have a validated Building Simulation Model (BSM) based on measured hourly indoor air temperature. To achieve this, the calibration methodology outlined in Chapter 5 was utilized. This methodology enables one to find the values of uncertain building parameters to ensure that the air temperature predictions from the BSM closely align with the actual measured indoor temperatures. **Table 9.2** presents the building specifications (properties) obtained based on the calibration of the simulation model.

Table 9.2 *Building parameter values based on the calibration process (Baba et al. 2022).*

Property	Value
Window *U*-value (W/(m²K))	2.40
Window *g*-value	0.65
Wall *U*-value (W/(m²K))	0.45
Roof *U*-value (W/(m²K))	0.24
Ground *U*-value (W/(m²K))	0.35
Airtightness (at 50 Pa) (1/h)	3.90
Max NV Amount (ACH)	9.00
NV Setpoint (°C)	24.00
Maximum Lighting Load (W/m²)	10.00
Maximum Equipment Load (W/m²)	2.50
Interior Shading Solar Reflectance	0.80

9.3.3 Design Development: Optimization Potentials of RC Technologies

Resilient cooling technologies were evaluated under extreme current and future years. Passive resilient cooling technologies that could be added to the building with minor renovation were studied using validated BSM to improve indoor operative temperature without increasing cooling energy demand. These technologies are listed in **Table 9.3**.

Table 9.3 *Passive measures considered to be resilient cooling technologies (Baba et al., 2022; 2023).*

Resilient cooling technology	Value	Description
Night Cooling (window opening area)	25%	By opening windows during the night-time.
External Overhang Shading	1.5 m	Applied to the southeast side with keeping the existing internal shading.
Exterior Blind Roll Shading	0.8	Automatically activated when the solar radiation on the window surface is > 120 W/m².
Cool Roof- Shortwave Reflectivity	0.8	By increasing the solar reflectance of the roof from 0.3 to 0.8.
Window SHGC (Solar Heat Gain coefficient)	0.3	By adding dark tinted film to existing windows to reduce SHGC to 0.3.
Green Roof	/	With a leaf area index (LAI) of 5.0 and an average height of 0.1 m in the soil.

9.3.4 *Resiliency assessment*

9.3.4.1 *Future Weather Files and Heat Waves*

The future climate generation and extreme future year detection methods adopted from "Annex 80: Group Weather Data" (Zhang et al., 2023) were used. According to the "heat wave detection operational" method, three heat wave thresholds determined for Montreal were applied, including 25.5°C for Spic, 24.1°C for Sdeb, and 23.3°C for Sint. These three percentile thresholds are as follows: 1) Spic threshold represents 99.5 quantiles of the daily mean temperature during the historical period (20 years), which defines the beginning of the heat wave; 2) Sdeb represents 97.5 quantiles, and 3) Sint represents 95 quantiles. Based on these three heat wave thresholds, four heat wave events over the historical period, 38 in the future mid-term (2041–2060), and 88 in the future long-term period (2081-2100) were detected. During the historical period, the extreme year (RSWY-Reference Summer Weather Year) was 2020, which had the most intense, severe, and longest heat waves. During the future mid-term, three extreme RSWY years were detected: 2059 (which had the most intense heat wave), 2042 (which had the most severe heat wave), and 2044 (which had the longest heat wave). In the long term, the most extreme RSWY year was 2090, which was simulated to have the longest, most intense, and most severe heat waves. Therefore, the indoor thermal condition of the school was assessed with 2020 observational weather data and projected future weather data in the future years 2042, 2044, 2059, and 2090.

9.3.4.2 *Key Performance Indicators*

The Building Bulletin BB101 Guideline was used for the assessment of the indoor thermal comfort of the school building based on the thermal comfort KPIs introduced in Chapter 3 (i.e., hours of exceedance, daily weighted exceedance, and Upper Limit Temperature). Standard Effective Temperature was also used.

To ensure the building achieves thermal comfort in accordance with BB101, these KPIs must meet the requirements shown in **Table 9.4** during the period Monday to Friday from 09:00 AM to 04:00 PM, from May 1 to September 30, including the summer holiday period (as if the school is occupied normally).

Table 9.4. *KPI performance requirements.*

KPI	Performance Requirements
Hours of Exceedance (*HE*)	The exceedance hours must not exceed 40 occupied hours. The adaptive thermal comfort threshold of Category I & II from EN 16798-1 (2019) is used.
Daily Weighted Exceedance (*We*)	The We value should not exceed 6°C on any day.
Upper Limit Temperature (T_{upp})	The operative temperature should not exceed T_{max} by 4K or more at any time.
Standard Effective Temperature (*SET*)	The standard effective temperature shall not exceed 30°C for more than 5 *SET* °C degree/day according to the LEED requirements (Sun et al., 2021; Wilson, 2015).

9.3.4.3 Thermal Comfort Under 2020

Table 9.5 shows the thermal comfort assessment of the four selected rooms during the summer period. According to criterion Cat. I (considering schoolchildren as a vulnerable population), the *HE* of Rm. 212 was 44 hours, while the *HE* of the other three rooms was more than 40 and was between 48–110. Furthermore, **Table 9.4** shows that the We exceeded the 6°C during 3 days in the southeast classrooms. According to the LEED requirements for Passive Survivability and Functionality During Emergencies, buildings must undergo testing during one week of heat wave events. In this building, while there were short periods where the Standard Effective Temperature (*SET*) exceeded 30°C, the cumulative *SET*-degree hours did not exceed 5°C/day during a 7-day heat wave from June 16th to June 23rd. This shows that there are no health risks associated with heat waves in this building equipped with natural ventilation (NV) and interior shading during this time.

***Table 9.5**. Thermal comfort assessment.*

Room number	Rm 200	Rm 203	Rm 208	Rm 212
HE (*T* > Cat. I) in summer*	110	102	48	44
HE (*T* > Cat. II) in summer*	38	35	11	10
We (Cat. I) > 6°C/day**	3	3	0	0
Tupp (Cat. I) > 4°C **	0	0	0	0
SET > 30°C ***	2	1	0	0

* Acceptance limit: 40 hours
** Acceptance limit: 0 day
*** Acceptance limit: 5°C/day

Figure 9.4 shows the indoor temperature of Rm. 200 (the hottest room) according to BB101 criteria and EN 16798-1 categories. The orange (Cat. II) and red (Cat. I) lines delimit the range of acceptable indoor thermal conditions to evaluate criterion 1 in BB101. It shows that the southeast classrooms had a high exceedance risk when compared with the northwest rooms, especially given the Cat. I-red and orange points (vulnerable people). Furthermore, the cumulative excess heat (*We*) in those classrooms exceeded the acceptable limit for three days.

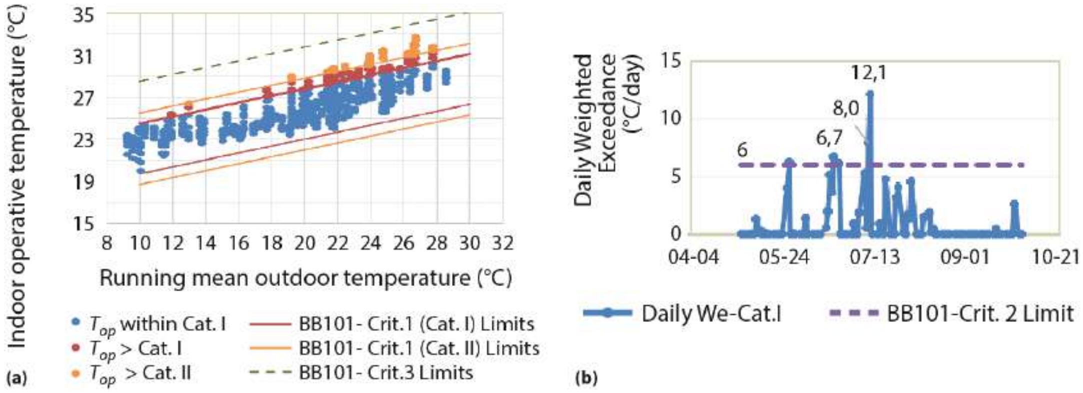


***Figure 9.4**. Thermal condition of room 200 under 2020 based on BB101 criteria 1 limit (a) and BB101 criterion 2 (b) (Baba et al., 2022).*

9.3.4.4 Thermal Comfort Under Extreme Future Years

The exceedance hours of all classrooms on the second floor under years 2042, 2044, and 2059 for mid-term future climate and 2090 for long-term future climate were calculated based on Cat. I and presented in **Figure 9.5**. It shows that the year 2044, which has the longest heat wave event, had the greatest impact on indoor thermal conditions, compared to the other years with the most intense and longest heat waves. Under 2044, the exceedance hours in the hottest and coldest northwest classrooms were 188 and 182, respectively, indicating that there was no significant difference between the indoor thermal conditions of northwest classrooms on the second floor. While in the southeast classroom, the difference between the exceedance hours in the hottest (333 hours) and coldest rooms (290 hours) was around 40 hours. It also shows that all rooms would not have acceptable conditions in future extreme years except the northwest rooms (206-212) under 2059, which had the most intense heat wave but not the longest or most severe heat waves (using Cat. II criteria). Due to climate change, the overheating risk in the hottest room would increase by 165 and 223 hours under 2044 (using Cat. II and I, respectively). The exceedance hours will increase by up to 327 hours in 2090 compared to those in 2020.

In accordance with LEED requirements, the indoor temperature should remain within the “liveable temperature” range, even during power outages. To achieve this, the *SET* should not exceed 30°C for more than 5 consecutive days. This provision ensures that buildings maintain a safe environment for occupants, even under challenging circumstances such as power disruptions or extreme weather events. The results show the number of days when *SET* exceeded 30°C is 2 days in the hottest room and about 0 days in all the other rooms.

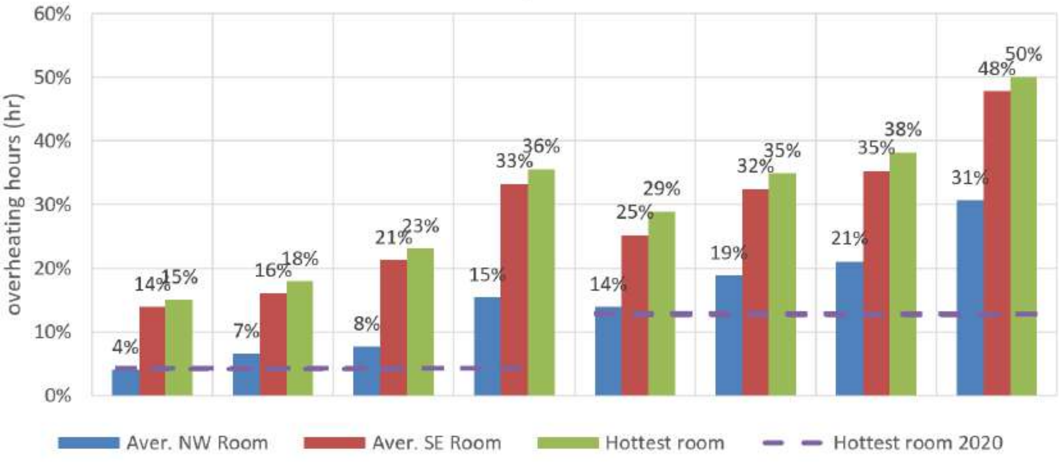


Figure 9.5. *HE based on BB101 Criterion 1 (Cat. I & II) under future RSWY compared to exceedance hours in the hottest room under 2020 (Baba et al., 2022).*

9.3.4.5 Potential Improvement of Indoor Thermal Conditions Under 2020

Figure 9.6 shows the effect of adding passive cooling strategies listed in **Table 9.3** on the exceedance hours under 2020 observational weather. As shown in **Figure 9.6**, the passive cooling strategies were evaluated singularly and in three paired combinations (i.e. no parametric analysis was undertaken to ascertain the best combination of all the strategies). Under 2020, the addition of the green roof to the original case reduces the exceedance hours by 4% in the hottest classroom. A similar reduction can also be observed in all other rooms.

Adding the cool roof to the original case reduces exceedance hours, especially for the northwest rooms, where the main source of solar heat gain for these rooms comes from the roof. With the cool roof, the exceedance hours in northwest rooms (206-212) are reduced to about 20 hours, while they are reduced to 144 hours (−28%) in the hottest room.

The night cooling, overhang shading, and lower *SHGC* reduced the exceedance hour significantly to 68, 60, and 56 hours, respectively, in the hottest room. The use of overhang shading or low *SHGC* measures can be sufficient to meet the BB101 requirement for all rooms except the hottest room (Rm. 200). The use of exterior screen shading (blind roll) can be the best solution to mitigate overheating, as it reduces the exceedance hours to 16 in the hottest room and almost 0 in the north rooms.

The effect of a combination of night cooling (NC) and cool roof (CR), overhanging shading (OH), or lower *SHGC* on indoor thermal conditions has also been studied. The results show that the exceedance hours were reduced to 39 by using night cooling and a cool roof, 25 by using night cooling and overhang shading, and 18 by using night cooling and lower *SHGC* in the hottest classroom. These mitigation measures can meet BB101 Criteria II (daily weighted exceedance) requirements.

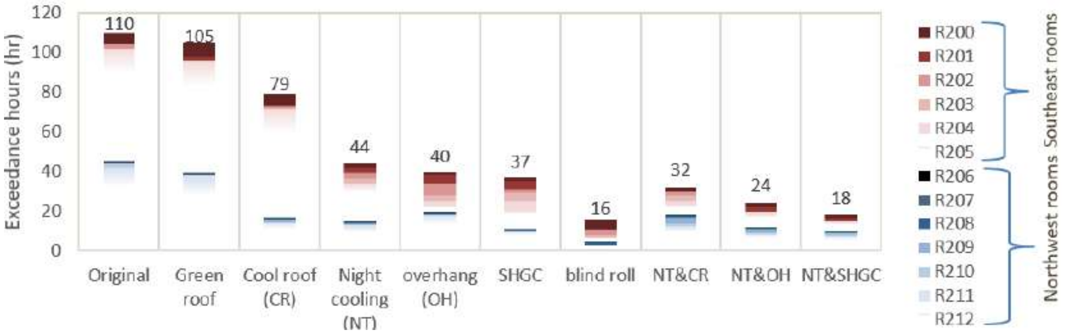
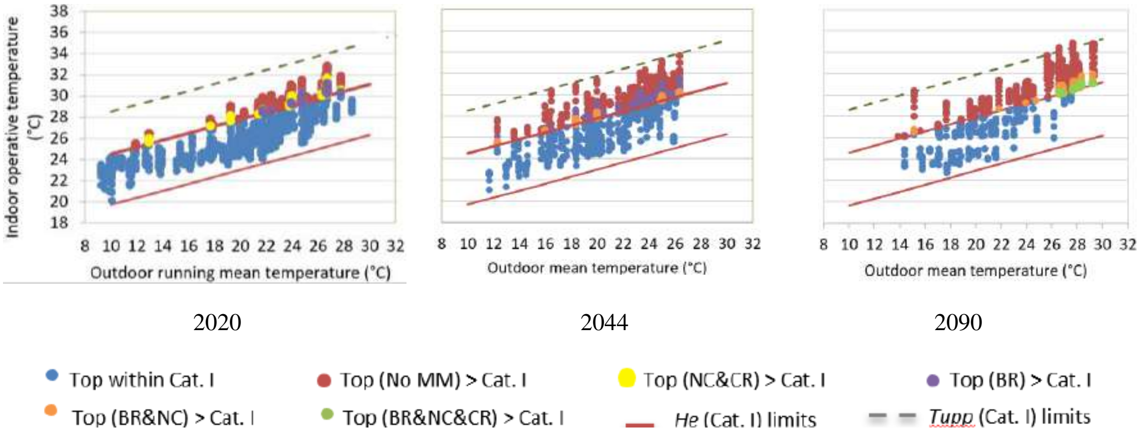


Figure 9.6*. Exceedance hours in room 200 under 2020 with various mitigation measures.*

9.3.4.6 Potential Improvement of Indoor Thermal Conditions Under Future Climates

Under 2044, blind shading will be able to reduce the exceedance hours from 330 (orange dots in **Figure 9.7**) to 100 (yellow dots), but these figures are still higher than the 40 hours required by BB101. Adding night cooling to blind shading can reduce the exceedance hours to 15 (green dots) in the hottest room based on Cat. I, meeting BB101 criterion 2 (daily weighted exceedance).

Under 2090, the combination of blind roll and night cooling will reduce the exceedance hours to 84 based on Cat. I. Therefore, cool roof measures are applied with the blind roll and night cooling. This combination will be able to reduce the exceedance hours based on Cat. I (EN 16798-1) to 39 in the hottest room and the combination can meet BB101 criterion 2 requirements.



2020 2044 2090

Figure 9.7. *Indoor operative temperature with various mitigation measures in Rm. 200 under summer 2020, 2044, and 2090 (Baba et al., 2022).*

9.4 Discussion and lessons Learned

The evaluation of thermal performance for existing buildings and the implementation of various mitigation measures, particularly resilient cooling technologies, have become essential, especially under extreme current and future climate scenarios. Validated building simulation models and KPIs are crucial tools in this process. KPIs that are recommended to be utilized to assess the performance of resilient cooling strategies as hours of exceedance, daily weighted exceedance, upper limit temperature, and *SET*.

The main findings and lessons learned from this case study are:

- Despite the presence of natural ventilation and indoor shading systems in schools located in cold climates, children inside have been exposed to a significant and unacceptable number of exceedance hours and severe excessive heat during the summer in recent years.
- The use of exterior blind rolls (screen shading) or a combination of night cooling and other mitigation measures that reduce solar heat gain (such as a cool roofs, exterior overhangs, and lower window *SHGC*) can achieve acceptable thermal conditions in the next 20 years.
- The number of heat waves will increase from four during the historical period (2001-2020) to 38 in the mid-term (2041-2060) and to 88 in the long-term (2081-2100) future years.
- The number of exceedance hours with the current operational situation in old Canadian schools will increase to two and four times in the extreme mid-term and long-term future years, respectively, if no mitigation measures are applied.
- The use of night cooling combined with the exterior blind roll can be sufficient to remove the excessive heat and achieve acceptable thermal conditions in the mid-term future. However, in the long-term future, additional measures such as the addition of a cool roof will be needed.
- In hot climates, mechanical cooling systems are often considered essential to maintain indoor thermal comfort. However, the role of passive mitigation measures in reducing cooling demand is still a critical question. Evaluating the effectiveness of various passive measures, such as insulation, shading, and natural ventilation, can provide valuable insights into their potential to significantly reduce cooling demand and provide adaptive thermal comfort.

10 Developed Case Study II

10.1 Introduction

This chapter provides an examination of a case study office building located in Belgium. The purpose of conducting simulations in this case study was to evaluate the effectiveness of resilient cooling technologies in different climate conditions, such as the current weather, future projections, as well as historical and long-term heat wave scenarios. Additionally, the simulations incorporated a 24-hour power outage on the hottest day of the heat wave to assess the resilience of the building under challenging circumstances. The thermal performance of the building and the effect of mechanical ventilative cooling (MVC) and natural ventilative cooling (NVC) were analysed by the energy and indoor comfort simulation tool "IDA ICE".

10.2 Project Description

The case study is a new low-tech office building encompassing 940 m² offices and architectural design studios in the inner city of Leuven (50°53′N 04°42′E). The building was designed by *archipelago* architects for their own use. **Figure 10.1** shows the exterior view of the northwest facade of the office building.

***Figure 10.1**. 3D design view of the office building (© archipelago architects).*

The office building is situated in an urban renewal project comprising housing, underground parking, and a new semi-public park with urban farming. The office consists of two levels, internally connected with a void and two staircases. The levels are organized around an outdoor patio and connected to the park. The park façade (oriented northwest) and the patio façades are the only glazed façades. Skylights provide additional daylight and can potentially be used for stack ventilation. Due to the urban context and strict urban planning rules, neither roof extensions nor chimneys are possible.

Table 10.1. *Key information about the building.*

Location	Leuven, Belgium
Building Category	Offices
Number of Floors	2
Number of Occupants on Each Floor	32 working days each week (8:00-18:00)
Year of Construction	2023
Floor Area (m^2)	1 019
Windows Area to Floor Area Ratio (−)	40%
Window-to-Wall Ratio (−)	21%
Climate Zone	4 (ASHRAE)

10.3 Design Process

10.3.1 Pre-Design

A stepped design approach was employed to achieve optimal comfort by predominantly applying passive design techniques. The potential of NVC in combination with exposed thermal mass and solar shading strategies has been optimized. The whole design process has been extensively documented in Declercq et al. (2021).

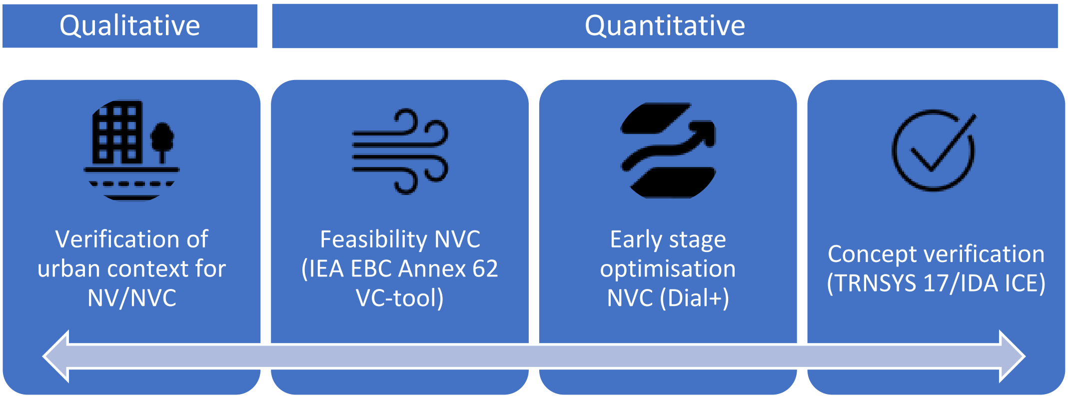


Figure 10.2. *Staged design process (© archipelago architects).*

The application of the described strategies has a crucial connection with the architectural design concept. It therefore needed to be addressed early in the design process. Additionally, the validation of these strategies requires simulations which do not typically fall within the scope of energy simulation efforts. To address these challenges, the architectural design team implemented a phased design approach. The outcomes of the simulations were systematically fed into the design process.

In the early design phase, the urban context of the case study was verified for the use of NVC strategies. The context of the project was checked for two important contextual parameters that can influence the application of certain passive design strategies, specifically the outdoor noise level and the outdoor air quality, which both influence the applicability of natural ventilative cooling. These conditions proved to be acceptable for the application of NVC (Declercq et al., 2021).

Consequently, the Ventilative Cooling Potential Tool worksheet v1.0 (developed in the IEA EBC Annex 62 Ventilative Cooling project) was used to assess the NVC potential in this early design stage (Declercq et al., 2021; Flourentzos et al., 2012; Flourentzos et al., 2015; Belleri et al., 2018).

In the early design phase, two sets of weather data were used: one for the current conditions and another for future climate conditions (RCP 8.5 TMY 2070-2100). For the latter, weather data extracted from Regional Climate Models (RCMs) was used. For Belgium, a climate model with a spatial resolution of 2.8 km was available due to the CORDEX.BE project (Ramon et al., 2019). This high resolution allowed for the Urban Heat Island effect to be considered, as the building is located in an inner-city location.

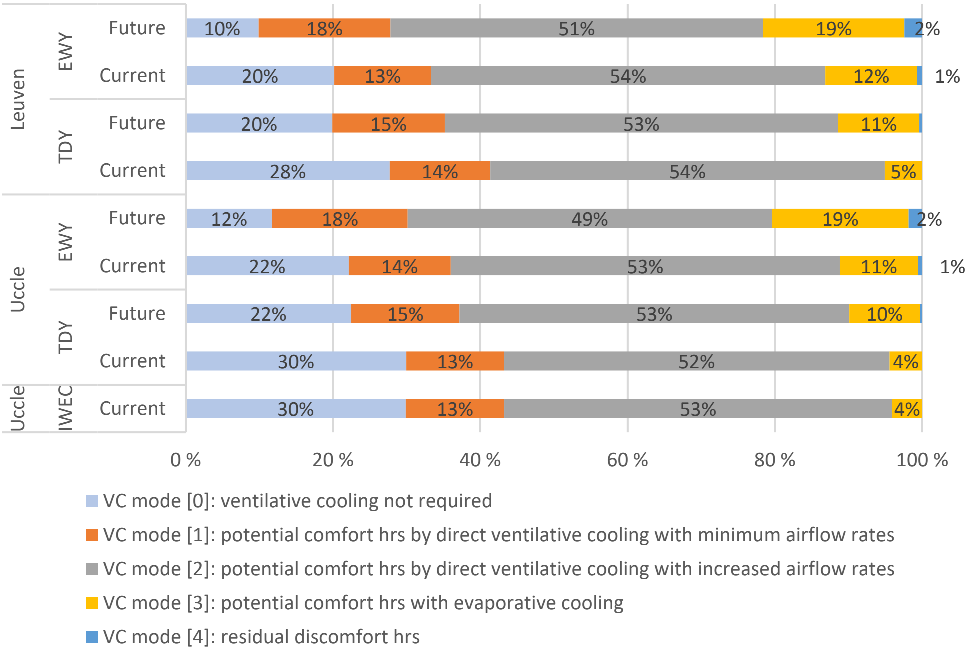


***Figure 10.3**. Output of the IEA EBC Annex 62 VC-tool for different current and future weather data showing the NVC potential.*

Thereafter, two dynamic simulations were set up. First, the software Dial+ v2.7 (Estia SA) was applied. This software is designed for architects to perform early-stage single-zone dynamic simulations of daylight, heating and cooling demand, and summer comfort. This simulation allowed the team to check the NVC concept, the early sizing of operable windows, and their positions. No wind was considered, only the stack effect.

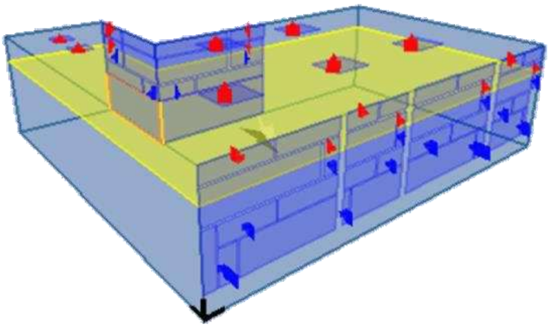


***Figure 10.4**. Model of the single zone model of the main building volume in Dial+ (© archipelago architects).*

Finally, TRNSYS 17 was used by the consulting engineering office to do a final check and validation of the design. This tool allows for detailed multi-zone simulations. Through the design process, the level of detail of the information increased, and hence the simulation parameters also evolved. In both cases, the thermal comfort was assessed according to the adaptive comfort model (EN 16798-1). The design was optimized to reach adequate summer comfort under typical current weather conditions and under the conditions of a historical heat wave (Brussels 1976) without mechanical cooling.

10.4 Finalization of the Design

10.4.1 Building Simulation Model

The final study involved a multizone thermal simulation, considering 10 zones in the building that are connected thermally and by airflow. For enhanced precision in the outcomes, the detailed model was reconstructed in IDA ICE v4.9.9 (EQUA).

To obtain more accurate resilience indicators, the thermal performance of three main areas (two open offices and one reception area) was assessed. The zones and their details are shown in **Tables 10.2–3**. Zone +0 open office and Zone −1 open office are connected through an internal void.

Figure 10.5. *Screenshot of the IDA ICE multi-zone simulation model (© archipelago architects).*

There are external shadings on the east, west, and south facades and on the skylights, which are controlled automatically (facade shading is considered ON when the radiation on the windows is above 150 W/m² and the skylight shading is ON when the radiation on the windows is above 250 W/m²).

Hygienic ventilation is organized through a central Dedicated Outdoor Air (DOA) handling unit with an enthalpy wheel and the air is preheated to between 18°C and 20°C, depending on the outdoor temperature. The ventilation rate per person is 40m³/h and CO_2 is controlled per zone (700-1 100 ppm). In this study, the control strategy of natural ventilative cooling was based on the indoor temperature, the temperature difference between indoor and outdoor temperatures, as well as the occupancy schedule for each scenario. Specifically, the natural ventilation system was activated during the day from 7 a.m. to 6 p.m. on working days when the indoor temperature is higher than 23°C and the outdoor temperature is higher than 14°C. During the night-time, the ventilation system is activated if the interior temperature is higher than 21°C, when the exterior temperature is lower than the interior, and when the exterior temperature is higher than 8°C.

The results of the simulation were analysed in a two-step process. Initially, energy consumption was computed for three different zones, considering both current and future climate conditions. Thereafter, the resilience indicators were assessed for the historical and long-term heat waves.

***Table 10.2**. Evaluated zones.*

	Zone A	Zone B	Zone C
Level	+0	+0	-1
Function	Reception	Open office	Open office
Floor Area	89 m²	225 m²	315 m²

***Table 10.3**. Building specifications of the evaluated zones.*

Property	Value		
Zone	**A**	**B**	**C**
Window *U*-value (W/(m²K))	1.1	1.1	1.1
Window *g*-value (–)	0.34	0.34	0.34
Wall *U*-value (W/(m²K))	0.16	0.16	0.16
Roof *U*-value (W/(m²K))	0.08	0.08	N/A
Ground *U*-value (W/(m²K))	N/A	N/A	0.24
Airtightness (at 50 Pa) (h–1)	0.50	0.50	0.50
Max NV Airflow Rate (ACH) (h–1)	9	6	8
Maximum Lighting Load (W/m²)	5.00	5.00	5.00
Maximum Equipment Load (W/m²)	2.00	6.00	6.00
Exterior Shading *	No	Yes	Yes
Shading Between Panes (Microshade F)	No	Yes	Yes

* Simulation scenarios (Table 10.4) for automated shading.

10.4.2 Design Development: Optimization Potentials of Resilient Cooling Technologies

A multi-zone simulation was conducted for six different scenarios.

Table 10.4. *Scenarios studied for the evaluated zones.*

Scenario	Automated Shading	Mechanical Ventilative Cooling 24/7	Natural Ventilative Cooling 24/7	Thermal Mass (DIN:2003)	Mechanical Heating and Cooling Devices (zone level)
1	No	No	No	Light	Radiant panel
2	Yes	No	No	Light	Radiant panel
3	Yes	Yes	No	Light	Radiant panel
4	Yes	No	Yes	Light	Radiant panel
5	Yes	No	Yes	Heavy	Radiant panel
6	Yes	No	Yes	Heavy	TABS

The controls of the heating and cooling systems are modelled as PI-controlled, with the control setpoints based on the air temperature.

10.4.3 Resilience Assessment

10.4.3.1 Future Weather Files and Heat Waves

In the simulation, two sets of heat wave data files were utilized: one corresponding to the “historical severe heat wave,” spanning 25 days from July 6th to July 31st, and the other representing the “long-term severe heat wave,” lasting for 45 days from July 2nd to August 15th.

10.4.3.2 Key Performance Indicators

The following KPIs were assessed for the three zones: Indoor Overheating Degree (IOD) and Overheating Escalation Factor (OEF).

10.4.4 Building Performance Assessment

- **Step 1:** Under current (TMY 2001-2020) and future weather conditions (TMY 2081-2100), the effect of passive design strategies on the energy consumption for heating and cooling was analysed for all the case studies. All cases were simulated with mechanical cooling (setpoint 26°C) and without mechanical cooling. This step of the study is summarized in **Table 10.5**. This allows the design team to choose the scenario with the lowest energy demand as the primary criterion. **Figures 10.6** and **10.7** display energy consumption for all the scenarios.

***Table 10.5**. First phase description.*

Scenario	Weather Data		Indicators:	
			Energy use for	
	Current	Future	Cooling	Heating
all	x	x	x	x

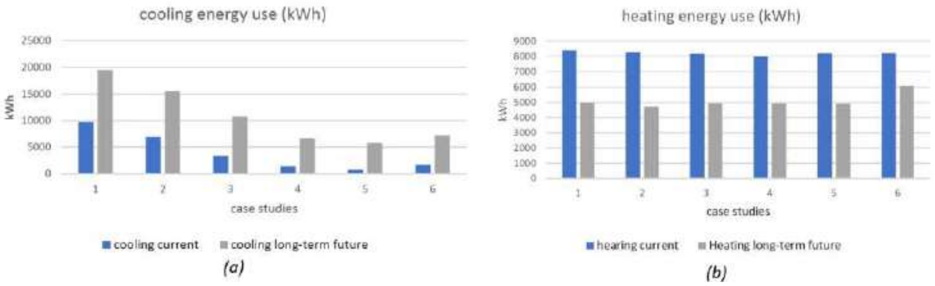


***Figure 10.6**. (a) Cooling energy use, (b) heating energy use (delivered to the building).*

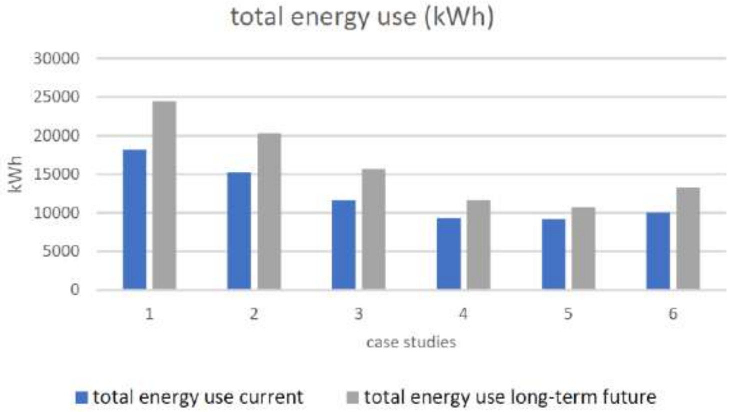


***Figure 10.7**. Overall energy use.*

As expected, cooling energy consumption increased across all scenarios due to climate change. The collective influence of passive design strategies on cooling energy consumption is clear in scenarios 1 to 5. Transitioning from a reactive cooling system (radiant panels) to a less reactive system (TABS) in scenario 6 appeared to have a counterproductive effect on cooling energy use due to the latency. This could be partially offset by more advanced control strategies.

Based on the findings, scenario 5 not only exhibited a reduced total energy consumption but also provided improved summer thermal comfort (**Figure 10.8**). Additionally, the comparison of all scenarios emphasizes the importance of passive cooling strategies. Consequently, it can be considered an exemplary model for the forthcoming design implementation.

Figure 10.8 shows the percentage of occupied hours above 25°C with and without the use of mechanical cooling showing the summer thermal comfort and emphasizing the effects of passive cooling (zone B).

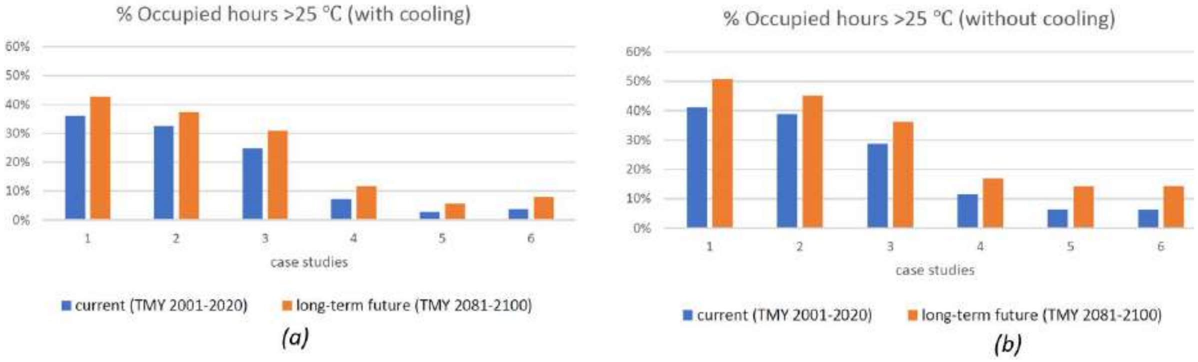


Figure 10.8*. a) Occupied hours above 25°C with mechanical cooling, (b) occupied hours above 25°C without mechanical cooling.*

- **Step 2:** At this step, the KPIs regarding resilience to overheating were evaluated for the three zones.

During building lifetimes, buildings are subject to sudden shocks and unforeseen events (e.g. fan failures and power outages) that cause the indoor thermal environment to deviate from the designed comfort level and causing overheating (Sengupta et al., 2021). To assess building resilience to overheating, historical severe heat waves and a power outage on the warmest day of the year were taken into consideration.

In the simulations, two sets of heat wave weather data were applied: a historical severe heat wave and a long-term severe heat wave. During this phase of the study, we considered all the scenarios with and without cooling to highlight the effect of passive cooling strategies. An overview of this step of the study can be found in **Table 10.6**. In **Figure 10.9**, the IOD for historical and long-term heat waves is displayed in three zones.

***Table 10.6**. Second phase description.*

Scenario	Weather Data		Power Outage
	HW historical severe heat wave (25 days)	HW long-term severe heat wave (44 days)	HW historical severe
All the scenarios	x	x	24 h (hottest day with average temperature of 30)

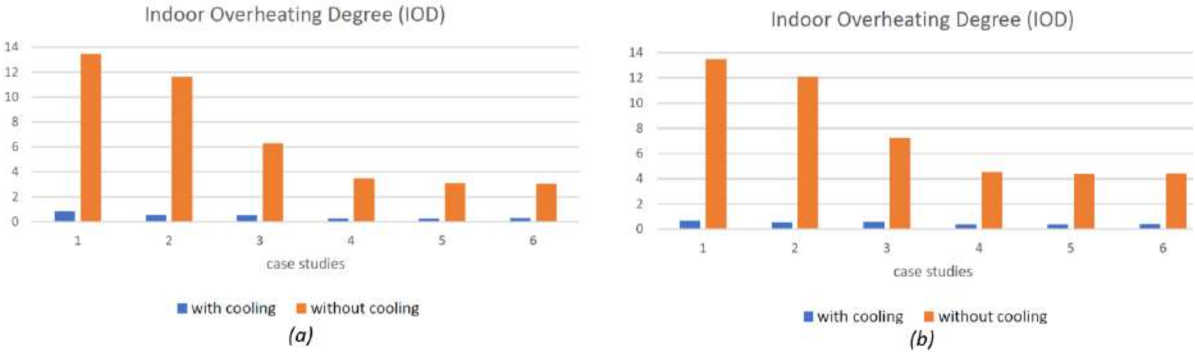


***Figure 10.9**. a) Indoor overheating degree (historical HW),*
b) indoor overheating degree (long-term future HW).

Assessing the building's resilience is crucial due to anticipated increased heat waves. This study shows that effective architectural design can mitigate these challenges. Furthermore, simulations have revealed that scenario 5 exhibits remarkable resilience. **Figure 10.11** shows KPIs for all the scenarios when there is a 24-hour power outage.

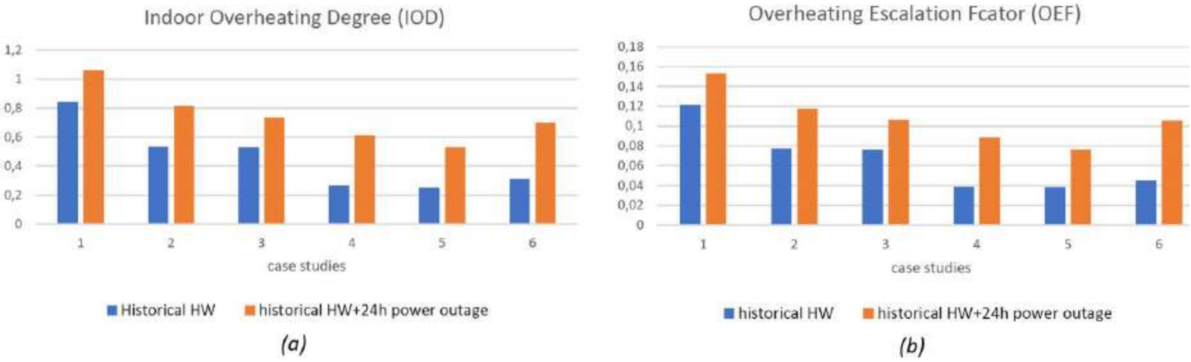


***Figure 10.10**. a) Indoor overheating degree (historical HW & 24 hours of power outage),*
b) overheating escalation factor (historical HW & 24 hours of power outage).

In conclusion, the results clearly demonstrate the impact of the shock, and scenario 5 appears to perform more efficiently in comparison to the other case studies.

10.5 Discussion and Lessons Learned

This chapter presents a case study of a Belgian office building, evaluating diverse design strategies for enhancing resilience to overheating in various climate conditions. The study includes simulations for current weather, future projections, and historical heat waves. Six scenarios were analysed in two phases, first assessing energy consumption and thermal comfort to identify the most efficient scenario. The second phase involved analysing resilience indicators during historical and long-term heat waves, along with a simulated 24-hour power outage.

Results clearly indicate that natural ventilation combined with thermal mass (scenario 5) can have a significant influence. According to the results of the study, despite the challenges presented by the increasing temperatures caused by global warming, natural ventilation continues to be an interesting approach for cooling indoor environments. In anticipated future climate scenarios, the inclusion of mechanical cooling is essential to achieving summer comfort under all circumstances and achieving resilience to overheating. However, the potential energy savings achieved by combining mechanical cooling with natural ventilation are projected to be even higher compared to the present climate. This is because the duration that natural ventilation can effectively reduce the cooling load is expected to increase, thereby providing more opportunity for energy-efficient cooling. At the same time, this strategy has a significant beneficial effect on the resilience of the building to overheating.

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Resilient cooling aims to mitigate heat stress and maintain safe building conditions during externally induced disruptions, going beyond mere thermal comfort. This Guidebook focuses on designing cooling systems that are resilient to such challenges.

The target audience includes practitioners in building design, architectural firms, building services sectors, consulting engineers, firms, national authorities, building owners, tenants, policymakers, government officers, and building services institutions. It is relevant for small and mid-size facilities, residential and commercial buildings, and both new construction and existing buildings in terms of operation, management, and maintenance.

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