ANNEX 80

EBC
Energy in Building and Communities Programme

International Energy Agency

Resilient Cooling of Buildings Technology Profiles Report (Annex 80)

Energy in Buildings and Communities Technology Collaboration Programme

May 2024

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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 and 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 have its 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 have been 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 operation;
– 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 taking into account 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 analysis (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) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such 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 completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)

Annex 2: Ekistics and Advanced Community Energy Systems (*)

Annex 3: Energy Conservation in Residential Buildings (*)

Annex 4: Glasgow Commercial Building Monitoring (*)

Annex 5: Air Infiltration and Ventilation Centre

Annex 6: Energy Systems and Design of Communities (*)

Annex 7: Local Government Energy Planning (*)

Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)

Annex 9: Minimum Ventilation Rates (*)

Annex 10: Building HVAC 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: BEMS 1- User Interfaces and System Integration (*)

Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)

Annex 18: Demand Controlled Ventilation Systems (*)

Annex 19: Low Slope Roof Systems (*)

Annex 20: Air Flow Patterns within Buildings (*)

Annex 21: Thermal Modelling (*)

Annex 22: Energy Efficient Communities (*)

Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)

Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)

Annex 25: Real time HVAC Simulation (*)

Annex 26: Energy Efficient Ventilation of Large Enclosures (*)

Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)

Annex 28: Low Energy Cooling Systems (*)

Annex 29: ☼ Daylight in Buildings (*)

Annex 30: Bringing Simulation to Application (*)

Annex 31: Energy-Related Environmental Impact of Buildings (*)

Annex 32: Integral Building Envelope Performance Assessment (*)

Annex 33: Advanced Local Energy Planning (*)

Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)

Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)

Annex 36: Retrofitting of Educational Buildings (*)

Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)

Annex 38: ☼ Solar Sustainable Housing (*)

Annex 39: High Performance Insulation Systems (*)

Annex 40: Building Commissioning to Improve Energy Performance (*)

Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)

Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)

Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)

Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)

Annex 45: Energy Efficient Electric Lighting for Buildings (*)

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

Annex 47: Cost-Effective Commissioning for 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 and Evaluation Methods (*)

Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)

Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)

Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)

Annex 57: Evaluation of Embodied Energy and CO2 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 and 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 (*)

Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)

Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)

Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)

Annex 67: Energy Flexible Buildings (*)

Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)

Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale

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Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings

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Annex 74: Competition and Living Lab Platform

Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables

Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions

Annex 77: ☼ Integrated Solutions for Daylight 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

Annex 81: Data-Driven Smart Buildings

Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems

Annex 83: Positive Energy Districts

Annex 84: Demand Management of Buildings in Thermal Networks

Annex 85: Indirect Evaporative Cooling

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 - Energy Efficiency in Educational Buildings (*)

Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)

Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)

Working Group - Cities and Communities

Working Group - Building Energy Codes

Foreword

The world is facing a rapid increase of air conditioning of buildings. This is being driven by multiple factors, such as urbanization and densification, climate change and elevated comfort expectations as well as economic growth in hot and densely populated regions of the world. The trend toward cooling seems inexorable. It is imperative to steer this development towards sustainable solutions.

Against this background, it is the motivation of EBC Annex 80 “Resilient Cooling of Buildings” to develop, assess and communicate solutions of resilient cooling and overheating protection. Resilient Cooling is used to denote low energy and low carbon cooling solutions that strengthen the ability of individuals and our community to withstand, and prevent, thermal and other impacts of changes in global and local climates.

The main objective of Annex 80 is to support a rapid transition to an environment where resilient low energy and low carbon cooling systems are the mainstream and preferred solutions for cooling and overheating issues in buildings.

This report is a main deliverable of Annex 80 and summarizes the investigated resilient cooling technologies of Annex 80. It provides an overview of cooling solutions and their performance related to resiliency against heat waves and power outages. The Technology Profile Sheets give recommendations for good implementation, commissioning and operation, present barriers to application and show opportunities. These shall support the Annex 80 mission of a rapid transition to an environment where resilient low energy and low carbon cooling systems are the mainstream and preferred solutions for cooling and overheating issues in buildings.

Additional outcomes of EBC Annex 80 Resilient Cooling of Buildings are: the Resilient Cooling Guidebook, the Field Studies Report, the Policy Recommendation Report and Sheets. These are available at: https://annex80.iea-ebc.org/

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Abbreviations

Abbreviations	Meaning
AC	Air Conditioning
AHP	Adsorption Heat Pump
CEM	Cool Envelope Material
COP	Coefficient of Performance
CP	Corrective Power
CRR	Cooling Requirements Reduction
CRRC	Cool Roof Rating Council
DSF	Ventilated Double-Skin Façade
EER	Energy Efficiency Ratio
ES-SO	European Solar Shading Organisation
GWP	Global Warming Potential
HE	Hours of Exceedance
HVAC	Heating, Ventilation and Air Conditioning
IOD	Indoor Overheating Degree
KPI	Key Performance Indicator
LAI	Leaf Area Index
LMI	Low-to-Moderate-Income
ODP	Ozone Depletion Potential
OEF	Overheating Escalation Factor
PCM	Phase Change Material
PCS	Personal Comfort Systems
PDEC	Passive Down Draught Evaporative Cooling
PM	Particulate Matter
PV	Photovoltaics
PV/Ts	Photovoltaic/Thermal Panels
SEER	Seasonal Energy Efficiency Ratio
SR	Solar Reflectance

SRI	Solar Reflectance Index
TABS	Thermally Activated Building Systems
TE	Thermal Emittance
TES	Thermal Energy Storage
TIR	Thermal Infrared
SCP	Specific Cooling Power
SET	Standard Effective Temperature
SFP	Specific Fan Power
SHGC	Solar Heat Gain Coefficient
SHP	Specific Heating Power
TEWI	Total Equivalent Warming Impact
VC	Ventilative Cooling
VCC	Vapor Compression Cycles
VGS	Vertical Greening Systems
VRF	Variable Refrigerant Flow
VRV	Variable Refrigerant Volume
WFR	Window-to-floor ratio
WWR	Window-to-wall ratio

1. Introduction

This report offers a collection of 16 technologies, well suited to form a part of Resilient Cooling solutions of Buildings. It is meant as a package of information for those who are in the position to draw decisions upon building-design, both retrofit and new constructions.

The 16 technologies are structured in four main sections, which represent the four general approaches to making a building resilient against heat:

1. Reducing heat gains to the indoor environment and people environments
2. Removing sensible heat from the indoor environment
3. Increasing personal comfort apart from space cooling
4. Removing latent heat from indoor environment

Each technology is described in a concise manner, sub structured in three chapters:

Description

In this chapter the reader finds Information about the physical principles, function, and characteristic applications of the specific Resilient Cooling Technology. Relevant subtypes of are listed. This chapter is somewhat an abstract of the full Technology Profile. If you have limited time, start reading here!

Key Technical Properties

In this chapter, technical properties of the specific Resilient Cooling Technology are presented and briefly explained. Readers find System Design Indicators and properties of the technology which are relevant when designing/purchasing the system.

Where appropriate, you will find a differentiation between Internal and external System Design Indicators, the earlier relevant to the technology itself, the latter relevant to the bordering conditions of the technology.

Performance and Application

This chapter addresses aspects of performance and proper application of the specific technology.

The reader finds information, to what extent the technology contributes to the whole building's performance. Where available, you will also find exemplary results from simulation runs, revealing the technology's benefits to the building performance in and against heatwaves. The simulation results are presented very briefly, addressing numbers of relative improvement to the building performance, achievable by the properly application of the specific technology.

Furthermore, good advice is given on the proper application as well as on possible limitations of the technology in different climate zones.

Finally, you will find information on compatibility and incompatibility with other technologies as well as information on the availability, maturity and expected developments of the technology.

A "Further Reading" chapter at the end offers a pathway to a deep-dive both in other Annex80 publications and external literature.

2. Reducing Heat Gains to the Indoor Environment and People Environments

This chapter presents resilient cooling technologies which reduce heat gains to the indoor environment and people environments. It addresses:

- Solar Shading Technologies
- Glazing Technologies
- Ventilated Façades
- Cool Envelope Materials
- Green Roofs and Green Façades

2.1 Solar Shading Technologies

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Michele Zinzi, ENEA, Italy.

2.1.1 Description

The solar radiation entering the built environment through the opaque and, mainly, transparent surfaces of the building envelope may reduce the space heating demand in winter but it is the major contributor to the cooling load and overheating risk in summer and intermediate seasons. Solar shading systems can effectively mitigate the latter phenomena by modulating the amount of solar radiation entering the building. Shading systems reduce the peak and average loads, thus reducing the cooling energy use in actively cooled buildings or mitigating extreme indoor thermal conditions in passively and actively cooled buildings. By reducing indoor air and mean radiant temperatures, shading devices also improve the thermal comfort of building users.

Shading devices can be categorised according to different criteria:

- Position with respect to the glazing system: internal, in one of the gaps of a multi-glazed element, and external. The efficacy of the solar protection is maximised for external shading; internal blinds should be used primarily for daylighting and glare protection.
- Activation: fixed or moveable. The former is external and has a strong impact on the construction and aesthetics of the building; the latter can be placed in any position with respect to the façade, can be manually or automatically operated, and, most important, can be activated when needed. Examples of solar shading systems are shown in Figure 1.
- Type of products, which includes many solutions regarding: the used materials (aluminium, plastic derivatives, natural fibres, wood.), the texture, the shape (e.g., homogeneous like curtains or discontinuous like venetian blinds and slats)

Figure 1: The wooden slats on the left figure can be tilted but not retracted. The shading system defines the façade of the building; on the right figure, fully moveable shading systems are integrated at the window level and can be operated by the users according to their requirements [1].

The latest development on shading devices have followed two main tracks. The first is the integration of fully automated solutions into smart energy management systems, in order to exploit the potential of the technologies. The aim is to optimize several functions, such as solar protection, daylighting, and view outside for users; requirements that can be sometimes conflicting. The second track is the development of new technological solutions, aimed at optimising solar protection and building integration by dynamic behaviour in response to different boundary conditions, as well as the integration of renewable systems in the shading elements.

The choice and operation of solar shading must always carefully balance between the daylighting access for users, their need to visually interact with the outdoor environment and solar protection. Critical issues for the proper design of such systems are: climatic conditions, building location, neighbourhood and surrounding buildings, the façade orientation, the characteristics of the transparent systems they have to protect, and the building use.

2.1.2 Key Technical Properties

Solar factor [-] (also referred to as Total solar energy transmittance, Solar Heat Gain Coefficient (SHGC), g_{tot}). Amount of solar radiation directly transmitted by the glazing and shading system plus the contribution of the secondary heat transfer (radiation absorbed by the system and re-emitted at higher wavelengths). A low solar factor decreases the solar gains, thus decreasing the cooling load and the overheating risk. A solar factor in the range of 0.10 - 0.15 has a high impact on thermal comfort and a solar factor lower than 0.1 has a very high impact on thermal comfort [2].

Light transmittance [-]. Amount of visible radiation directly transmitted by the glazing and shading system. High light transmittance increases daylight availability, thus decreasing the need for artificial lighting and related internal gains. Light transmittance in the range of 0.25 - 0.40 has a high impact on thermal comfort, above 0.40 a very high impact on thermal comfort [2].

<u>Internal System Design Indicators</u>

Window-to-wall ratio (WWR) [%]. Ratio of the fenestration area to the gross exterior wall area

Window-to-floor ratio (WFR) [%]. Ratio of the fenestration area to the net floor area

These parameters are critical as the size of the transparent envelope elements will drive the cooling loads determined by the solar irradiation entering the built environment. The design of the façade and balance of opaque and transparent components is important, depending on the building use, the outdoor conditions, and the façade orientation, as discussed below.

External System Design Indicators

Global solar irradiation [kWh/m^2] on a horizontal and on the facade planes during the cooling/overheating period. In this context, albedo is also significant. Albedo describes the fraction of global solar irradiation that is diffusely reflected by the ground.

Surroundings such as vegetation and neighbouring buildings

2.1.3 Performance and Application

2.1.3.1 Solar Shading Effect on the Whole Building Performance

Fixed and dynamic shading systems ensure a relevant reduction of the cooling loads and peak demand in insulated and uninsulated buildings. In this case, they decrease the vulnerability and increase the resistance of buildings to the long-term effects of climate change by reducing solar gains. Moveable shading devices should be preferred as they ensure the solar control in the summer without compromising the solar gains in winter.

Table 1: Changes in Key Performance Indicators (KPIs), based on [3], of HVAC-related energy usage and heat stress for a detached house in Brazil (hot and humid climate) from the application of solar shading technologies [4]:

KPI	Reduction from fixed solar shading[d]	Reduction from moveable solar shading[e]
Daily heat stress[a] [°C·h]	30%	65%
Annual HVAC primary energy intensity[b] [kWh/m^2]	7%	31%
Annual HVAC carbon emission intensity[c] [kg CO_2/m^2]	6%	27%

[a] Degree hours of exceedance against a standard effective temperature (SET) of 30 °C during a severe heat wave (14 days) in the midterm future (2041-2060) with grid power outage.

[b] Annual primary energy usage related to HVAC energy need normalized to conditioned floor area in the midterm future (2041-2060) in normal operation with mechanical cooling throughout the year with average primary energy factor of 1.6 for electricity [4].

[c] Annual carbon emission related to HVAC energy need normalized to conditioned floor area in the midterm future (2041-2060) in normal operation with mechanical cooling throughout the year with CO_2 emission factor for electricity: 42.6 g/kWh [5].

[d] In this scenario a porch around the building was designed, which heavily shaded walls and windows. The building was naturally ventilated during the analysis.

[e] In this scenario moveable exterior shutters on windows were designed. The building was naturally ventilated during the analysis.

Shading devices should be designed to balance solar shading, daylighting, and the view of the outside. Dynamic solutions, however, can be very effective during extreme events, such as heat waves or even power outages. As such phenomena take place in a limited period of time, the shading devices might be operated to maximise solar protection as the main strategy limiting the visual requirements during disruptive events.

It should be noted that the technology is useful in reducing the amount of heat entering the building. The absorptive capacity can be described as low to moderate during heatwaves and/or power outages for fixed shading devices.

Dynamic shading devices have moderate to high absorptive capacities during heat waves, but low absorptive capacities during power outages. Adaptive capacities are low during heat waves and/or power outages, except for dynamic shading devices during heat waves, which show high adaptive capacity. Solar shading does not provide restorative and recovery capacity. Once the building is overheated, it is necessary to combine solar shading with active, passive, or hybrid cooling technologies to remove the excess heat and bring the building back to the conditions before the disruptive event [6].

2.1.3.2 Solar Shading Technologies Application in Different Outdoor Conditions

Solar protection devices should be activated during the summer and intermediate seasons to avoid indoor overheating and high cooling energy use. Dynamic systems should be preferred as they can be activated according to the “instantaneous” climatic conditions, having to enhance solar protection under clear sky (high irradiation levels) and daylighting under cloudy sky (low irradiation level).

The above strategies cannot be pursued with fixed shading, which also affects the solar gains during the heating season.

2.1.3.3 Solar Shading Technologies Application and Building Orientation

Orientation plays a relevant role in the solar gain through the transparent elements of the building envelope. Solar irradiation is lower on the north/south façade in the north/south hemisphere; direct solar irradiation occurs only for a few hours during summer, otherwise diffuse radiation occurs. Solar irradiation is relatively low on south/north facades in the north/south hemisphere in summer, as the sun is high in the sky vault; an effective design of fixed elements can provide adequate solar protection in summer, while allowing solar gains in winter. East and west façades are the most exposed to solar irradiation in summer, with a high solar radiation rate through the season and the day; here dynamic shading devices are required to minimise the energy needs and the overheating risk.

2.1.3.4 Compatibility and Incompatibility with other Technologies

The design and operation of the shading devices should always be related to the characteristics of the installed glazing system, taking into account the solar protection requirements with daylight availability for the building occupants. The same consideration applies to the application of shading devices in ventilated façades and double skin envelopes.

Internal and external shading devices can negatively affect ventilative cooling if it is pursued by the simple window opening, as the shading devices represent an obstacle to natural air circulation.

The use of cool colours is a new trend in curtains, which is an evident synergy with the application of cool materials. No other relevant incompatibilities with other cooling technologies and strategies were identified.

2.1.3.5 Technology Maturity and Expected Developments

As inferred in the images below, solar protection devices are available worldwide in a wide range of cost and performance, with market segments ranging from international corporations to single artisans.

Figure 2: Individual low-cost external blinds in a social housing building in Rome, Italy (left) and the fully automated shading façade at a newspaper headquarter in Milan, Italy (right) [1].

Concerning the materials used for shading systems, developments focus on the robustness and expected lifetime, the integration of solar energy systems (e.g., PV integrated into lamellae and louvers) and special surface treatments to improve solar protection (use of cool coloured materials, retro-reflective films, selective coating, etc.). Also, innovative selective angle behaviour solutions are being explored to optimise the solar control and natural light requirement duality.

Strong interest is also in the control of dynamic shading systems, focusing on two aspects: i) implementation of control strategies and logics to optimise the energy performance of buildings in a holistic perspective, ii) the integration of automated devices in building energy management systems in order to operate the envelope components in synergy with the energy systems and the monitored indoor and outdoor conditions.

2.1.4 Further Reading

Further information can be found in the following publications:

- Section 2.1: Advanced window/glazing and shading technologies, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Section 4.1.1 Advanced Solar Shading/Advanced Glazing Technologies in: Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- Section 3.3 in STD Policy recommendation report
- Section 3.1 in Annex 80 STC case study report
- ES-SO European Solar Shading Organisation, https://es-so.com/

2.2 Glazing Technologies

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2.2.1 Description

Glazings are key building components that provide the vision of the outside while also managing the admission of light, heat, and air. Although glazings typically account for a minor portion of the overall building envelope, their influence on cooling energy consumption, peak cooling loads, and occupant comfort can be substantial. Advanced glazing technologies are designed to limit heat transmission into indoor spaces while optimizing natural daylight access by absorbing, transmitting, and reflecting solar radiation based on the materials used in the glass and glazing system.

These technologies are classified as **fixed** or **dynamic**. **Fixed glazing**, with its predetermined optical and thermal qualities, lacks the capacity to adapt to changing environmental conditions, whereas **dynamic glazing** technologies, like optically switchable (or smart) windows, can alter their properties. This alteration occurs in different modes, including being either environmentally activated or actively controlled [7]. A type of dynamic technology allows for independent adjustment of visible and near-infrared transmittance, resulting in improved performance in colder climates and minimizing solar heat gain while allowing daylight to enter warmer climates [8]. In addition, a developing technological glazing solution integrates photovoltaic layers into the window glass to control solar heat accumulation and produce electricity [9].

The utilization of advanced glazing technologies can play a crucial role in decreasing the building's cooling energy need and enhancing the comfort of its indoor environment. The extent of these contributions depends on the technology properties, outside climate, building type and orientation, shading control devices, and internal heat gains and occupant behaviour.

2.2.2 Key Technical Properties

Total solar energy transmittance (solar factor) [-]. The total transmitted fraction of the incident solar radiation consists of directly transmitted solar radiation and the part of the absorbed solar radiation transferred by convection and thermal radiation to the internal environment [10].

A low solar factor decreases the solar gains, thus decreasing the cooling load and overheating period. Solar control glazing has a g-value of less than 0.5 [11], but many products have values lower than 0.35.

Light transmittance [-]. The transmitted fraction of the incident solar radiation in the visible part of the solar spectrum [10].

High light transmittance increases daylight availability, thus decreasing the use of artificial lighting and related internal gains. The acceptable range of light transmittance is 0.35 to 0.65.

Thermal transmittance [$W \cdot m^{-2} \cdot K^{-1}$]. The steady-state density of heat transfer rate per temperature difference between the ambient temperatures on each side, which characterizes the heat transfer through the central part of the glazing, i.e., without edge effects [11].

Low thermal transmittance decreases the heat transfer through the glazing, thus decreasing energy needs for heating and cooling.

Internal System Design Indicators

Window-to-wall ratio (WWR) [-]. Ratio of the fenestration area to the gross exterior wall area [12].

Window-to-floor ratio (WFR) [-]. Ratio of the fenestration area to the net floor area.

Example: Analysing the future performance of Italian residential building stock, considering a significant range of shape factors and window-to-wall ratios, shows buildings with higher WWR are more sensitive to overheating risk due to external climate [12].

External System Design Indicators

Global solar irradiation on a horizontal plane [13] during the summer period.

2.2.3 Performance and Application

2.2.3.1 Advanced Glazing Technologies' Effect on the whole Building's Performance

Fixed and dynamic glazing technologies are viable options for reducing cooling loads, especially for uninsulated buildings. In this case, they decrease the vulnerability and increase the resistance of buildings to the long-term effects of climate change by reducing solar heat gain while allowing most daylight to enter.

Table 2: Key Performance Indicators (KPIs), based on [3], for replacing a single-pane window (with clear glass of 6mm) with a double-pane window for a naturally ventilated detached house in a hot and humid climate [4]:

KPI	Reduction
Daily heat stress[a] [°C·h]	21%
Annual HVAC energy need[b] [kWh/m^2]	10%
Annual HVAC carbon emission intensity[c] [kg CO_2/m^2]	8.5%

[a] Daily degree hours of exceedance against a standard effective temperature (SET) of 30 °C during a heatwave without AC during the most severe and longest heatwave (14 days) in the midterm future (2041-2060) with the grid power outage.

[b] Annual energy need normalized to conditioned floor area in the 2050s (2041-2060) in normal operation.

[c] Annual carbon emission normalized to conditioned floor area in the 2050s (2041-2060) in normal operation.

Furthermore, fixed glazing with low solar factor and dynamic advanced glazing technologies increases the buildings' robustness, especially during heat wave events. Smart glazing can be activated passively through temperature changes (thermochromic) or solar irradiation exposure (photochromic) or actively through the application of an electric voltage (electrochromic). These specialized glazing materials can achieve a dark state with a solar factor of 0.15 or lower, offering an attractive solution for managing overheating risk, especially during heatwave periods.

To increase the building's recoverability, advanced glazing technology should be combined with other technologies like ventilative cooling. In this case, the resilience of the building can be ensured, mainly due to ventilative cooling, because the building can return to the same behaviour it had before the heatwave sooner.

Regardless of the type of building, advanced glazing technologies can be applied. At the same time, their capacity to improve resilience against heat waves with or without power outages and against long-term climate change depends on outdoor climatic conditions, building orientation, window-to-wall ratio, and the heat capacity of the building.

2.2.3.2 Advanced Glazing Technologies Application in Different Climates

Low thermal transmittance is essential for reducing heat loss in cold climates. Moreover, a high solar factor facilitates more significant solar heat gain through the glazing. Conversely, a low solar factor is crucial in temperate and hot climates to minimize solar heat gain and prevent the risk of overheating.

Regardless of the climate, it is essential for glazing to have increased light transmittance in the visible spectrum while simultaneously reducing solar transmittance in the infrared region.

2.2.3.3 Advanced Glazing Technologies Application and Building Orientation

The solar irradiance profile during summer and winter differs according to the latitude and outdoor climate. For cold climates, glazings exposed to higher solar irradiance are recommended. In contrast, in temperate and hot climates, this exposure should be minimized either by a lower solar factor or the use of solar shadings.

2.2.3.4 Compatibility and Incompatibility with other Technologies

Investigating the combination of advanced glazing with different cooling systems is critical. Solar protection devices, especially if adjustable or controlled, can greatly minimize solar heat gain and reduce the glazing's dependence on orientation. Furthermore, the combination of cooling methods that can efficiently reduce excess heat, such as ventilative cooling or evaporative cooling, must be considered. For example, using thermochromic glazing together with indirect evaporative cooling can efficiently keep indoor temperatures up to 15 °C lower than the outside temperature [14].

2.2.3.5 Availability and Expected Developments

The availability of spectrally selective fixed glazing and highly insulating glazing are widespread. Their costs range from low to moderate. For active and passive smart glazing, the availability is limited to several companies globally, and the cost is higher. Three essential sectors are seeing significant breakthroughs in the present markets and R&D: the development of new materials and coatings that can be manufactured at a reduced cost, faster switching capabilities, and enhancements in the durability of products. Although passive smart (responsive) coatings are being refined, most ongoing research and development focuses on active glazing systems due to their perceived higher performance potential. Integrating active smart glass controls with building control systems is essential for promoting comfort and energy efficiency while fostering higher market adoption.

2.2.4 Further Reading

Further information can be found in the following publications:

- Chapter 4.1.1. Advanced solar shading/advanced glazing technologies, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Liu, X., Wu, Y., (2022) A review of advanced architectural glazing technologies for solar energy conversion and intelligent daylighting control, Architectural Intelligence 1,10, doi.org/10.1007/s44223-022-00009-6
- Favoino, F., Fiorito, F., Cannavale, A., Ranzi, G., Overend, M., (2016) Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates, Applied energy, Volume 178, Pages 943-961, doi.org/10.1016/j.apenergy.2016.06.107.
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- Kyrou, E., Goia, F., Reith, A., (2023) Current performance and future development paths of transparent PV glazing in a multi-domain perspective, Energy and Buildings, Volume 292, 113140, doi.org/10.1016/j.enbuild.2023.113140.

2.3 Ventilated Façades

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2.3.1 Description

Conventional façades contribute significantly to heat gain through the building envelope, particularly transparent façades.

The ventilated façade concept is defined by the AIVC [15] as "[…] a traditional single facade doubled inside or outside by a second, essentially glazed facade. Each of these two facades is commonly called a skin. A ventilated cavity - having a width which can range from several centimeters at the narrowest to several meters for the widest accessible cavities - is located between these two skins". In the following, we will refer to this technique as the "ventilated double-skin façade" (DSF), without discussing comparable or similar techniques like Trombe walls or parietodynamic windows.

Façade ventilation can prevent heat gain from opaque or transparent components, and act as a passive cooling solution. Ventilated double-skin façades are increasingly used in commercial and office buildings due to their thermal and architectural benefits. While DSF are often used for their acoustic benefits in fully glazed buildings, the potential for cooling through ventilation is limited without an integrated shading device.

Ventilated façades are a technique for mitigating external heat gains resulting mainly from convective heat transfer with outdoor air, longwave radiation between the envelope and the external environment (building, street, and sky), and solar heat gain during the day.

In summer, the convective airflow within the ventilated cavity of the DSF acts as a passive cooling system, mitigating solar gains and controlling the inner skin temperature. This reduces air conditioning energy requirements and maintains indoor thermal comfort in buildings without air-conditioning.

Ventilation of the DSF cavity cools both the internal and external walls, while convecting heat to the circulating air from the cavity to the outside. The two main driving forces for air movement within the cavity are wind (forced convection) and thermal buoyancy (natural convection).

Ventilated double-skin façades are adaptable throughout the seasons, e.g., by adjusting inlets and outlets that require manual or automated control. This enables the appropriate ventilation strategy to be selected for each season (wintertime strategies are note discussed here). These passive cooling strategies can be divided into two categories: the exhaust air façade and the outdoor air curtain façade.

The **exhaust air façade** is coupled to the indoor air ventilation system. The ventilation pattern in the DSF cavity is designed to circulate air from the inside wall of the building to the outside, in a bottom-up direction. The DSF heat gains amplify this bottom-up airflow, thanks to the natural stack effect caused by the increased temperature difference between the heated air within the cavity and the outdoor air.

The **outdoor air curtain façade** is connected to the outdoor air only. The DSF cavity is naturally ventilated through an inlet located at the bottom of the outer skin, and an outlet at the top of the outer skin. The stack effect amplifies the ventilation rate and cooling potential, while this natural ventilation effect is further increased by the height of the cavity.

Similarly, **perforated double-skin façades** are ventilated through a perforated outer skin.

In addition to ventilation mechanisms, transparent DSF sometimes incorporate shading - e.g., Venetian blinds - in their cavity to reduce the solar radiation transmitted to the adjacent room. Another cooling enhancement of DSF can be achieved through additional components and latent heat transfer, which delays overheating by absorbing sensible heat during phase changes, similar to the cooling effect of water spray. Vegetation, water misting, or phase-change materials, are typical additional components used in some DSF cavities, which can offset heat peaks under summer conditions.

2.3.2 Key Technical Properties

The benefit of ventilated surfaces for cooling is mainly driven by the air flow rate within the double-skin cavity. Outdoor air is the main heat sink. The cooling potential and limitations are linked to the ventilation rate and temperature difference between indoor and outdoor air. Then, this cooling effect works best for reducing over-heating within DSF caused by radiative gains (applicable to opaque DSF, or integrated venetian blinds), when outdoor air temperatures are moderate. For opaque DSF with thermal inertia, nocturnal ventilation within the cavity can remove the heat absorbed by the walls, and mitigate the daytime temperature peaks of the inner opaque wall.

The **ventilation rate** of the double-skin air gap depends on geometric parameters that can affect the airflow (turbulence, stack effect, …) such as the size and shape of the air inlet, the height of the cavity, and the width of the air layer.

Increasing the **air cavity height** (from inlet to outlet) improves the thermal performance of ventilated façades by boosting the stack effect, which increases both airflow and convective heat transfer between the air within the cavity and the walls.

Wind exposure - the ventilation rate is higher with winds blowing perpendicular to the building (upwind or downwind façades) than with parallel winds.

The **perforation rate** is an important parameter for perforated DSFs. For example, a study in Japan showed that 50% perforation is optimal for natural ventilation of the double-skin façade [16].

Natural ventilation is sometimes replaced by a **mechanical ventilation system**, which increases the cooling potential but increases the electrical consumption. This is then a low-energy active cooling technique. However, this is not necessarily an additional electrical consumption when coupled with the building ventilation system, as in the case of the "exhaust air façade" typology.

Other properties:

Transparent double-skin façades with **Venetian blinds** are designed with specific slat angles, air cavity thicknesses, and façade heights. The slat tilt angle must be optimized for maximum shading during summertime, with consideration for its impact on ventilation rate due to aeraulic resistance.

The **thermophysical properties of DSF materials** are also decisive design parameters (e.g., thermal mass, insulation layers, albedo, and thermal emittance). Ventilated façades with a reflective outer cladding can strongly reduce solar gain.

2.3.3 Performance and Application

2.3.3.1 Building Performance

Ventilated double-skin façades can act as a thermal buffer in all seasons, while adjusting the ventilation strategy and the DSF configuration, to either minimize or maximize heat loss. During winter, the ventilation strategy has to be modified to boost the buildings or DSF's solar gains, while preventing heat losses with convective heat exchange. Similar to summertime ventilation patterns (described in. section 2.3.1 Description), there are various options for winter with opaque or transparent walls (e.g., Trombe walls). See 2.3.4 Further Reading for more information about wintertime operation of DFSs.

Additionally, ventilated double-skin façades reduce noise transmission across the building envelope, thanks to the additional outer skin, which blocks sound transmission, and the airspace in the DSF cavity, which acts as an acoustic buffer that can absorb outdoor noises.

2.3.3.2 Resilience

During a heatwave, ventilated façades with natural ventilation and stack effects will continue to operate even if there is a grid power failure. In contrast, DSF ventilated by mechanical ventilation, such as some “exhaust air façades” coupled to building ventilation systems, will not be able to maintain the necessary ventilation of the cavity, which might cause overheating issues.

2.3.3.3 Limitations

The limitation of the ventilated double-skin façade system is the additional structural weight on the existing façade when adding a double-skin façade to the building envelope, which is mainly an issue for thicker cladding materials. Therefore, in building renovation, it is necessary to check that the existing facades can withstand the DSF, or to hang the DSF from supplementary external structures.

2.3.3.4 Application and Climate Conditions

In recent years, ventilated facade systems have gained popularity in various climates thanks to their energy performance, the variety of design and their architectural interest, their ability to provide natural light while reducing solar gains (for glazed buildings, the glazed outer skin reduces solar radiation transmission, and the DSF allows the integration of protected shading devices), their good noise attenuation.

For cold climates, ventilated double-skin façades have been widely developed, especially for commercial buildings. Since the 1980s, this technique has been improved for both summer and winter performances, and has widely adopted in Europe, North America, and Japan. In the northern hemisphere, Barbosa and Ip [17] recommend a southern orientation for naturally ventilated DSF.

In hot climates with high solar heat gain, the ventilated double-skin façade is an efficient passive cooling design for large glazed-façades.

Opaque DSFs are more commonly used for single-family homes, and there are some regional standards that help in spreading the technique, together with evaluation procedures for assessing thermal performance.

2.3.3.5 Availability

While ventilated double-skin facades have been well-developed for several decades, but new variations continue to emerge. Although there are some commercial offers for these techniques, emerging techniques include DSFs with controlled Venetian blinds, perforated cladding for DSF, and new experiments with integrated phase change materials or evaporative techniques.

2.3.4 Further Reading

Further information can be found in the following publications:

- EBC Annex 80 Resilient Cooling of Buildings: State of the Art Review - Chapter 5.4, Ventilated Envelope Surfaces
- Agathokleous, R. A., & Kalogirou, S. A. (2016). Double skin facades (DSF) and building integrated photovoltaics (BIPV): A review of configurations and heat transfer characteristics. *Renewable Energy*, *89*, 743–756. https://doi.org/10.1016/j.renene.2015.12.043
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- Liu, L., Yu, Z., & Zhang, H. (2017). Simulation study of an innovative ventilated facade utilizing indoor exhaust air. *Energy Procedia*, *121*, 126–133. https://doi.org/10.1016/j.egypro.2017.08.009
- Srisamranrungruang, T., & Hiyama, K. (2020). Balancing of natural ventilation, daylight, thermal effect for a building with double-skin perforated facade (DSPF). *Energy and Buildings*, *210*, 109765. https://doi.org/10.1016/j.enbuild.2020.109765
- Zhou, J., & Chen, Y. (2010). A review on applying ventilated double-skin facade to buildings in hot-summer and cold-winter zone in China. *Renewable and Sustainable Energy Reviews*, *14*(4), 1321–1328. https://doi.org/10.1016/j.rser.2009.11.017

2.4 Cool Envelope Materials

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2.4.1 Description

A cool envelope material (CEM) is a roof or exterior wall product whose elevated solar reflectance and high thermal emittance keep it cooler in the sun than a conventional roof or wall.[1] Common examples include white roofing membranes, "cool-colored" roofing tiles, and light or cool-colored exterior wall paints, but cool options are available for virtually all types of roof and exterior wall materials.

Cool roofs and walls reduce radiative heat gain at the building's opaque envelope to decrease heat flow into the conditioned space, saving energy in an air-conditioned space or lowering the temperature inside a free-running building. (They can also increase the need for heating energy in cold weather, but in hot-summer climates the annual cooling energy savings typically exceed the annual heating energy penalty.) Annual heating, ventilation, and air conditioning (HVAC) energy savings are greatest for older buildings in climates with hot summers and mild-to-warm winters. As a passive cooling strategy, cool envelope materials boost resilience to extreme heat events in all climates, especially when heat waves coincide with power outages.

Cool roofs and walls also mitigate the urban heat island effect, slow the temperature-dependent formation of smog, and provide global cooling ("negative radiative forcing") by reflecting sunlight out of the Earth system.

2.4.2 Key Technical Properties

Key technical properties of a CEM are its initial and aged values of solar reflectance, thermal emittance, and - for roofs - solar reflectance index, as well as color. Other technical properties relevant to specialized CEMs with limited commercial availability include fluorescent benefit, directional solar reflectance, and selective thermal emittance; these will not be discussed here but are detailed in Section 2.2 of the Annex's State of the Art Report [18].

Solar reflectance [- or %] (SR), also known as "solar reflectivity" or "albedo". It is the fraction of incident sunlight (solar radiation) that is reflected. Increasing solar reflectance reduces solar heat gain (heating induced by absorption of sunlight), helping the surface to stay cool in the sun. Most conventional dark surfaces have a low solar reflectance (about 0.05 – 0.30), and most light-colored surfaces have a high solar reflectance (about 0.60 – 0.95). *Elevated solar reflectance is the defining characteristic of a cool envelope material.*

Thermal emittance [- or %] (TE), also known as "thermal emissivity" is the ratio of the thermal infrared radiative flux emitted by the surface at a temperature near 300 Kelvin (27 °C or 80 °F) to that emitted by a black body (perfect absorber and emitter of radiation) at the same temperature. High thermal emittance helps the surface cool itself by emitting radiation to a cooler environment such as the sky. Roof or wall products with bare shiny metal surfaces have low thermal emittance (about 0.05 – 0.10), while virtually all others[2] have high thermal emittance (about 0.80 – 0.95).

The surface temperature of a cool envelope material depends more on its solar reflectance than on its thermal emittance. For example, on a sunny summer afternoon, the temperature of a well-insulated horizontal roof surfaced with non-metallic, light-colored material (solar reflectance 0.60, thermal emittance 0.90) is about five times more sensitive to a small change in solar reflectance than to the same change in thermal emittance.

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[1] Technically, a cool envelope material is a solar-opaque surface whose net radiative heat gain, equal to [absorbed solar radiation minus emitted shortwave radiation (fluorescence)] plus [absorbed TIR radiation minus emitted TIR radiation], is lower than that of a traditional envelope material. Other strategies for reducing heat gain at or through the building envelope, such as solar-control glazing, evaporative cooling, ventilation, or insulation, lie outside the scope of cool envelope materials.

[2] A polymeric or asphaltic coating exposing shiny metal flakes may have an intermediate thermal emittance of about 0.50.

Solar reflectance and thermal emittance are independent properties[3] that can be combined to compute the **solar reflectance index (SRI)**. SRI gauges "coolness" by comparing the temperature of a horizontal, adiabatic (perfectly insulated) test surface on a reference sunny summer afternoon to that of a reference black surface (SRI 0) and to that of a reference white surface (SRI 100). The SRI can be lower than 0 if the surface is exceptionally hot or exceed 100 if the surface is exceptionally cool. The SRI is calculated rather than measured and characterizes only well-insulated near-horizontal surfaces, such as roofs. It does not apply to walls.

Natural soiling and weathering processes, such as the deposition of soot, microbiological growth, and rainfall, can alter solar reflectance and thermal emittance over time. Eventually, an equilibrium is reached between processes that soil the surface, such as deposition, and those that clean the surface, such as rain. Since the solar reflectance and thermal emittance of an outdoor surface typically attain steady values within one to three years, the solar reflectance and thermal emittance of roofing and wall products are measured before and after three years of natural exposure. For example, an initially bright white roof that reflects 80% of sunlight when clean might reflect only 60% of sunlight after several years of outdoor soiling and weathering. Roof and wall product ratings available from the Cool Roof Rating Council (CRRC) [19] report both initial (unexposed) and 3-year-aged values of solar reflectance and thermal emittance.[4] The benefits of cool roofs and walls are evaluated from aged values of solar reflectance and thermal emittance.

Reflection of visible light governs color. Color alone is not used to predict the performance of a cool envelope material, but it is a key consideration for consumers and thus for manufacturers. Slightly less than half of sunlight is visible to the human eye. Most light-colored materials strongly reflect both visible light (spectrum 0.4 – 0.7 µm, about 45% of the incident solar energy) and near-infrared light (spectrum 0.7 – 2.5 µm, about 50% of incident solar energy); few surfaces other than bare shiny metals and uncommon "ultra-white" materials reflect the ultraviolet component of sunlight (spectrum 0.3 – 0.4 µm, about 5% of incident solar energy). However, darker "cool-colored" surfaces available in any color can provide intermediate solar reflectance (about 0.30 – 0.60) by selectively reflecting near-infrared light. For example, cool-colored natural red clay "terracotta" roofing tiles reflect about 20% of visible sunlight and 60% of near-infrared sunlight, yielding a solar reflectance of about 0.40.

2.4.3 Performance and Application

2.4.3.1 Performance

Cool roofs and walls reduce radiative heat gain at the building's opaque envelope to decrease heat flow into the conditioned space, saving energy in an air-conditioned space or lowering the temperature inside a free-running building. They also mitigate the urban heat island effect, slow the temperature-dependent formation of smog, and provide global cooling ("negative radiative forcing") by reflecting sunlight out of the Earth system.

The resilient cooling benefit of a cool roof or wall depends mostly on its ability to deliver reliable passive cooling on a hot day; small annual HVAC energy savings or even a modest annual HVAC energy penalty might be acceptable. As a passive cooling strategy, cool envelope materials boost resilience to extreme heat events in all climates, especially when heat waves coincide with power outages. Energy-saving or indoor-cooling benefits are greatest on sunny days because cool roofs and walls are primarily solar-control strategies.

Cooling energy savings and heating energy penalties in a conditioned building and thermal comfort or safety improvement in a free-running building are proportional to (a) the increase in aged solar reflectance attained by selecting a cool material instead of a less-reflective conventional material, and (b) the solar energy incident on the building envelope during hours of the year in which cooling or heating is required. Benefits scale

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[3] The solar spectrum (0.3 – 2.5 µm) does not overlap the thermal infrared spectrum (4 – 80 µm). Note that one micrometer (µm) is a millionth of a meter.

[4] All 3-year-aged values in the CRRC's wall product directory are pending in 2023 because less than 3 years has elapsed since the start of the CRRC's wall rating program.

inversely with both the thermal resistance of the roof or wall assembly and the efficiency of the air conditioner (if the space is mechanically cooled).

High thermal capacity ("thermal mass") in a heavy roof material (e.g., clay or concrete tile) can delay heat transfer between the roof and the interior of the building. This lag can help to increase the cooling benefit of a reflective roof by reducing the space-cooling load when electric power demand peaks in the late afternoon on a summer day. It can also diminish the penalty of a reflective roof by keeping the roof and attic warmer over-night, decreasing the space-heating load on a winter morning [20].

Table 3 reports the reductions in daily thermal stress during a heat wave without air conditioning (AC), annual HVAC energy use, and annual HVAC carbon emission after the application of cool envelope materials to a single-family home in Los Angeles, California circa 2050. This pre-1980 two-story prototype house has gas furnace heating and direct-expansion space cooling with efficiencies that meet California's 2019 building energy standards [21].

Table 3: Reductions in daily thermal stress in a heat wave without air conditioning, annual HVAC energy use, and annual HVAC carbon emission after application of cool envelope materials to a single-family home in Los Angeles, California circa 2050 [21]:

KPI	Baseline	Reduction from cool roof[f]	Reduction from cool wall[g]	Reduction from cool roof + cool wall[f,g]
Daily heat stress[a] [°C·h]	101	6%	13%	19%
Annual HVAC electricity need intensity[b] [kWh/m²]	33	6%	14%	20%
Annual HVAC heating need intensity[c] [kWh/m²]	27	-1%	-4%	-6%
Annual HVAC primary energy intensity[d] [kWh/m²]	98	4%	8%	12%
Annual HVAC carbon emissionintensi-ty[e] [kg CO_2e/m²]	15.1	3%	6%	9%

[a] Daily degree hours of exceedance against a standard effective temperature (SET) of 30 °C during a heatwave without AC.

[b] Annual HVAC electricity need per unit conditioned floor area.

[c] Annual HVAC heating need per unit conditioned floor area.

[d] Annual HVAC primary energy usage per unit conditioned floor area based on 2021 eGRID database for California-average primary energy factors of 2.05 for electricity and 1.09 for gas [22].

[e] Annual HVAC carbon emission per unit conditioned floor area based on 2021 eGRID database for California-average CO_2 emission factors of 272 g/kWh electricity and 225 g/kWh [22].

[f] Roof solar reflectance raised to 0.60 (bright-white asphalt shingle) from 0.10 (conventional asphalt shingle).

[g] Wall solar reflectance raised to 0.60 (white paint) from 0.25 (conventional medium-lightness color paint).

2.4.3.2 Application

Cool versions are commercially available for virtually all widely used types of roof and wall products, including but not limited to fiberglass asphalt roofing shingles, clay and concrete roofing tiles, slate roof tiles, metal roofing, elastomeric roofing coatings, wood roofing shakes, and single-ply roofing membranes (Figure 3), as well as painted walls, stucco walls, vinyl siding, and metal cladding (Figure 4).

Figure 3: Examples of common roofing products (top row, left to right: fiberglass asphalt shingle [23], clay tile [24], slate[25], standing-seam metal bottom row, left to right: field-applied coating [26], wood shake, single-ply membrane [27], asphaltic membrane [28]).

Figure 4: Examples of common exterior wall products (left to right: painted wall [29]; stucco wall [30], vinyl siding [31], metal cladding).

Cool roofs and walls are most helpful when applied to buildings with poorly insulated envelopes. These are typically older buildings and are often (though not exclusively) found in low-to-moderate-income (LMI) communities.

Annual HVAC energy savings are greatest for older buildings in climates with sunny hot summers and cloudy warm/mild winters (e.g., ASHRAE zones 0 – 3 [32]). In hot-summer climates, the energy-cost or source-energy annual cooling savings provided by a cool roof typically exceeds the corresponding heating penalty, even when winters are cold—because roofs far from the equator receive much less sunlight in winter than in summer. Analyses that do not account for snow in winter may substantially overestimate cool-roof winter heating penalties because both conventional roofs and cool roofs are white when covered with snow.

Even without the snow effect, cool roofs yield positive annual HVAC energy savings in office and retail buildings across nearly the entire United States (ASHRAE climate zones 1 – 6 [32]), while cool walls do so over the southern half of the United States (ASHRAE climate zones 1 - 4 [32]) and across California. Cool walls receive about half as much sunlight per unit area as cool roofs, but cool-wall benefits are comparable to cool-roof benefits because walls typically have only about half as much insulation as roofs.

Roofs are typically re-covered after about 20 years and exterior walls are typically repainted after about 10 years. Since enhanced solar reflectance does not increase the price of most roof or wall materials, the most economical time to install a cool roof or wall is during the building's initial construction or when replacing an existing roof or wall at the end of its service life.

2.4.4 Further Reading

Further information can be found in the following publications:

- Section 2.2 Cool Envelope Materials, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Section 4.1.2: Cool Envelope Materials in: Advanced Solar Shading/Advanced Glazing Technologies in: Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- *A Practical Guide to Cool Roofs and Cool Pavements* published by the Global Cool Cities Alliance [33]
- Educational materials and product ratings published by the Cool Roof Rating Council [19]

2.5 Green Roofs and Green Façades

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2.5.1 Description

Green roofs and green façades are passive cooling solutions mainly based on evapotranspiration from plants and substrate. Then, this cooling potential depends on water retention capacity, water supply, plant species, and vegetated envelope typologies. In addition, the plants provide solar shading, while the substrate adds additional thermal insulation and thermal mass to the building envelope. Green roofs, or green façades with a vertical substrate layer, typically need an air layer, between the substrate and the building envelope, which acts as an additional thermal barrier.

The evaporative cooling effect on the external side of the building prevents heat gains through the building envelope. The evaporative process absorbs the sensible heat fluxes that are derived from solar irradiance, conducted heat flux, and convective heat flux with outdoor air. Thus, the cooling effect on the outside is due to the latent heat flux resulting from the growing medium and foliage evapotranspiration, and to a lesser extent in longwave radiation to the sky. The evaporative process is strongly amplified by direct solar gains. This cooling effect has a direct impact on reducing interior surface temperature.

In terms of typologies, there is a wide range of techniques and subcategories for both roofs and façades. Regarding the cooling potentials, these can be summarized into the four following categories: **extensive** or **intensive green roofs**, and **living walls** or **green façades providing shading** only for the variety of vertical greening systems (VGS) [34].

Extensive green roofs have a growing medium thickness of less than 10 - 15 cm, a low water retention capacity, short vegetation like herbs or succulents and robust plants like those of the sedum genus (whose roots are not well developed), and low evapotranspiration rates.

Intensive green roofs have a growing medium thickness of more than 15 - 20 cm, a better water retention capacity, taller vegetation such as shrubs and even trees, and higher evapotranspiration rates.

Living walls are green façades with substrates, which behave similarly to green roofs, but they require regular watering and fertilizer to counteract the drainage effect.

Green façades for shade are designed with climbing plants, which have a low evaporative potential but have the advantage of providing shade, while transmitting natural light.

The cooling effect of vegetated envelopes depends on **water supply and rainfall water retention.** The primary difference between green façades and green roofs is linked to the vertical water runoff, which amplifies the water effect in the thermal balance of green façades. Green roofs are robust in drought events, while they can regulate storm water events with heavy rainfall.

2.5.2 Key Technical Properties

For evaporative envelopes with water retention, the cooling performance mainly depends on the thermal properties of the wall or roof (e.g., capacity, resistance, and surface albedo) and the quantity of water stored, which in turn depends on pond level and the porosity and moisture content of the external materials.

There are many variations among the typologies of green roofs and green façades, which cannot be fully characterized here. However, all these variations have plants and substrate - the growing medium for the plants - with specific technical properties listed hereafter (some of which are specific to certain categories).

Key technical properties which are important for green roofs and green façades cooling potential are:

The **thermal mass capacity [J/K]** added to the building envelope by the green roof or green façade substrate. Compared to a bare roof, a green roof, even with dry growing medium, will mitigate the cooling peak demand of buildings, and can reduce the annual cooling energy use. This thermal mass capacity depends mainly on the substrate thickness, its dry thermal capacity, density, and water content, which varies over time.

The **thermal conductance [W/(m·K)],** mainly in the substrate, which highly depends on water content. Water content may vary strongly over time for vegetated envelopes, and so do thermal conductance and most other key technical properties.

The **water retention capacity [%]** (typical values from 35% to 65% [35] for green roof substrates), and therefore the evaporative cooling effect. For green roofs, this water capacity is mainly determined by the **soil thickness [m].**

The **drainage and rainfall management capacity**, which can be quantified by the runoff coefficient **[0 - 100%]**. This metric represents the ratio of drainage water to the water supply or rainfall amount. So, the vegetated envelopes with higher water retention capacity (generally from the substrate) have lower runoff coefficients. Green roofs reduce the risk of water flooding and are used in order to prepare for the potential impacts of changing rainfall patterns that could overwhelm the capacity of existing drainage systems. Intensive green roofs are advantageous because of their increased rainwater retention capacity.

The plant characteristics which affect their thermal effects, such as **plant physiology, type, and morphology**. Indeed, a comparison with herbaceous plants showed that the lowest rooftop temperatures were obtained with the tallest plants. These complex combinations of plants' characteristics are simplified in thermal models with the determination of aggregated defined hereafter: the leaf area index and the stomatal resistance.

The **leaf area index (LAI) [0-1]** depends on the plant canopy distribution and covering effect on the substrate. This is a key property for the shade effect, but more generally for the overall longwave and shortwave radiation balance, as well as the convective heat transfer.

The **stomatal resistance** of plants **[s/m].** This value characterizes the capability of plants to limit evapotranspiration, and some plants with low stomatal resistances can be selected for high cooling potential.

The substrate and plants **albedo [0-1]** and **thermal emittance [0-1]** impact shortwave and longwave radiative balances.

2.5.3 Performance and Application

2.5.3.1 Building Performance

These evaporative surfaces are of direct benefit in terms of air-conditioning energy consumption or the passive cooling of a non-cooled building, together with the related reduction in greenhouse gas emission.

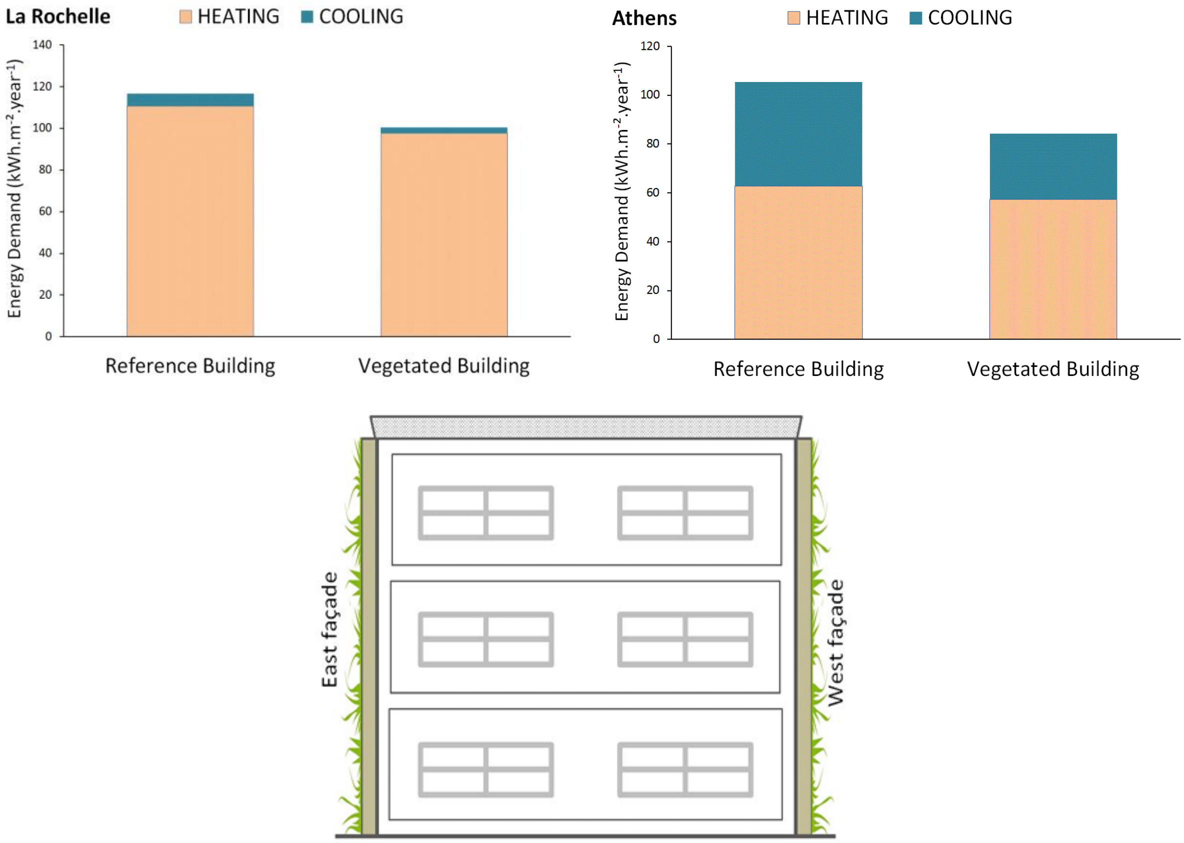

Figure 5: Impact of living walls on heating and cooling energy need for green for a three-story building [36].

The direct effect of heat gain reduction mitigates the roof surface temperature peaks during hot days, which has a direct impact on thermal loads and on the durability of roofing membranes.

The cooling benefit of green roofs depends on the level of insulation of the building. Large roofs of commercial buildings with poor insulation experience a more substantial cooling effect from green roofs.

However, green roofs and green façades help to mitigate the urban heat island effect and may eventually create local cool islands, which have an indirect cooling effect on buildings in dense urban areas. Figure 5 shows that the use of green infrastructure increases final energy savings. For instance, [36] demonstrated that cooling energy savings of up to 50% are feasible in Athens (ASHRAE Climate Zone 3A [32]).

2.5.3.2 Resilience

In the event of heatwaves, even with parallel power outage, green roofs, and green façades offers a good cooling potential for both mechanically cooled buildings and buildings in free-floating conditions. As long as the potential for evaporative cooling is provided by the well-watered vegetated envelope, this technique can effectively mitigate heat gains.

Whereas green roofs are usually designed with selected plant species adapted to local climate characteristics and ecosystems, the main resilience issues are linked to the water availability during heatwaves combined with water restrictions. Plant survivability during extreme events depends on the species and the water-retention capacity of the substrate.

2.5.3.3 Limitations

These techniques consume water, which can be affected by limited water resources during hot seasons in dry climates. Wastewater can be used and is an interesting alternative that requires selected plants and specific consideration of health risks and could affect the soil properties. This could also be a solution for greywater treatment by drainage or infiltration through living wall and green roof systems.

In terms of typologies, there are numerous ways to enhance cooling potential while also reducing water consumption. Moreover, water consumption limitations vary between tropical or an arid climate. Plants, and green roof or green façade typologies, have to be selected regarding these limitations.

The added weight of intensive green roofs, which may exceed 180 - 500 kg/m², may require additional structural reinforcement**.**

2.5.3.4 Application and Climate Conditions

Green roofs and green façades apply in all climates, from temperate climates to hot and dry climates. The roof surface may decrease from 60 to 30 °C during the daytime for a temperate climate.

For hot and arid climates, the evapotranspiration effect is more effective, contributing to increase the cooling effect of vegetated envelopes for both indoor and outdoor environment. However, while this passive cooling technique decreases the cooling energy need for buildings, water availability in hot and dry seasons can be a limitation for the application and the performance of this technique, which depends on numerous externalities linked to water use, regional customs, and not only related to the climate zone.

For hot and humid climates, the cooling mechanism provided by evapotranspiration from the green roof or green façade remains effective, especially in direct sunlight.

For green façades, in the urban context, the interactions are more complex. In summer conditions, green façades are less directly exposed to solar radiation. The cooling effect due to green walls and urban canyon orientation is more significant for hot and dry climates.

2.5.3.5 Availability

Green roofs and green façades have been commercialized and are widely available; options include intensive or extensive green roofs and green walls (climbers or with a vertical substrate). These solutions can also have social benefits such as urban food production, social networking, and access to nature in the workplace. However, these solutions are still expensive and require maintenance and fertilizers. Experimental testing and the development of models of green envelopes is still an ongoing research topic, although their thermal performance has already been incorporated into most construction standards.

2.5.4 Further Reading

Further information can be found in the following publications:

- EBC Annex 80 Resilient Cooling of Buildings: State of the Art Review - Chapter 5-3 Evaporative Envelope Surfaces
- Alexandri, E., & Jones, P. (2008b). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment, 43(4), 480–493. https://doi.org/10.1016/j.buildenv.2006.10.055
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3. Removing Sensible Heat from the Indoor Environment

This chapter presents resilient cooling technologies which remove sensible heat from the indoor environment. It addresses:

- Ventilative Cooling
- Thermal Mass Utilization
- Evaporative Cooling
- Sky Radiative Cooling
- Compression Refrigeration
- Adsorption Chiller
- Natural Heat Sinks
- Radiant Cooling

3.1 Ventilative Cooling

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3.1.1 Description

Ventilative Cooling (VC) is defined as the use of the cooling capacity of the outdoor air flow through ventilation to reduce or even eliminate the cooling loads and/or the energy consumption by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment. It is important to distinguish between ventilative cooling and comfort ventilation. In contrast to personal comfort systems (PCS), which include comfort ventilation and are described in more detail in chapter 4.1 Comfort Ventilation and Elevated Air Movement, ventilative cooling refers to total volume systems which condition entire indoor spaces. Personal comfort systems (PCS) however condition the immediate surroundings of the occupants.

Ventilative Cooling utilizes the cooling and thermal perception potential of cool outdoor air, and driving force of the airflow can be either natural, mechanical or a combination of the two. The most common technique is the use of increased daytime ventilation airflow rates and/or nighttime ventilation.

Daytime ventilation, often referred to as daytime comfort ventilation, introduces outdoor airflow through the building during the day. It aims to improve the occupant's thermal comfort via convective and evaporative heat transfer. Only at moderate outdoor temperatures can daytime ventilation also remove heat from the interior.

Nighttime ventilation, also known as night flush ventilation, discharges the building's thermal mass during the night, while the thermal mass acts as a heat sink during the day.

Natural ventilation occurs when natural forces, such as wind and buoyancy drive cool outdoor air through a building. In naturally driven systems there is no energy use. The control requirements for the air flow rate are not very strict and the systems are technically relatively simple (such as manual or automatic window opening in the façade).

Mechanical ventilation or cooling strategies use some form of energy to drive outdoor air through a building. Mechanical ventilation has higher requirements for control units and therefore needs accurate designing.

Hybrid systems combine natural and mechanical ventilation.

Different systems can also be used at different times of the day. For example, in office buildings during daytime occupancy, mechanical ventilation maintains indoor air quality and can be used to reduce cooling loads. During unoccupied hours at night, natural ventilation can increase the building's cooling capacity without consuming energy. However, the use of different ventilative cooling systems is not only limited to office buildings.

3.1.2 Key Technical Properties

The type of ventilation system installed and the ventilation control strategy depends mainly on regulation requirements, climatic conditions, installation, and operating cost, building and site characteristics, thermal loads, and design preferences. The effectiveness of ventilative cooling strategies mainly depends on the available heat sinks (external air temperature) with pronounced temperature gradients between the indoor and outdoor and coupling between the thermal mass and sink.

Hybrid systems are the most common type of system for ventilative cooling and the use of mechanical fans to complement a passive system should be strongly considered where possible. A combination of automated and manual control seemed to be the most adaptable and reliable solution to providing a system that worked well, with its users satisfied with its operation.

The most important Key Technical Properties are:

Thermal mass capacity of the building [J/K], which is the ability of the building to absorb, store and release heat. It is calculated by summing the heat capacities of all (internal and external) building elements in direct thermal contact with the internal air of the area under consideration [37]. Thermal mass influences the usability of ventilative cooling by influencing the time the maximum temperatures in buildings are reached. It is heated up or cooled down only by indoor temperature fluctuations and does not rely on any mechanical facility or additional energy.

Coefficient of Performance (COP) [-]. The COP is the ratio of the net cooling capacity to the effective power input [38].

The Seasonal Energy Efficiency Ratio (SEER) [-] of the ventilative cooling system expresses the energy efficiency of the whole system. The SEER rating of a system is the reduction in cooling demand during a typical cooling season divided by the electrical consumption of the ventilative cooling system, in case ventilation rates are provided mechanically.

Cooling Requirements Reduction (CRR) [-1 - +1] expresses the percentage of reduction of the cooling demand of a scenario in respect to the cooling demand of the reference scenario.

(Maximum) ventilation rate. The ventilation rate is the minimum outdoor airflow rate which is required to maintain minimum air quality levels in the building. The ventilation rate impacts the fan power design. The higher the ventilation rate, the higher the energy consumption of the fan. The maximum ventilation rate defines **specific fan power (SFP).**

3.1.3 Performance and Application

3.1.3.1 Building Performance

Ventilative cooling can make a significant contribution to reducing the cooling energy demand of a building and improving indoor thermal comfort. The extent of these contributions depend on outside climate, building properties, internal heat gains and, finally, the achievable airflow rates and user behaviour. Occupants' behaviour is identified as a major factor influencing the performance of ventilative cooling. The impact becomes more critical in passive low energy buildings. Table 4 shows performance data for this technology.

Table 4: Key Performance Indicators (KPIs), based on [3], of HVAC-related energy usage and heat stress for a single-family home in Los Angeles, California, U.S. for CORDEX 2050 weather conditions and changes in KPIs from the application of natural ventilation [39]:

KPI	Baseline	Reduction from window opening 5%[f]	Reduction from window opening 10%[f]	Reduction from window opening 25%[f]	Reduction from window opening 50%[f]
Daily heat stress[a] [°C·h]	101	23%	27%	30%	31%
Annual HVAC electricity need intensity[b] [kWh/m²]	40	18%	27%	34%	37%
Annual HVAC heating need intensity[c] [kWh/m²]	27	0%	0%	0%	-1%
Annual HVAC primary energy intensity[d] [kWh/m²]	113	13%	20%	25%	27%
Annual HVAC carbon emission intensity[e] [kgCO_2e/m²]	17,1	12%	17%	22%	24%

[a] Daily degree hours of exceedance against a standard effective temperature (SET) of 30 °C during a heatwave without AC.

[b] Annual electricity need per conditioned floor area related to HVAC usage.

[c] Annual gas need per conditioned floor area related to HVAC usage.

[d] Annual primary energy usage per conditioned floor area related to HVAC energy need with primary energy factor for electricity: 2.05 and gas: 1.09 based on 2021 eGRID California State average [22].

[e] Annual carbon emission per conditioned floor area related to HVAC energy need with CO_2 emission factor for electricity: 272 g/kWh and gas: 225 g/kWh based on 2021 eGRID California State average [22].

[f] Windows are open only when the outside air temperature is above the heating setpoint and below the cooling setpoint.

3.1.3.2 Resilience

In the event of heat waves, even with parallel power outage, ventilative cooling offers good possibilities for manually controlled emergency operation of buildings. A distinction must be made between the different ventilative cooling techniques. Natural nighttime ventilation requires no energy input and can therefore be described as a resilient cooling strategy.

Active ventilative cooling requires energy input. This poses no concern during heat waves, but it does so in the event of a power outage or a combination of both. To increase resilience to power outages, the combination with local power generation from a PV system would be useful. Combinations with passive cooling technologies are recommended in any case.

3.1.3.3 Limitations

The implementation of natural ventilation is challenging due to the lack of precise information in predicting the cooling load needed, the integration of ventilative cooling in energy performance calculations, indicators, and control strategies. In addition, the operation of windows to provide natural ventilation depends on the occupant's behaviour, which is related to lifestyle, psychological and physiological factors, and ease of access to openings, making it difficult to predict how well it can be managed in practice.

Outdoor noise levels in the urban environment can be a major barrier to the application of ventilative cooling by natural driving forces and methods for estimating noise levels in urban canyons are needed to assess the potential as well as to assess the risk that occupants will close windows to keep out noise but also compromise the ventilative cooling strategy.

Key outdoor pollutants like NO_2, SO_2, CO_2, O_3 and suspended particulate matter (PM) are usually measured continuously in larger urban environments and are often considered as a major barrier to the application of natural ventilative cooling. Estimating the indoor/outdoor pollution ratio is the key to assessing the potential use of natural ventilation cooling in an urban environment.

Manual and/or automated window opening in ground floor apartments is partly undesirable for safety reasons. The issues of burglary, weather and injury protection need to be assessed on a case-to-case basis.

3.1.3.4 Application and Climate Conditions

Passive Ventilative Cooling, especially with openable architectural apertures as ventilation components, is a very robust and reliable technology. Ventilative Cooling is applicable to all types and sizes of buildings.

The ventilative cooling process is highly dependent on the outdoor climate, the microclimate around the building as well as the thermal behaviour of the building.

Ventilative Cooling is a widely used and effective solution in moderate climates, as well as in hot and dry climates with significant temperature fluctuations between day and night. Ventilative cooling is applied to all types and sizes of buildings.

In hot climates, namely in hot and humid climates, daytime comfort ventilation can still have a valuable effect on the perceived temperature, whereas nighttime flush ventilation does not work in areas and seasons with warm nights.

The appropriate ventilative cooling principles depend on the outdoor climatic conditions and the available building ventilation systems.

Ventilative Cooling during cold outdoor conditions: For buildings with high internal gains or high solar gains, cooling may be necessary even at low outdoor temperatures. In this case, outdoor air can be used to cool the space throughout the day. Care must be taken to ensure effective throttling of the air flow and draught-free air intake. For mechanically driven systems, the cooling capacity can be controlled by reducing or increasing the recovery efficiency. This applies roughly for ASHRAE Climate Zones 5A, 5B, 5C, 6A, 6B and 7 [32].

Ventilative Cooling during temperate outdoor conditions: Under temperate conditions, outdoor air can be provided to the building and the occupied zone without creating a risk of draught. The air flow rate should be controlled according to the temperature and will typically be higher than required to ensure an acceptable indoor air quality.

In naturally driven systems, technically relatively simple systems (such as manual or automatic window opening in the façade) can handle the ventilative cooling appropriately. However, in periods with low temperature differences between the indoor and outdoor air, it might be necessary to enhance naturally driving buoyancy forces by implementing additional technical solutions to the building. In windy climates, solutions that can enhance wind forces are typically suitable (wind catchers, high positioned roof openings, cross ventilation), while in sunny climates, enhancement of buoyancy forces by solar chimneys might be useful.

To enhance the ventilative cooling capacity of the outside air, it is important to position the air intakes in a cool environment (shaded side of the building). It might also be necessary to further reduce the outdoor air intake temperature by supplementary natural cooling solutions like ground cooling (earth to air heat exchange) or evaporative cooling. This applies roughly for ASHRAE Climate Zones 4A, 4B and 4C [32].

Ventilative cooling during hot and dry outdoor conditions, with significant day/night fluctuation: In dry climates with high outdoor air temperatures during daytime, the air flow rates should be controlled to a minimum to ensure an acceptable indoor air quality and minimum additional heat load on the building.

Effective nighttime ventilation should be applied to remove the heat absorbed during daytime by cooling the thermal mass of the building. If the nighttime cooling capacity is high enough, and the building is well designed with well-balanced glass area in the facades, efficient solar shading and exposed thermal mass, the next day's indoor temperature profile will be lower than the outdoor temperature. For effective nighttime heat extraction from the thermal storage masses, at least five air changes per hour are advisable.

In climates with significantly hot summers, when nighttime temperatures are still above the comfort zone, the applicability of nighttime ventilation is limited to the shoulder seasons, while in mid-summer it must be substituted or supplemented by other cooling solutions. This applies roughly for ASHRAE Climate Zones 1B, 2B and 3B [32].

Ventilative Cooling during constantly hot and humid outdoor conditions: In constantly hot and humid outdoor conditions, the outside air has no capacity to extract heat from the room. Still, moving air can improve the occupant's thermal comfort through convective and evaporative heat transfer (see chapter 4.1 Comfort Ventilation and Elevated Air Movement). This applies roughly for ASHRAE Climate Zones 1A, 2A and 3A [32].

Ventilative Cooling embedded in hybrid cooling solutions: There are numerous climatic zones where ventilative cooling is often useful, but at times not sufficient. In these cases, hybrid solutions can be considered: This can be temporally hybrid, i.e., when mechanical cooling replaces or supplements ventilative cooling at certain times of the day or year. Or it can be hybrid in terms of location, i.e., if mechanical cooling is only offered for special rooms, such as bedrooms, while the other rooms are cooled exclusively by natural ventilation.

3.1.3.5 Availability

Natural ventilation through openings and other passive devices is widely available for most applications. Traditional examples, developed through centuries of trial and error, are modified to provide contemporary solutions. Mechanical ventilation techniques and solutions are also readily available for most applications.

3.1.4 Further Reading

Further information can be found in the following publications:

- Chapter 3.2, Ventilative Cooling, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- All publications and deliverables that were developed in IEA EBC Annex 62 Ventilative Cooling
- Psomas, T. C., Heiselberg, P. K., Duer, K., Bjørn, E., (2016) Control Strategies for Ventilative Cooling of Overheated Houses, CLIMA 2016, retrieved from https://vbn.aau.dk/ws/portalfiles/portal/233719320/paper_198.pdf
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3.2 Thermal Mass Utilization

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3.2.1 Description

Thermal mass materials, such as heavy construction materials, are often used in the passive cooling strategies to absorb and store heat during the daytime of the summer and should seasons when outdoor temperature is higher than indoor temperature. This stored heat is released at nighttime when outdoor temperature is lower than indoor temperature. In the winter, thermal mass stores heat during the day and releases it at night, helping to keep the building warm.

Thermal mass energy storage refers to a material's capacity to absorb, store and release heat, essentially functioning as a thermal battery. Thermal energy can be stored in different ways, such as through a change in the internal energy of a material as sensible heat (e.g., using the ground, water tanks and aquifer energy storage), latent heat (e.g., Phase Change Materials (PCMs) that include organic and inorganic substances and ice storage), or chemical energy (e.g., thermochemical storage) [6]. A property implementation of thermal mass can contribute to reduced peak heating/cooling loads and minimize fluctuations in indoor air temperature. This allows heating/cooling loads to be shifted to hours with low tariff, and contributes to a decreased demand of peak electricity and improves thermal comfort and resilience in buildings [40].

Thermal mass materials can encompass various forms, such as concrete slab floors, blocks, bricks, PCMs, ice, etc. When a phase transition occurs, PCMs absorb or realise a substantial amount of heat energy, proving heating or cooling. Additionally, thermal mass can be heated or cooled through the utilization of pipes that contain water or a mixture of water and additives, known as hydronic activation. The thermal mass utilization can be achieved through thermal energy storage (TES) systems. These TES systems can be classified based on the type of heat storage, namely sensible, latent, or a combination of both. Common building materials like concrete and gypsum, being single-phase solids, solely store sensible heat, whereas PCMs can store latent heat. As a result, to store the same amount of energy, PCMs require much less mass compared to single-phase solid materials. In addition to their high heat storage potential, PCMs offer another advantage: they maintain nearly constant temperatures during phase changes [40].

3.2.2 Key Technical Properties

The key technical properties of thermal mass include specific heat capacity, density, and heat conductivity. For PCMs, the technical properties also encompass the melting point, and heat of fusion of the PCM. Details about these properties are listed below.

Specific heat capacity [$J \cdot kg^{-1} \cdot K^{-1}$]. The amount of heat energy required to raise the temperature of a substance by a specific amount per unit mass. Materials with higher specific heat capacity can store more heat energy per unit mass.

Density [$kg \cdot m^{-3}$]. Mass per unit volume of a thermal mass material. Higher density materials tend to have higher thermal mass as they contain more mass within a given volume. The density influences the amount of heat energy that can be stored within a material.

Heat conductivity [$W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$]. A thermal mass's ability to conduct heat. It quantifies how effectively a thermal mass transfers heat through conduction when there is a temperature difference across it. Materials with higher thermal conductivity can transfer heat more efficiently, allowing for faster heat exchange with the surrounding environment. However, in the context of thermal mass, lower thermal conductivity is often desirable as it helps to retain stored heat for longer periods.

Additional technical properties of PCM:

PCM melting point [°C]. The temperature at which PCM changes state from solid to liquid. Each PCM has a specific melting point depending on its chemical composition. The melting point of PCM can vary widely, ranging from below freezing temperatures to well above room temperature, depending on the specific PCM used.

PCM heat of fusion [$J \cdot g^{-1}$]. The change in enthalpy of a PCM, resulting from providing energy, usually in the form of heat, to a specific quantity of the substance to change its state from a solid to a liquid at constant pressure.

3.2.3 Performance and Application

3.2.3.1 Building Performance

The thermal property of thermal mass has a significant impact on the resilient performance of buildings, which can be categorized as energy, carbon and thermal performances. The energy performance can be evaluated by the key performance indexes (KPIs) annual cooling demand, annual cooling site energy use, peak heating and cooling loads. The carbon performance can be evaluated by the KPI, annual carbon emission and thermal performance can be evaluated by the KPIs, Hours of Exceedance (HE), Indoor Overheating Degree (IOD), Overheating Escalation Factor (OEF), and Standard Effective Temperature (SET). Detailed definitions of the KPIs can be found in [3] and [41]. It should be noted that thermal mass utilization is often combined with other resilient cooling technologies, such as ventilative cooling and solar shading. The resilience performance is often evaluated on the combined cooling technologies, rather than on the thermal mass utilization only.

Table 5 presents the KPIs of the five field studies of IEA-EBC Annex 80 project that use thermal mass utilization. Building WW is cooled through ventilation, utilizing a cooling coil supplied by well water cooling. Building SL was constructed using reinforced concrete and solid timber frame. The massive base plate is a crucial element of the thermal activation building system (TABS), which is employed conjunction with ventilation and well water cooling. Buildings SAS and GES are cooled via natural ventilation, aided by the opening of exterior windows. The KPIs presented in Table 5 show that the annual cooling load of these building ranges from 0.63 to 12.1 $kWh/(m^2 \cdot y)$ and carbon emissions ranges from 143 to 2,951 $gCO_2e/(m^2 \cdot y)$. The range of HE is 110 to 1,245 unmet hours, IOD ranges from 0.078 to 0.393 °C, AWD spans from 3.57 to 8.29 °C, OEF varies between 0.009 and 0.11, and SET ranges from 25.2 to 28.3 °C.

Table 5: Field studies of IEA-EBC Annex 80 [42]:

Buildings[a]			WW	SL	SAS	GES
Country[b]			AT	AT	CA	CA
ASHRAE climate zone [32]			4A	5A	6A	6A
Building Type			Residential	Sports	Educational	Educational
Cooling technologies: Thermal mass + additional technologies			Ventilative Cooling Natural Heat Sinks	Ventilative Cooling Natural Heat Sinks	Solar Shading Ventilative cooling	Solar Shading Ventilative Cooling
Performance	Energy	Annual cooling demand/cooling load [kWh/(m²·y)]	0.63	12.1	0	0
		Annual cooling site use [kWh/(m²·y)]	1.52	13	0	0
	Carbon	Carbon Emissions [$gCO_2e/(m^2 \cdot y)$]	143	2951	/	/
	Thermal resilience	HE [unmet hours]	1245	110	Max.110 (Rm 200)	Max.130 (Rm 118)
		IOD [°C]	0.393	0.078	/	/
		AWD [°C]	3.57	8.29	/	/
		OEF [-]	0.11	0.009	/	/
		SET [°C]	25.2	28.3	/	/

[a] WW: Wohnprojekt Wien; SL: Sporthalle Liefering; SAS: Sainte Antoine School; GES: Grands-Êtres School.

[b] AT: Austria; CA: Canada.

Two laboratory buildings (functioning as residential buildings), B1 and B2, in Denmark were tested in August of 2015 [43]. The buildings are located in Climate Zone 6C. Building B1 is constructed using heavy materials, while B2 represents typical buildings in Denmark made of extra-light to medium-light materials. During the August heat wave, the average outdoor air daily temperature fluctuation was 16.7 °C. There were 14 days when outdoor temperature was higher than 30 °C and another eight days when it exceeded 32 °C. In this period, the average indoor temperature fluctuations were 1.4 °C in B1 building (heavy materials) and 1.8 °C in B2 building (extra-light to medium-light materials).

To assess effects of thermal mass and climate change on CO_2 emissions, a semi-detached house in south-east England was evaluated [44]. The house is situated in Climate Zone 4A. Four different levels of thermal mass were investigated, ranging from lightweight timber frame to very heavyweight concrete construction. Table 6 shows the predicted CO_2 emissions from fully use of air conditioning system during the cooling season, average over 20-year periods. It indicates that due to climate change, the predicted annual CO_2 emissions increases for the four different levels of thermal mass. Using heavyweight materials aids in reducing CO_2 emissions compared to light/medium-weight materials.

Table 6: Predicted CO_2 emissions from fully use of air conditioning system, average over 20-year periods [44]. Unit [kg $CO_2e/(m^2 \cdot a)$]:

Building materials	Lightweight	Mediumweight	Medium-heavyweight	Heavyweight
2021-2040	7.6	/	/	/
2041-2060	8.5	7.9	/	/
2061-2080	9.6	9.1	8.9	8.8
2081-2100	11.1	10.6	10.4	10.3

The utilization of thermal mass highly depends on the prevailing climate conditions, which is discussed below.

3.2.3.2 Resilience

By storing heat and cooling energy, thermal mass in buildings stabilizes the temperature and reduces the heating and cooling loads; thereby improving thermal comfort. Meanwhile, it shifts the peak demand of these loads, reducing and shifting the peak electricity. This contributes to a reduction of HVAC equipment capacity and diverse energy resources, which improves the building resilience.

3.2.3.3 Limitations

Thermal mass utilization depends on climate conditions, as well as the building's design, orientation, and occupancy patterns. Generally, in hot and humid climates, such as the tropics, where outdoor temperatures do not drop at night, the use of thermal mass is generally not recommended. Highly insulated buildings with light thermal mass can overheat if building technologies are not well integrated, such as when effective solar shading is missing, and the window-to-wall ratio is unreasonable.

3.2.3.4 Climate and Application

Hot and Humid Climate (Climate zone: 1A and 2A):

In hot and humid climates such as the tropics, where outdoor temperatures do not drop at night, the use of thermal mass is generally not recommended, to reduce heat storage. Lightweight construction materials with low thermal mass, such as timber or lightweight concrete, are preferred. Additional resilient cooling technologies, such as shading, ventilation, insulation, or reflective exterior surfaces, can also be considered for maintaining comfort [45].

Hot and Dry Climate (Climate zone: 1B and 2B):

In regions with hot and dry climates, such as desert areas, thermal mass can help with temperature regulation. During the day, materials with high thermal mass, such as adobe or rammed earth walls, absorb heat from the surrounding air. As the temperature drops at night, these materials release the stored heat, keeping the interior cooler. The key is to have adequate insulation to prevent heat transfer during the day and maximize heat release at night. Additional resilient cooling technologies can also be considered for utilizing thermal mass, such as shading (minimize direct solar radiation on buildings), natural ventilation (cool the thermal mass), reflective exterior surfaces (reflect solar radiation), etc.

Moderate Climate (Climate zone: 3):

In moderate climates with varying temperatures throughout the year, thermal mass utilization can help balance temperature fluctuations. Materials like concrete, brick, or stone can absorb excess heat during the day in summer, and release it slowly during cooler evenings. This can reduce the need for mechanical cooling systems during the day and provide some passive heating during the colder seasons. Design considerations should include appropriate insulation levels and a well-planned distribution of thermal mass throughout the building.

Mixed Climate (Climate zone: 4-6):

In regions with mixed climates that experience both hot summers and cold winters, a combination of thermal mass strategies can be employed. Designing the building envelope to optimize insulation, solar gain, and thermal storage capacity is crucial. This may involve using different materials and configurations based on specific orientations and requirements for each climate season.

Cold Climate (Climate zone: 7 and 8):

In cold climates, thermal mass utilization can assist in storing heat generated by active heating systems and solar gain. Materials like concrete or masonry have high thermal mass and can absorb and store heat efficiently. During periods of low external temperatures, the stored heat is released, helping to maintain comfortable indoor conditions. It is essential to combine thermal mass with good insulation to minimize heat loss and maximize energy efficiency.

It is important to note that the successful application of thermal mass utilization also depends on factors such as building design, orientation, and occupancy patterns. Energy efficiency goals, and available construction materials should be considered when implementing thermal mass strategies in different climate zones around the world. As indicated before, thermal mass utilization is often combined with other cooling technologies, such as the advanced solar shading technology, ventilative cooling, or mechanical cooling systems.

3.2.3.5 Availability

Thermal mass utilization can be applied to both new constructions and the retrofitting of existing buildings. Designers have the advantage of incorporating thermal mass considerations into the design phase by selecting suitable thermal mass materials and positions. When retrofitting existing buildings, particularly those with low thermal mass like lightweight timber or steel frame constructions, adding thermal mass materials can be effective. In such cases, a thorough assessment of the building's structure and layout is essential to identify the most optimal locations for adding thermal mass materials.

3.2.4 Further Reading

Further information can be found in the following publications:

- Chapter 5-5, Heat storage and release, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- D. Qi, G. Hofer, S. Schoisengeier, X. Zhang, et al. IEA-EBC Annex 80 - D3 Resilient Cooling case studies. 2023.
- Sengupta, A., Steeman, M., & Breesch, H, (2020) Analysis of Resilience of Ventilative Cooling Technologies in a Case Study Building, iCRBE Procedia. 1-10, 10.32438/iCRBE.202041.
- EBC Annex 62 Ventilative Cooling, Project Summary Report, https://www.iea-ebc.org/Data/publications/EBC_SR_Annex62.pdf
- Section 4. Task 58/Annex 33 Subtask 2P Summary of Work. Subtask 2 PCM: On development and characterization of improved Materials. https://task58.iea-shc.org/Data/Sites/1/publications/D2P-T58A33-Subtask-2P-Summary-of-work.pdf
- IEA EBC Annex 67 Summary report - Energy in Buildings and Communities Programme Annex 67 Energy Flexible Buildings. http://www.annex67.org/media/1920/summary-report-annex-67.pdf

3.3 Evaporative Cooling

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3.3.1 Description

Evaporative cooling is a passive/hybrid cooling technique that uses the latent heat of vaporization of water to reduce the temperature of air coming from outside. Evaporative cooling can be classified into three types: passive downdraught, direct, and indirect.

3.3.1.1 Thermodynamics of Evaporative Cooling

Evaporative cooling involves a phase change of water from liquid to vapor, which requires a large amount of heat. This heat is taken from the surrounding air, which lowers its sensible heat and its dry bulb temperature. The latent heat and the humidity ratio of the air increase, while the wet bulb temperature remains constant. The process follows an isenthalpic line (constant enthalpy) on a psychrometric chart. The process follows an isenthalpic line (constant enthalpy) on a psychrometric chart. The picture below shows a direct (blue) and two stage evaporative cooling (red). Isenthalpic cooling means cooling without changing the enthalpy of the system. Enthalpy is a measure of the total energy of the system, which includes the internal energy, the pressure, and the volume.

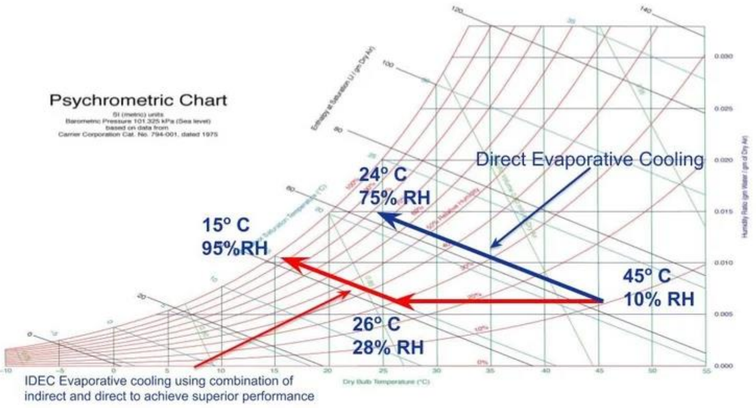

Figure 6: Simple extreme examples of direct and indirect + direct evaporative cooling.

3.3.1.2 Humidification Mechanism

Spray humidification: This technique involves spraying controlled volumes of microscopic water droplets into the air with high pressure nozzles, where they evaporate in the form of a fog which disappears with complete evaporation of the water and cool the air. It allows reaching very high level of relative humidity. The high-pressure nozzles require high pressure pumps and a network of pipes to create a homogeneous fog.

Pad humidification: This technique involves passing hot and dry air through a wetted medium, such as a pad or a mesh, where it absorbs moisture and cools down. It does not allow to reach so high level of relative humidity as high-pressure spray.

3.3.2 Key Technical Properties

There are essentially three kinds of evaporative cooling systems. There are also more but one must see in recent developments papers for more advanced systems [46], [47].

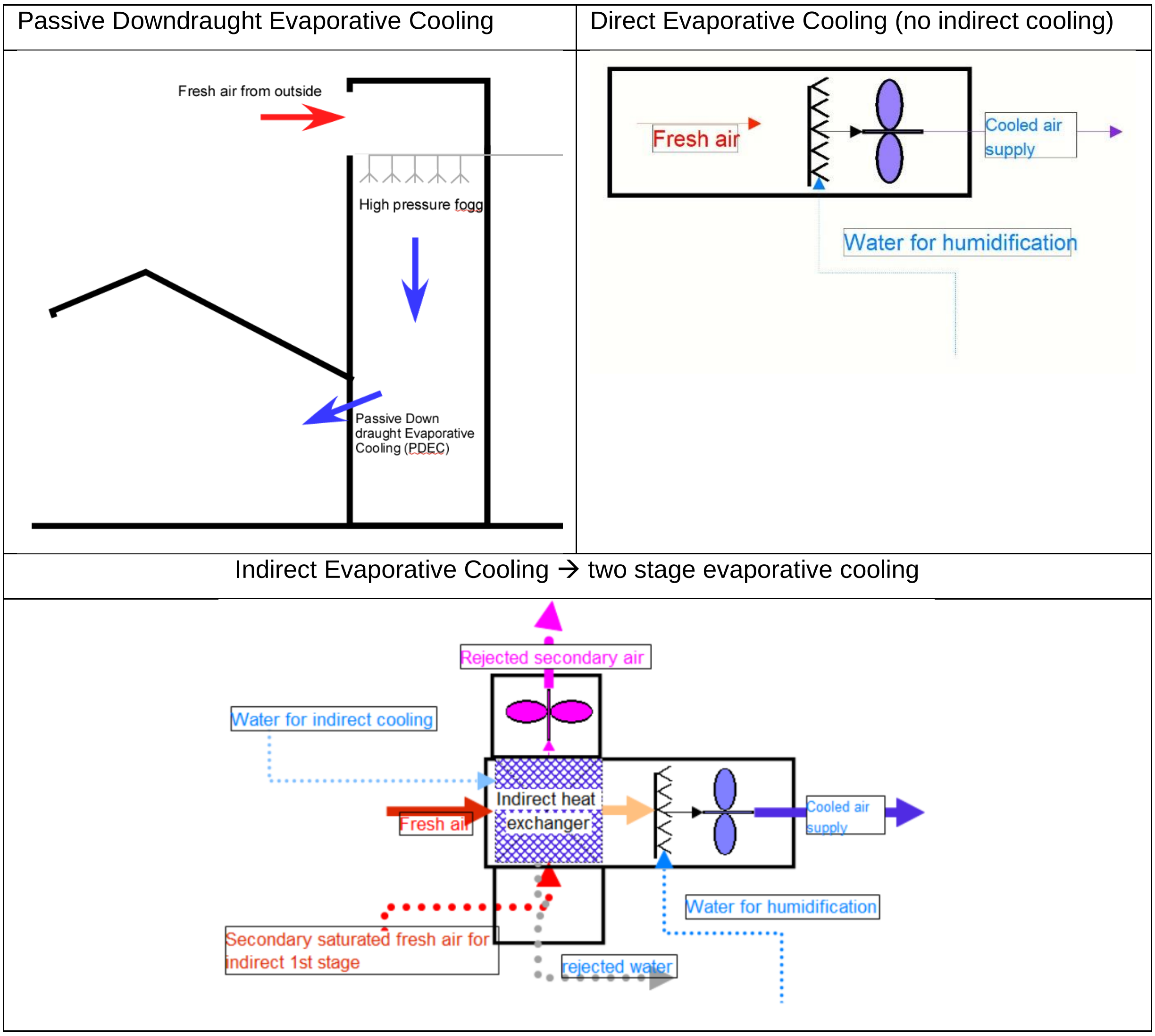

Figure 7: Schematic graphics of three most common evaporative cooling systems.

The primary function of evaporative cooling is to lower the air temperature in a space by introducing evaporated water into the air, all without the requirement for active cooling mechanisms. Its efficiency cannot be directly compared to active cooling in term of temperature and humidity, but can be compared against sensible active cooling.

Sensible Cooling Load [BTU/hr or W]. The sizing of an evaporative cooling system should match the sensible cooling load of the target building area.

Airflow [ACH]. The recommended Air Change Rate per hour (ACH) for evaporative cooling ranges from 6 to 20, depending on cooling loads.

Wet-Bulb Depression [ΔT; °F or °C]. Wet-bulb depression is the difference between dry bulb and wet bulb temperatures, measured on a psychrometric chart.

Saturation Efficiency [%]. Saturation efficiency measures how effectively the air becomes saturated with moisture during cooling. It's expressed as a percentage.

3.3.2.1 Direct Evaporative Cooling

Water Evaporation [-]. Water is evaporated directly into the space, typically using a wet pad or high-pressure fogging system.

Cooling Process [ΔT; °F or °C]. The air passes through a wet pad or mist, reducing temperature and increasing humidity.

Energy Inputs [W]. Fan Energy, Water Pump Energy, Water Supply Energy, Electricity for Controls

3.3.2.2 Fogging or Misting System

Fine Mist Generation [-]. Fine water mist is created with high-pressure pumps and nozzles.

Cooling Process [ΔT; °F or °C]. Rapid evaporation of mist lowers air temperature.

Energy Inputs [W]. High-Pressure Pump Energy, Water Supply Energy, Electricity for Controls, Electricity for Fans or Air Circulation.

3.3.2.3 Indirect Evaporative Cooling

Operation [-]. Outside or return air is humidified, cooled, and then used to pre-cool incoming outside air by sensible convective heat exchange.

3.3.2.4 Two-Stage Evaporative Cooling [48]

Operation [-]. In the first stage, air is saturated and used for sensible heat exchange; in the second stage, pre-cooled [48]. Air is further humidified through direct evaporation.

Temperature Reduction [ΔT; °F or °C]. Two-stage systems can achieve temperatures below ambient wet bulb temperature.

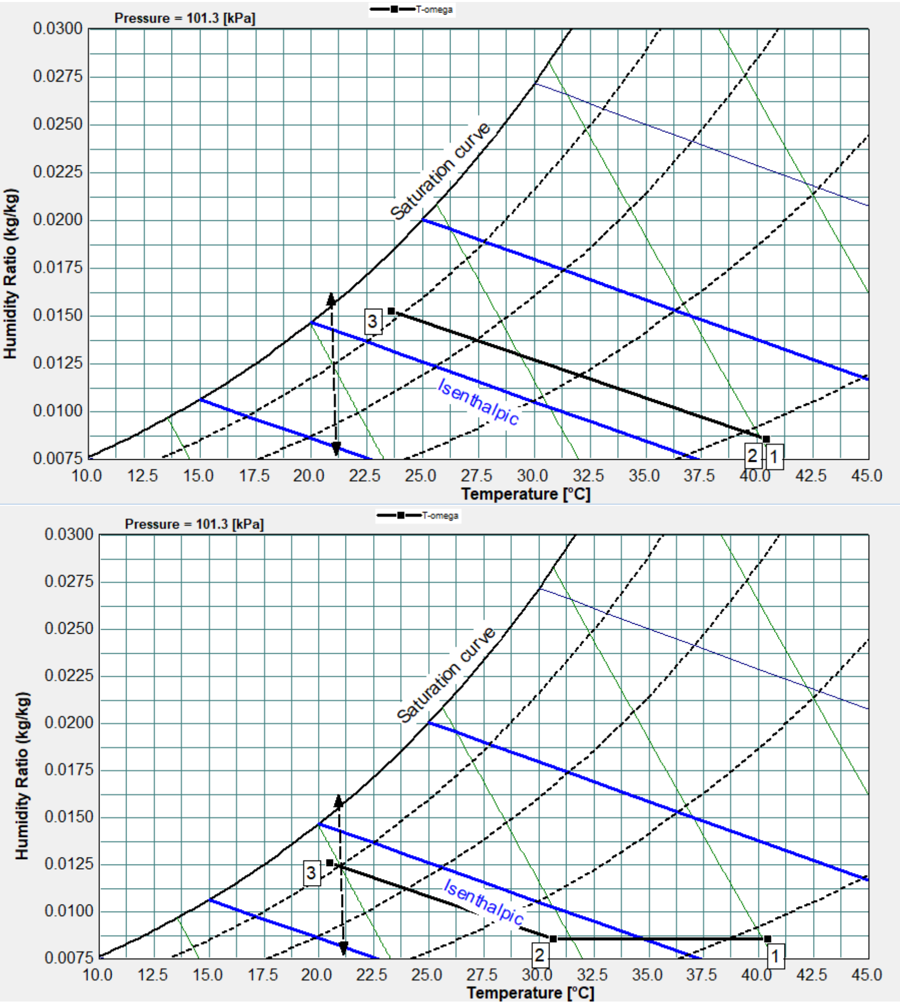

Figure 8: Psychrometric diagram of direct evaporative cooling and two-stage indirect/direct evaporative cooler.

With a two-stage system, it is possible to reach a temperature below the wet bulb of the ambient temperature, the data above for the two-stage system are taken from a based on measured data [49], with an extrapolation if the single indirect state is not used.

3.3.3 Performance and Application

3.3.3.1 Building Performance

Evaporative cooling can reduce cooling energy significantly by using different methods. One method is to use low-pressure ventilation fans to supply air that is cooled by evaporation directly through the façade, instead of using conventional HVAC systems with high-pressure ducts and components. Another method is to use a fogging system with low-energy fans and a large exhaust area, or passive down draught evaporative cooling (PDEC) system. These methods can achieve very low energy consumption for cooling.

As an example, a PDEC systems can effectively reduce indoor temperatures by as much as 5 - 10 °C below the ambient outdoor temperature, if the outside temperature is 37.8 °C, a well-designed PDEC system can help maintain indoor temperatures at around 26.7 -32.2 °C. PDEC systems increase the relative humidity of the air. However, the increase is usually within comfortable and safe limits for human health (typically below 60% RH). For instance, if the outdoor relative humidity is 20%, a PDEC system can raise the indoor relative humidity to around 40 - 50%. The cooling capacity of a PDEC system depends on factors like the size of the system, the airflow rate, and the quality of the wetted medium. An example would be PDEC system with an airflow rate of 1,000 cubic meters per hour (CMH) having a cooling capacity of approximately 2,950-5,900 watts. PDEC systems require a constant supply of water for evaporation. The water consumption depends on system size and operating conditions. PDEC systems require a constant supply of water for evaporation. The water consumption depends on system size and operating conditions. A medium-sized PDEC system may use around 38 – 76 liters of water per hour.

3.3.3.2 Climate Applicability

Evaporative cooling technology is essentially applicable in climates which are extremely hot (ASHRAE Climate Zone: 0B [32]), very hot (1B), hot (2B), warm (3B). but in other warm climates, study of applications and its cooling reduction potential have to be established depending on the duration of the high humidity occurrences.

3.3.3.3 Market Availability

Swamp coolers have been available in hot and dry climates since long. More sophisticated systems like two-stage evaporative cooling have appeared more recently in the last 30 years. There are now numbers of manufacturers of evaporative cooling systems either for domestic or for larger HVAC systems with either special modules or integration in the complete systems. Application of Evaporative Cooling can happen for new construction and retrofits.

3.3.3.4 Combination with Ventilative Cooling

Example principle from the project Smart Ghar at Rajkot, centralised night ventilative cooling and a test with window covering with a wet-pad for day operation [50]. The short duration performance test allowed to show a temperature difference between 8-10 °C between outside and entering air across the wet-pad. The pressure loss is so low that it does hardly influence the air flow for other flats.

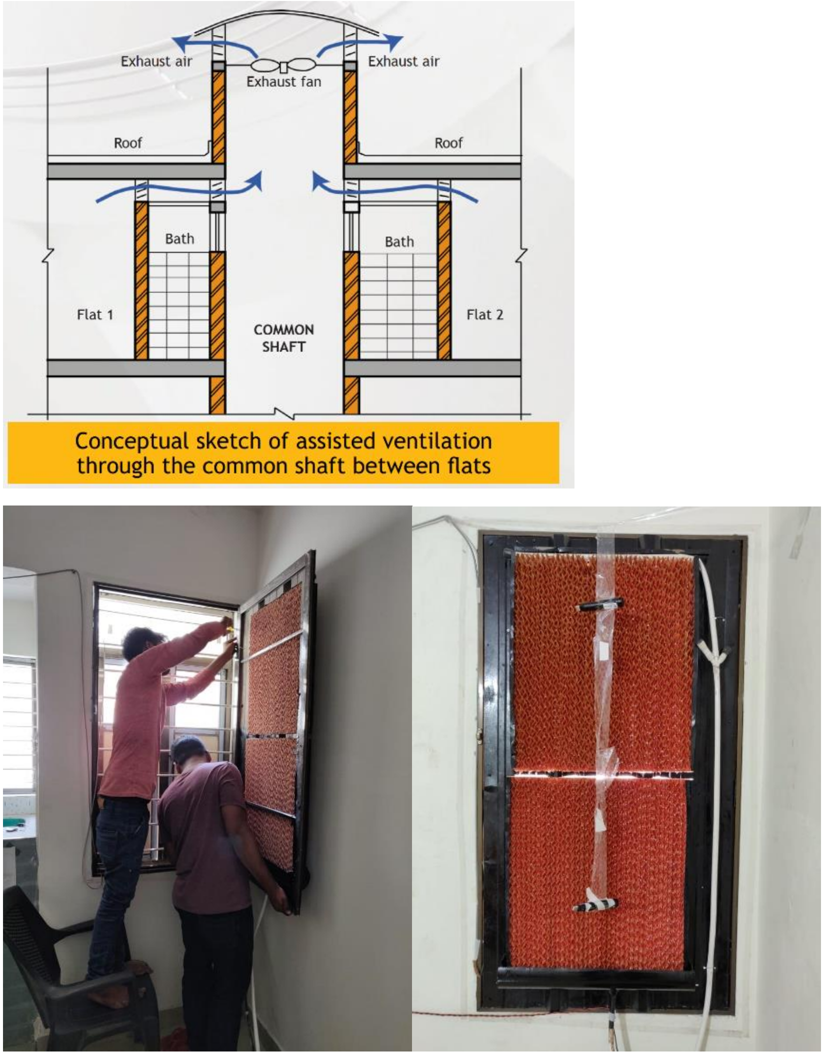

Figure 9: Centrally assisted night ventilative cooling with entering through windows: test of direct evaporative cooling of a window covered with a low-pressure loss wet pad.

The exhaust fan creates negative pressure inside the building, causing outdoor air to be drawn in through the windows with evaporative cooling pads. As the outdoor air passes through the wet pads, it cools down through the process of evaporation. The cooler outdoor air enters the building, displacing the warm indoor air, and provides natural cooling.

3.3.3.5 Resilience

Extreme heat waves

Evaporative cooling is a suitable method for coping with extreme heat waves. Heat waves are usually characterized by hot and relatively dry air, which lowers the humidity outside during the day. This creates favourable conditions for evaporative cooling to work effectively. The very low energy required in comparison to active compression cooling makes it possible to operate even during power break with the help solar photovoltaic and/or battery storage.

Solar Photovoltaic (SPV)

The evaporative cooling is used mostly during hot and dry days, SPV can run the fans and pumps in an autonomous arrangement.

Battery Storage

It is also possible to incorporate energy storage solutions, such as batteries, to store excess solar-generated electricity. This enables the system to operate during periods of low solar insolation (e.g., cloudy days or nighttime) and ensures continuous cooling.

3.3.3.6 Limitations and Risks

Water Quality

When using high-pressure fogging systems, the nozzles have a very small hole, so the water quality is very important. Adequate water treatment must be planned.

Legionella

In the case of water recirculation and worse, stagnant water, there is a risk of development of legionella, the system must be planned accordingly to avoid recirculation and stagnant water

Warm and humid climate

In warm and humid climates, the two-stage option is the only one which can be useful, often in tandem with active cooling. Two-stage systems can achieve more significant temperature reductions compared to single-stage evaporative cooling systems, even in humid conditions.

3.3.4 Further Reading

Further information can be found in the following publications:

- O. Amer, R. Boukhanouf, H. Ibrahim, (2015) A Review of Evaporative Cooling Technologies, International Journal of Environmental Science and Development, 6. 111, 10.7763/IJESD.2015.V6.571.
- N. Kapilan, Arun M. Isloor, S. Karinka, (2023) A comprehensive review on evaporative cooling systems, Results in Engineering, Volume 18, 101059, doi.org/10.1016/j.rineng.2023.101059.
- A. Tejero-González, A. Franco-Salas, (2021) Optimal operation of evaporative cooling pads: A review, Renewable and Sustainable Energy Reviews, Volume 151, 111632, doi.org/10.1016/j.rser.2021.111632.
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- Ford B., Wilson R., Gillott M., Ibraheem O., Salmeron J., Sanchez F. J., (2012) Passive downdraught evaporative cooling: performance in a prototype house, Building Research & Information, 40:3, 290-304, 10.1080/09613218.2012.669908

3.4 Sky Radiative Cooling

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3.4.1 Description

Sky radiative cooling represents the passive process in which any object located on the Earth's surface (sky facing terrestrial object or surface) releases heat to the sky through net loss of long-wave (thermal infrared) radiation. Sky radiative cooling represents a renewable technology, which harnesses the free cooling energy of the sky.

Sky radiative cooling is mostly associated with nighttime, when there is no additional heat gain from the incident solar radiation. Air temperature, humidity, air speed, and clouds are other environmental parameters that influence the radiative cooling potential of the sky. An outdoor air temperature higher than the object's temperature reduces the net cooling potential while a lower one increases it. The cooling potential is also decreased in hot and humid environments and by clouds that can trap infrared radiation.

The building's roof may be used directly as the radiator, i.e., the object radiating heat to the sky. For this, cool paints, tiles, and coatings may be employed to increase solar reflectivity and emissivity of the roof. Roof ponds and movable insulation systems represent solutions that can further enhance the net cooling potential through evaporative cooling and reducing the radiator's wall resistance, respectively. For further details on such systems the reader is referred to the chapters 2.4 Cool Envelope Materials and 3.7 Natural Heat Sinks.

Sky radiative cooling may also be harnessed using a heat transfer medium, i.e., air or water based systems. The heat transfer medium is circulated through a radiator. The radiator represents an object with an intricate or structured surface which increases the surface area (e.g., corrugated metal sheets) and a network of tubes and channels attached to the surface of the radiator through a heat conductive interface. Air based systems make use of a radiator with channels usually placed on the roof that pre-cools the air. Certain applications employ the roof directly as the radiator. These systems make use of a fan to drive the air. The air can be directly supplied into the space or the radiator can be coupled with air-conditioning systems to improve their performance [51]. Water based systems generate cold water by circulating it through the radiator, which may be directly employed or stored for later use. These systems may be combined with thermoelectric systems that require a source to dissipate heat, heat-pumps to improve their performance [52], or thermo active building systems (TABS) for directly conditioning the indoor space [53]. Solar heating systems and photovoltaic/thermal panels (PV/Ts) are commonly used as water-based system radiators, thus enhancing their utilization factor.

3.4.2 Key Technical Properties

When selecting the radiator with the main purpose of enhancing the radiative cooling potential, relevant technical properties of the radiator are emissivity and reflectivity. For an ideal radiator, a maximum reflectivity in the short-wave range (0.25 – 2.8 µm) is desired to reflect solar radiation, while the emissivity should be as close as possible to unity, especially in the atmospheric window band (8 – 13 µm) and zero otherwise.

The system design indicators are the area, orientation, and slope of the radiator. A horizontal placement would enhance the sky radiative cooling but expose the radiator to direct solar radiation for the longest duration. An anti-sunward orientation would lead to the highest cooling potential. However, if cooling represents a by-product, e.g., PV/T for the production of electricity, heating, and cooling, then the slope and orientation should be selected according to the system's main function or highest need.

A widely investigated sky radiative application in buildings is making use of solar collectors and photovoltaic/thermal panels (PV/Ts) for the production of cold water. The presence of polyethylene films on the radiator is desired since they suppress convective thermal loss [54]. For such systems, operational design indicators should also be considered, such as the flow rate of the heat transfer medium and the size of storage.

The following indicators can be used to assess the performance of the sky radiative cooling system:

Specific Cooling Power [W/m^2]. The ratio between the average cooling power obtained and the area of the radiator or system.

Coefficient of Performance (COP) [-]. The ratio between the power used to circulate the heat transfer medium and the generated cooling power.

Cover Ratio [-]. The share of the cooling load covered by the net cooling energy generated by the radiator.

According to literature where water-based radiators were employed (mainly PV/T's and unglazed solar collectors), an average cooling power between 23 and 120 W/m [55], [56], [57], [58], [59] was obtained depending on the climate. High COPs, which can register values up to 30 for PV/Ts characterize sky radiative cooling and unglazed solar collectors where the energy use is solely associated with circulating the heat transfer medium (e.g., pumping power). Passive roof cooling can lead to a cooling power between 40 to 100 W/m^2 (D. Zhao et al., "Radiative sky cooling: Fundamental principles, materials, and applications," no. May, 2022, doi: 10.1063/1.5087281.; Y. Wu, H. Zhao, H. Sun, M. Duan, B. Lin, and S. Wu, "A review of the application of radiative sky cooling in buildings : Challenges and optimization," Energy Convers. Manag., vol. 265, no. May, p. 115768, 2022, doi: 10.1016/j.enconman.2022.115768.). The average net cooling power of air-based radiator systems is the lowest, registering values between 20 and 30 W/m^2 [51].

Sky radiative cooling may be used to cover a share or the entire cooling load and therefore indicators such as cover ratios may be estimated. If dimensioned accordingly, it is expected that a considerable share (up to 100%) of the cooling load may be covered in cold and dry environments [57]. The cover ratio may vary depending on the outdoor conditions, but can be adapted through the surface area, number of radiators, and fluid flow rate.

3.4.3 Performance and Application

3.4.3.1 Building Performance

As sky radiative cooling represents a high temperature cooling solution, it may be coupled directly with thermo active building systems, where heating and cooling is realized through the thermal mass of the building. Heat pump efficiency may also be increased if sky radiative cooling radiators (e.g., PV/Ts) are employed as the condenser [54].

Sky radiative cooling is associated with all building types except high-rise buildings due to their low roof to floor area ratio. The technology can also be used in building refurbishment.

3.4.3.2 Resilience

Sky radiative cooling does not present absorptive or adaptive capacities during heat waves or power outages. A low to moderate restorative capacity is expected, as increased humidity and outdoor temperatures (environmental conditions expected during and after heat waves) would reduce the cooling capacity. The recovery speed could vary between low and high depending on the way sky radiative technology is employed, passively or actively. Active use could ensure an increased recovery speed through an increased flow rate of the heat transfer medium (e.g., air, water). Blackouts would not pose an issue; thus, the sky radiative cooling restorative capacity after blackouts was rated as moderate. During blackouts, however, one challenge would be ensuring the circulation of the heat transfer medium; thus, the recovery speed would be low without backup power.

3.4.3.3 Limitations

As an application, the optimum sky radiative cooling solution must be chosen according to the climate and setting (high versus low building density), i.e. good planning is required for a high exploitation potential. Solutions that employ the building's roof as the radiator are not suitable for multi-storey buildings since the rest of the floors, except for the top one, are not in contact with the radiator.

The available building roof area will limit the installed capacity. Furthermore, the potential is limited in highly dense environments where other buildings obstruct the view of the sky.

Cool roofs may increase heat load and cause overcooling in winter. The range of colours is also limited [52].

3.4.3.4 Application and Climate Conditions

The highest long-wave radiative cooling potential is achieved under clear skies as clouds trap the long-wave radiation. The highest cooling potential is registered in cold (5A to 6B [32]) and dry environments. High air temperatures and humidity reduce the cooling potential. For example, an increase in relative humidity (50 to 100%) and outdoor air temperature (9 K) could reduce the cooling power of thermal solar collectors by 18% to 41%, respectively. High air speeds can increase the convective heat exchange, which further enhances the net cooling power.

3.4.3.5 Availability

Water-based radiators such as PV/Ts represent market available solutions that may be employed in multi-storey buildings and can also be coupled with storage solutions. A storage system enables the system to store cooling during periods with favourable conditions and make use of it at times when the sky radiative cooling potential is limited. Cooling throughout the day may also be realized with radiators dedicated to cooling purposes using highly reflective optical films.

3.4.4 Further Reading

Further information can be found in the following publications:

- Information on roof ponds can be found in chapter 3.7 Natural Heat Sinks
- Information on cool paint, tiles, and coatings can be found in chapter 2.4 Cool Envelope Materials
- Section 3.7, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Section 4.2.6 in: Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- Zhao, D., Aili, A., Zhai, Y., Xu, S., Tan, G., Yin, X., Yang, R., (2019) Radiative sky cooling: Fundamental principles, materials, and applications, Applied Physics Reviews, 6(2), doi.org/10.1063/1.5087281
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3.5 Compression Refrigeration

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3.5.1 Description

Compression refrigeration appliances for domestic cooling purposes are operated using thermodynamic cycle processes. These cycle processes make use of the heat transported in the refrigerant, which is absorbed via evaporation and released via condensation of the refrigerant, similar to the working principle of a refrigerator. A compression refrigeration machine thus consists of four main components (Figure 10):

1. An evaporator, in which the cold refrigerant evaporates through the uptake of heat from the warm environment (the so-called heat source), thus producing a cooling effect.
2. A compressor, where the gaseous refrigerant is compressed which increases the pressure and temperature of the refrigerant vapour.
3. A condenser where the refrigerant – which is now considerably warmer than the environment (or heat sink) used to cool the condenser – releases heat until it is fully condensed.
4. An expansion valve where the liquid refrigerant is expanded, thus decreasing its pressure and temperature.

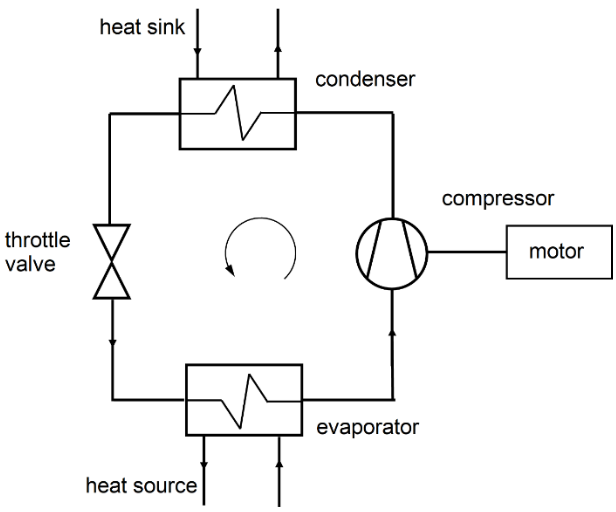

Figure 10: Main components of a compression refrigeration machine.

To make use of the cooling effect of the refrigerant's vaporisation, the evaporator is situated within or coupled to the indoor environment to be cooled. The condenser, on the other hand, is placed within or coupled to the heat sink destined to absorb the discarded heat from the cooling process. Most commonly, the heat sink is the outdoor air; however, other media with better thermal transmission such as the ground or ground water allow higher efficiency and do not contribute to overheating of the exterior environment; see the technology profile on natural heat sinks (chapter 3.7) for further information. There are several solutions for the application of compression refrigeration machines:

Single split air conditioners. These systems consist of an indoor unit and an outdoor unit. The indoor unit contains the evaporator and the outdoor unit contains the condenser, and both units are connected by piping containing the refrigerant. Single split air conditioners can be used to cool a room by extracting heat directly from the indoor air via evaporation and fanning the cooled air back into the room.

Multiple split air conditioners. Here, one outdoor unit is connected to several indoor units.

VRF/VRV units. Variable refrigerant flow or variable refrigerant volume systems are similar to multiple split air conditioners, but differ in that they allow the individual setting of the refrigerant flow to every indoor unit via a thermostat. Using a three-pipe instead of a two-pipe system even allows simultaneous heating of spaces while cooling others.

Packaged units. In this case, all components are contained in one casing which is installed in a recess in an exterior wall of the building.

Portable units. If there is no constructive recess available, packaged units are also available to be used free-standing with an air duct leading the hot exhaust air to the exterior environment. Usually, the end of the duct is placed in an open window. However, this, as well as the fact that the condenser radiates heat to the room to be cooled, makes portable units rather inefficient in their operation.

Rooftop systems. These are packaged systems in charge of cooling and ventilation. They are installed on top of a building and mix ducted indoor air with fresh air, subsequently cool it down to the desired room temperature and feed it to the ventilation system. To increase the efficiency of the compression refrigeration machine, an exhaust to inlet air heat exchanger is included to pre-cool the inlet air.

Chillers. In this case, an intermediate hydraulic circuit containing chilled water transports the heat from the conditioned areas to the refrigeration machine. The heat is taken up via fan coil units (Figure 11) or heat exchangers in an air handling unit and released to the refrigerant of the refrigeration machine, which, in turn, releases it to the heat sink.

Thermal activation. Here, the refrigeration machine also cools water in an intermediate hydraulic circuit whose cooling coils are laid into a massive building component such as a ceiling, wall or floor. Thus, the heat is taken up via a massive building component rather than directly from the indoor air. These systems are particularly efficient as they run on higher flow temperatures than the convective systems mentioned above. Thermally activated building systems (or 'TABSs') make the thermal mass of a building accessible for heat or cold storage and thus can be used for peak shaving and load shifting. Due to their high thermal storage capacity, they take longer to react to changes in the cooling water temperature and therefore produce a time lag between cooling water temperature change and room air temperature adjustment. Furthermore, TABSs cannot be used for dehumidification as condensation occurring at flow temperatures lower than 18 °C leads to hygienic as well as static complications. For further information, see chapter 3.8 Radiant Cooling.

Heat recovery systems. As compression cooling systems produce a thermal discharge which is usually released to a heat sink, the system efficiency increases if the discharged heat is instead recovered and used. Hereby, unwanted thermal discharges into the urban environment of air conditioners using the outdoor air as a heat sink can be eliminated at the same time.

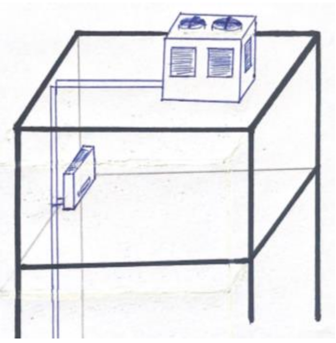

Figure 11: Example of an air-cooled chiller located on the building's roof and supplying multiple fan coil units.

3.5.2 Key Technical Properties

Compression refrigeration machines can be dimensioned according to the cooling load of the building. This makes compression refrigeration machines a versatile technology with many application possibilities. In practice, the greatest given restriction is the availability of different types of heat sinks and for air-cooled systems, the availability of space for the outdoor unit.

The efficiency of a refrigeration machine depends on the temperature levels in the evaporator and the condenser, whereas larger temperature differences mean a lower efficiency. Therefore, cooling the building at an outdoor temperature of 30 °C requires less electrical power for the compressor than at an outdoor temperature of 40 °C. In the same way, the desired indoor temperature has an effect on the machine's efficiency: lower required indoor temperatures require higher electrical power. Furthermore, the medium of the heat sink has an impact on the efficiency of the cooling system: using water instead of air leads to a higher efficiency as water has a higher thermal capacity than air and can therefore absorb a larger amount of heat per mass unit.

As multiple split units are often supplied via one outdoor unit, these systems display lower efficiency than single split units. VRF/VRV systems capable of simultaneous cooling and heating of different spaces, offer even higher efficiencies than single or multiple split systems. The highest efficiencies are observed for chillers. Making use of the discharged heat via heat recovery systems also increases the overall efficiency of the building's conditioning system.

Refrigerants continue to be a prevalent matter for research since aspects such as the ozone depletion potential, global warming potential, flammability and others are sought to be optimised. An ideal refrigerant should display a low risk to the environment, the climate and humans, while offering expedient thermodynamic properties.

<u>System Design Indicators</u>

Cooling Capacity [kW]. This gives the maximum cooling power of the appliance. Compression refrigeration machines can be scaled up from a few hundred watts for domestic space cooling up to several megawatts for industrial use.

Nominal Power [kW]. The maximum amount of electrical power drawn by the appliance. This depends on the efficiency and size of the appliance and can extend to within the megawatt range for industrial appliances.

Energy Efficiency Ratio (EER) [-] [60], [61], [62], [63] This describes the amount of cooling power in relation to the amount of required electrical power for a set of standard test conditions. These conditions vary between countries. Internationally, the market average of the not strictly comparable EERs for air conditioners and chillers in 2018 of selected countries varied between 2.8 and 3.5 with the best available technologies reaching an EER of up to 6.7 [64].

Seasonal Energy Efficiency Ratio (SEER) [-] [65] [66] and Cooling Seasonal Performance Factor (CSPF) [-] [67]. The SEER is calculated as the total amount of extracted heat in relation to the total amount of electricity consumed during a cooling season with an outdoor temperature distribution typical for the local climate. The calculation assumptions are again country specific. In 2018, the market average for air conditioners and chillers was between 3 and 4.7, with the best available technologies reaching a SEER of up to more than 12 [64]. Similarly, the CSPF is defined as the ratio of total extracted heat to the total amount of electricity consumed during the cooling season, depending on specific climate conditions, but under variable load conditions to obtain a more realistic value. For instance, the minimum required CSPF for single split air conditioners lies between 3.7 and 6, depending on the climate zone [68][5].

Refrigerant toxicity, flammability class [70], [71] and **ecological properties (Ozone Depletion Potential (ODP) [CFC-11-eq.], Global Warming Potential (GWP) [CO_2-eq.])**. Toxicity and flammability properties are divided into occupational exposure limit and flame propagation categories, with refrigerants of the category A showing lower toxicity than those of the category B, and refrigerants with a higher numeral showing higher

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[5] Further country-specific information can be found in [69].

flammability. The ODP is a metric for the amount of ozone destruction in relation to the substance CFC-11. The GWP gives the amount of thermal radiation absorbed by a greenhouse gas in relation to the amount of thermal radiation absorbed by the same mass of CO_2. Several international agreements such as the Montreal Protocol, the Kyoto Protocol and the Kigali Amendment, as well as national regulations, limit the production and use of high-ODP and -GWP substances [72].

Total Equivalent Warming Impact (TEWI) [kg CO_2-eq.] [73]. This metric takes into account indirect greenhouse gas emissions caused by the operation of the refrigeration machine (through electricity consumption) as well as direct emissions in the form of refrigerant leakage. The current amendment of the EU F-gas Regulation [74] as well as the expected ban of PFAS (per- and polyfluoroalkyl substances) [75] will very likely lead to a strong prohibition of fluorinated refrigerants within the EU until 2040 at the latest, leaving only natural refrigerants such as hydrocarbons (propane, butane, ethane), ammonia, CO_2, air and water as an option.

3.5.3 Performance and Application

From a general perspective, compression refrigeration technologies offer a good opportunity to integrate renewable energy into the energy system. Great renewable energy potentials from wind or sunlight are convertible to electrical energy, which in turn, is the sole energy source required to operate compression refrigeration machines.

3.5.3.1 Resilience

Compression refrigeration systems display a high adaptive capacity in the face of heat waves, meaning that during times of particularly high outdoor temperatures, the air conditioning system can actively meet the increased cooling demand. This comes with the price of higher electricity demand. After a heat wave, compression refrigeration technologies are capable of quickly reinstating the desired indoor temperature.

During power outages, grid-fed compression refrigeration systems are not operable as they require electrical power to run the compressor and any pumps or fans needed to distribute the cold or operate the refrigeration machine. They therefore show high vulnerability in this respect. After power outages, the desired indoor temperature can quickly be restored.

Due to the aforementioned low power outage resilience as well as electricity demand considerations, compression refrigeration technologies are recommended to be operated in combination with passive cooling technologies to increase resilience as well as decrease the cooling demand that is to be met by the machine. Here, the priority should be given to passive cooling technologies such as shading in order to decrease the cooling demand as much as possible before turning to active technologies to cover the remaining cooling demand.

There are some options to increase power outage resilience: For example, the highest cooling loads arise at times when electricity production from photovoltaics (PV) peak, making a direct use of PV electricity possible. Refrigeration machines can also be used to store cold in thermal storage at times of high renewable electricity supply, thus contributing to the integration of renewables into the energy system as well as shaving cooling demand peaks during hot periods and stabilising the electricity grid.

A study evaluating the efficiency of a geothermal heating and cooling system using 56 borehole heat exchangers with a depth of 100 m and four heat pumps which can also operate as refrigeration machines in a university building in Leicester, Great Britain, has found that for a cooling water flow temperature of 6 – 12 °C (to be used in air handling units and fan coil units), the monthly CSPF fluctuated between 2.6 and 5.7, with a median of 4, during an observation period of 30 months. The temperature of the undisturbed soil was found to be 12.3 °C [76].

A simulation study for a schoolroom building in Mogadishu, Somalia, investigated the energy consumption of various cooling options, including air-cooled chillers coupled with radiant ceiling panels. Mean monthly outdoor air temperatures in Mogadishu amount to between 26.5 and 30.4 °C, and monthly maximum outdoor air temperatures can reach an average up to 39 °C. The desired indoor conditions showed a significant impact on the required energy demand: keeping indoor temperatures at 26 °C required a chiller for the air handling unit supplying and dehumidifying fresh air for the indoors in addition to a second chiller to feed the radiant panels and resulted in an annual electricity consumption of about 148,000 kWh (appr. 250 kWh/(m^2·a)), whereas setting the maximum indoor temperature to 28 °C meant that one chiller could feed the radiant panels and cover the residual sensible and latent cooling demand within the air handling unit. Ceiling fans for an acceptable comfort level were added in this option, which displayed a total annual energy consumption of about 85,000 kWh (appr. 140 kWh/(m^2·a)) [77]. Assuming a carbon emission factor of 0.634 kg CO_2-eq./kWh for electricity in Somalia [78], annual greenhouse gas emissions would amount to 93.8 and 53.9 tons of CO_2-eq. for the 26 and 28 °C indoor temperature option, respectively. This example makes obvious how quickly energy consumption and emissions rise due to increasing comfort demands.

3.5.3.2 Technology Maturity

Compression refrigeration machines for space cooling are a mature and internationally widely used technology.

3.5.3.3 Limitations

The main constraints in the application of compression refrigeration machines are vibration, noise pollution, heat emissions as well as space demand of the outdoor unit for air-cooled systems as well as the availability of heat sinks for systems not cooled by air. Also, the energy demand of compression refrigeration machines and especially air conditioners should not be underestimated and leads to considerable power demand and thus high grid load at times of high outdoor temperatures. Foresighted planning of resilient cooling systems should therefore look to implementing highly efficient cooling technologies with very little energy consumption.

3.5.3.4 Application and Climate

The compression refrigeration technology is a powerful cooling method providing thermal comfort at all temperature and humidity levels. It therefore may be applied in all climates and is suitable for new buildings as well as retrofit. For humid climates, cooling is often done in combination with dehumidification. Easy installation and low room demand are the main advantages of split systems; however, vibration, noise pollution as well as the contribution to urban heat islands make them increasingly unattractive in densely populated areas. In comparison to systems using thermal activation, their efficiency is also lower.

If water is used as a heat sink, the efficiency of the air conditioner increases; however, as water is not as readily available for cooling purposes as air, an evaporatively cooled system or a district cooling solution with centralised cold generation offer a sensible alternative.

3.5.4 Further Reading

Further information can be found in the following publications:

- Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- Basic Literature on Refrigeration Technologies: Dinçer, İ., Kanoğlu, M., (2010) Refrigeration Systems and Applications, 2nd edition. Chichester Wiley, 10.1002/9780470661093
- Information on types of geothermal heat exchangers for use with geothermal heat pumps: US Office of Energy Efficiency & Renewable Energy, Geothermal Heat Pumps, https://www.energy.gov/energysaver/geothermal-heat-pumps
- Section 3.4 Compression refrigeration, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Voluntary guidance for governments for improved energy-efficiency for air conditioners: United Nations Environment Programme - United for Efficiency Initiative, Model Regulation Guidelines September

2019. Energy-Efficient and Climate-Friendly Air Conditioners. https://united4efficiency.org/wp-content/uploads/2021/11/U4E_AC_Model-Regulation_EN_2021-11-08.pdf

– Publication on most ambitious efficiency requirements for air conditioners and five other emission intensive technologies for the ten of the highest emitting economies globally: Mavandad, S., Malinowski, M., (2023) World's Best MEPS: Assessing Top Energy Efficiency Standards for Priority Appliances, Washington: CLASP. https://www.clasp.ngo/research/all/worlds-best-meps/
– Report on the future cooling demand and its impacts on the energy system with recommendations for regulations on efficiency improvements of cooling equipment: IEA, (2018) The Future of Cooling. Opportunities for energy- efficient air conditioning. https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf
– IIR publications on new developments of refrigeration technologies and refrigerants available via FRIDOC: https://iifiir.org/en/fridoc.
– Website of certification association AHRI: https://www.ahrinet.org/.
– Website of United States EPA's Energy Star programme: https://www.energystar.gov/.
– Website of the European Union on the Energy label: https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign_en.
– Website of the European Heat Pump Association: https://www.ehpa.org/.
– Website of the United States Geothermal Exchange Organization: https://www.geoexchange.org/.

3.6 Adsorption Chiller

Gamze Gediz Ilis, Gebze Technical University, Turkey.

3.6.1 Description

Air conditioning systems are divided into thermally driven and mechanically driven air conditioning systems. An adsorption heat pump (AHP), a type of thermally driven heat pump, is an efficient system that can convert heat from a heat source such as solar, geothermal, or any waste heat application into cooling or heating without wasting electricity. Adsorption heat pumps have many advantages such as low operating costs, no vibration or noise, and environmental friendliness. Industrial adsorption heat pumps work for cooling purposes and can be called Adsorption Chillers.

Low-temperature thermal energy sources can be used for heating and cooling with adsorption heat pumps. It is possible to work with heat sources at temperatures as low as 50 °C. Since there are no moving components, the system is quiet, has a long service life, has low maintenance costs, and is also very easy to install due to its simple operating principle. The chiller is easy to install because it can be connected to the mains with simple water pipes and water pumps.

Compared to mechanical chillers, Adsorption Chillers offer several important advantages. They are not electrically driven like mechanical coolers, but rather rely on thermal energy for operation. As a result, electricity is only consumed for automatic control units, not the cooling system itself. This makes Adsorption Chillers more energy efficient than traditional mechanical systems, such as commercial Heating Ventilating Air Conditioning - HVAC systems. The obtained chilled water can be transported to the required location through commercial means, using water pumps commonly found in HVAC systems.

They have many advantages over Absorption Chillers, another system working with waste heat:

- Unlike Absorption chillers, Adsorption chillers do not use chemical materials that harm the environment as working fluids.
- While Absorption Chillers have a corroding structure and a lifespan of around 7 – 9 years, Adsorption Chillers can last up to 20 years.
- Absorption systems do not operate at temperatures below 80 °C, while Adsorption chillers continue functioning at temperatures as low as 50 °C.

By converting the hot water obtained from any heat source (geothermal, solar panel, etc.) into cooling energy, space cooling can be achieved with Adsorption chillers without consuming electricity. Moreover, Adsorption chillers can operate in any climate and condition. Their performance may vary with the temperature of the waste heat source, which should be around 80 – 90 °C for maximum performance. On the other hand, if they are located outside where the ambient temperature directly impacts them, their performance may decrease under extremely hot conditions.

An Adsorption chiller is basically a thermally driven heat pump. A basic Adsorption chiller consists of four main components: adsorbent beds, a condenser, an evaporator, and an expansion valve. Adsorption chillers are manufactured using high vacuum technology and operate under vacuum. Since the refrigerant (water) in the evaporator is under vacuum, it is evaporated at low temperatures and transferred to the adsorbent bed containing adsorbent (such as silica gel, zeolite, etc.) with the help of a valve. Then, hot water (50 - 90 °C) obtained from waste heat is introduced into the bed, the refrigerant fluid (water) in the adsorbent is evaporated thanks to the refrigerant (water) absorbed by the adsorbent and transferred to the condenser via the valve. The refrigerant passing through the expansion valve returns to the evaporator. In this way, the water in the evaporator is always kept at a low temperature, and the chilled water supply to the facility is provided with the help of a heat exchanger located inside the evaporator (Figure 12). Adsorption and desorption periods take place in the bed by waiting for a certain period of time. For this reason, as shown in Figure 12, commercial adsorption chillers generally have two adsorbent beds in order to avoid intermittent working conditions. When the first adsorbent bed works for the adsorption (evaporated refrigerant from the evaporator) and waits to complete the adsorption process, the second bed simultaneously works for desorption (condensed refrigerant to condenser). With the help of more than one bed, the system can generate chilled water continuously.

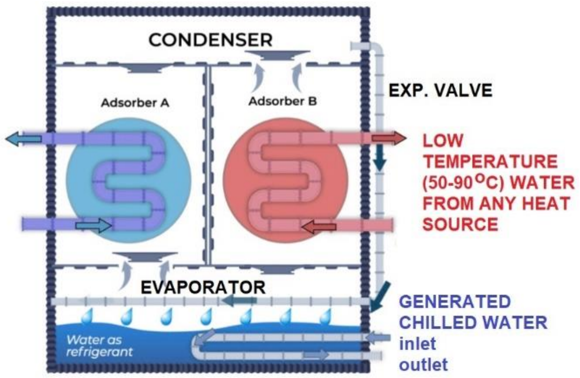

Figure 12: An Adsorption chiller and its working principle.

One of the major disadvantages of Adsorption chillers is their relatively low specific cooling and heating capacities (SCP/SHP) and coefficients of performance (COP) compared to mechanical chillers. However, it should be noted that the primary energy efficiency values of Adsorption chillers are comparable to those of conventional chillers. It would not be wrong to say that their performance is infinite thanks to the cooling energy obtained from the waste heat that is not yet used.

Adsorption chillers are environmentally friendly because they do not contain any environmentally hazardous materials and have no carbon footprint thus, as an example, a 400 kW cooling capacity Adsorption Chiller can save around 1.000 tone/year CO_2 emissions compared to the same cooling capacity using a conventional mechanical chiller (HVAC system).

3.6.2 Key Technical Properties

Adsorption chillers can be powered by sustainable heat sources such as geothermal, solar energy, and waste heat. They are environmentally friendly novel systems with high primary energy efficiencies. In addition to the traditional definitions of equipment efficiency and performance, primary energy efficiency is becoming very important. Since mechanical refrigeration systems work with electrical power, their primary energy efficiency is less than their coefficient of performance (COP). For example, the primary energy efficiency of conventional refrigeration cycles is around 90 - 100%, whereas the primary energy efficiency of thermally actuated heat pumps is around 130 - 180% [79].

Although the COP values of electric air conditioning systems are between 2 and 4, the theoretical COP values of Adsorption chillers vary between 0.5 and 0.9. The focus should be on obtaining cooling without electricity consumption, rather than the theoretical COP value, as it converts waste heat that is not used for any purpose into utility.

System Design Indicators

(Cooling) Coefficient of Performance (COP) [-]. The COP is the ratio of the net cooling capacity to the effective power input [80].

Specific Cooling Power (SCP) [W/kg]. SCP is the ratio of cooling power per mass of adsorbent per cycle time [80].

Specific Heating Power (SHP) [W/kg]. SHP is the ratio of heating power per mass of adsorbent per cycle time [81]**.**

3.6.3 Performance and Application

3.6.3.1 Performance and Working Conditions

Adsorption Chillers are systems used in the market, especially on an industrial scale. In general, an Adsorption chiller system with a cooling capacity of 400 – 500 kW is driven by hot water at a temperature of 90 - 100 °C and a flow rate of 60 – 70 m^3/h. Consequently, due to the need for large flow rates, these chillers have not yet been used for cooling buildings. As it is known, it is difficult to obtain mass flow rates of around 60 – 70 m^3/h in buildings from a hot water system unless there is an additional geothermal or alternative source that can provide such high flow rates. However, thanks to new innovative designs, Adsorption chillers with the same cooling load (400 – 500 kW) can be driven by hot water at lower flow rates, such as 4 – 5 m^3/h [82]. The hot water range can also drop down to 50 °C and despite a decrease in performance, the chiller can continue to operate even at such a low temperature. Therefore, with the development of Adsorption Chiller systems that can operate at variable low temperatures (50 - 90 °C) and flow rates (4 - 5 m^3/h), resilient building and ambient cooling becomes possible with low flow rates and temperature water that can be obtained from solar panels, photovoltaic-thermal (PV/T) panels [83] or any waste heat source.

3.6.3.2 Limitations and Climate

Adsorption heat pumps require high technology and special designs to maintain high vacuum. They have a large volume and weight compared to traditional mechanical heat pump systems. However, this criterion will cease to be a significant disadvantage in the near future due to new innovative designs. One of the important drawbacks of an adsorption heat pump is its high working flow rates, which are mentioned above and are around 60-70 m^3/h. As previously stated, the introduction of new designs has led to a reduction in flow rates, which now stand at 4-5 m^3/h, comparable to the mass flow rate of tap water. This significant reduction in flow has the potential to increase the utilisation of adsorption chillers, particularly in resilient buildings. Another limitation of adsorption chillers is that their performance is negatively affected by high ambient temperatures, as is the case with all air conditioning systems. Consequently, its operation is almost entirely halted at temperatures exceeding 40 °C. In such instances, it can continue to function with the assistance of a cooling tower; however, this inevitably impairs its performance, potentially leading to a decline in efficiency or even a complete cessation of operation.

3.6.3.3 Resilience

Adsorption chillers display a high adaptive capacity in the face of heat waves, meaning that during times of particularly high outdoor temperatures, the system can actively meet the increased cooling demand. This comes with the price of higher electricity demand. After a heat wave, adsorption chillers are capable of quickly reinstating the desired indoor temperature.

Although absorption refrigeration systems are partially activated by thermal energy, they are not robust during power outage events due to the inability of the chilled and cooling water distribution system to operate without power input. As with compression refrigeration, the system could integrate with local electricity production and energy storage to enhance its resilience during power outages.

3.6.3.4 Space Cooling by Adsorption Chillers

When building air conditioning technologies are considered, especially in the field of cooling, apart from simple dehumidification units, the demand for cooling in buildings that are exposed to high outdoor temperatures is met by conventional electrically driven commercial chillers (HVAC systems). In this case, almost all the energy used in buildings, especially in summer, is used for cooling. At this point, Adsorption chillers can be used to reduce or even eliminate the electricity consumed by buildings for cooling. However, since commercially available Adsorption chillers work with high flow rates and high temperature waste heat, adsorption systems are not yet applicable to building cooling. However, with the ability of the new innovative Adsorption chillers that operate at low temperatures and flow rates, it has become possible to operate with hot water that can be obtained from solar panels, PV panels, PV/T panels, and existing boilers. In short, since the cooling capacity of the Adsorption chillers will increase with the increase in the amount of waste heat that can be given to the Adsorption chillers, especially in cases of high insolation and high heat waves, the cooling load has become more possible. In this context, the figure below summarizes how Adsorption chillers can be applied to buildings. The utilisation of geothermal energy for instance, allows for the generation of cooling via adsorption chillers and a fan coil system, with the latter enabling cooling to be distributed across multiple spaces via a resilience strategy.

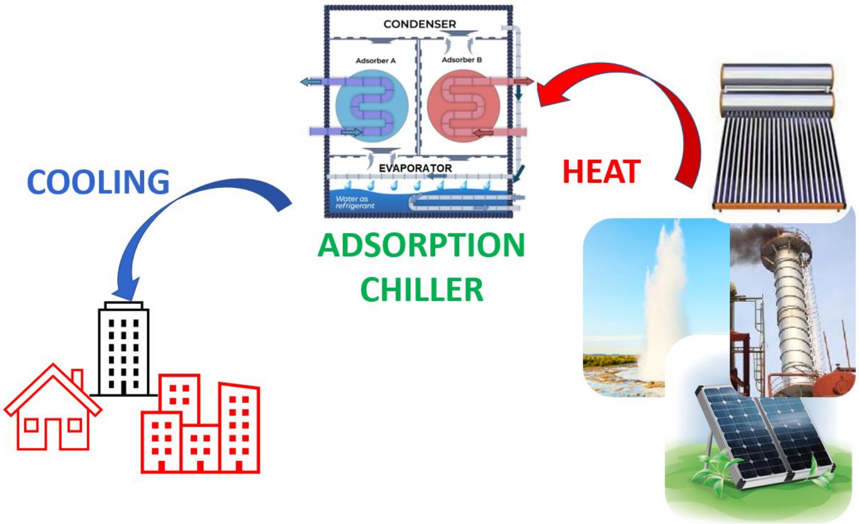

Figure 13: Application Example of an Adsorption Chiller to Buildings.

3.6.3.5 Cooling PV Panels by Adsorption Chillers

Another use of Adsorption chillers is to increase the performance of PV panels. As it is known, PV panels convert the heat they receive from the sun into electrical energy. In addition to these, PV/T panels are systems that can produce both electricity and hot water concurrently. The electricity generation performance of PV panels decreases in areas with high insolation due to high irradiation. Therefore, another way to increase the electricity generation capacity of PV panels is to cool down the panels. In this case, the cold water produced by the existing electrically operated cooling units is used to reduce the surface temperature of the PV panels. Some of the electrical energy produced by PV panels is currently used in HVAC systems to produce cold water and lower surface temperatures. However, Adsorption chillers, which can produce cold water without using electricity, can be used instead of existing HVAC systems. In order to achieve a low PV surface temperature to improve the performance of the electricity generation of the PV panels, the waste heat obtained from the system (i.e., solar panels, geothermal, waste heat of boiler systems, etc.) can be used directly in the cycle of the Adsorption chiller. Without electricity, chilled water can be obtained by using the Adsorption chiller, thus the generated chilled water can be used to cool down the surface temperature of the PV panels as illustrated in Figure 14.

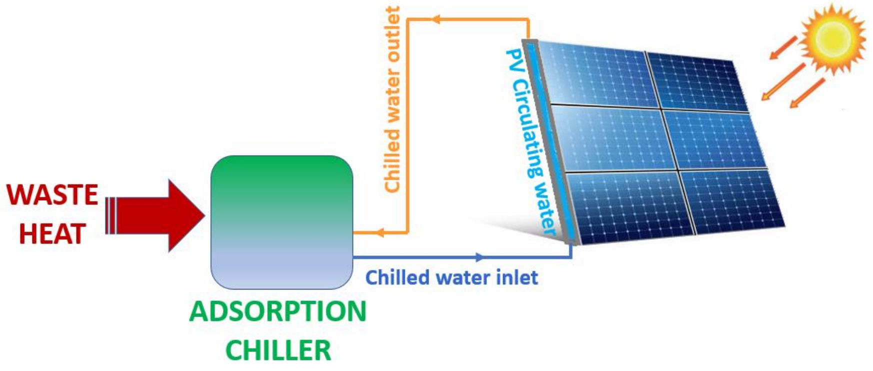

Figure 14: Example of An Adsorption Chiller used to cool down the PV panel surface temperature.

3.6.3.6 Cooling PV/T Panels by its Generated Hot Water and Adsorption Chillers

A subject like the cooling of PV panels mentioned in the chapter above title will also be discussed in this title. In this title, unlike the PV panels mentioned above, PV/T panels that can produce their hot water as well as electricity, will be discussed. For both, industrial and building applications, instead of using only PV panels for electricity generation, PV/T panels may be preferred. It is well known that PV/T panels generate both electricity and hot water. The generated hot water can also be used for cooling by passing it through Adsorption chillers and to improve the electricity production of the PV/T panels [83]. In current applications, vapor compression cycles (VCC) working with electricity are used to cool down the PV surface temperature, . Instead of wasting the electricity produced by PV panels to cool their surface temperature by using VCC systems, cooling can be achieved by using the hot water produced by PV/T panels in an Adsorption chiller. The schematic explanation of the Adsorption chiller-assisted PV/T panel cooling is shown in Figure 15. Based on this study, the PV/T + Adsorption Chiller achieves more cooling power than the PV+VCC system on typical and peak days. With the highest power demands (i.e., on the busiest days), PV/T + Adsorption Chiller provide the highest electrical efficiency and help to reduce the risk of power outages. In addition, the generated cooling energy can be used elsewhere instead of enhancing the PV panel electricity production.

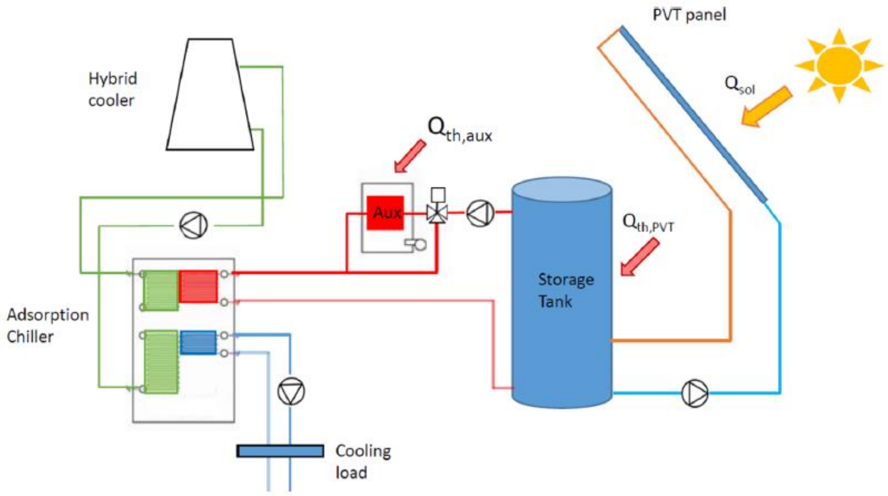

Figure 15: Using the generated hot water of PV/T panels by Adsorption Chillers [83].

In conclusion, the use of Adsorption chillers will increase in both industrial and building cooling applications with the help of the new improved innovative Adsorption chiller designs. With the new innovative Adsorption chiller designs working with low flow rates and low waste heat temperatures [84], the application areas will be expanded and thus will be promising systems for the cooling of buildings.

3.6.4 Further Reading

Further information can be found in the following publications:

- R.Wang, L. Wang, J.i Wu, (2014) Adsorption Refrigeration Technology: Theory and Application, John Wiley & Sons, Singapore. Print ISBN:9781118197431 |Online ISBN:9781118197448 |DOI:10.1002/9781118197448

3.7 Natural Heat Sinks

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3.7.1 Description

Heat sinks are media that can be used to directly absorb unwanted heat discharge from buildings. The night sky, ambient air, ground, groundwater, and surface water bodies such as oceans and lakes are natural heat sinks. The night sky can be used as a heat sink via sky radiative cooling, and the ambient air via ventilative cooling or air-cooled compression refrigeration machines; see the respective chapters: 3.1 Ventilative Cooling, 3.4 Sky Radiative Cooling, and 3.5 Compression Refrigeration for further information. Cooling systems using natural heat sinks can be operated as free cooling systems using only pumps or fans to circulate the cooling medium, or alternatively using refrigeration machines to amplify the natural heat sink's cooling effect.

The functioning principle of natural heat sinks is based on the temperature gradient between the heat transport medium and the heat sink, therefore allowing a heat flow from the heated indoor air or cooling medium to the cool heat sink. Natural heat sinks are capable of reducing the indoor temperature significantly and can either partially or entirely meet a building's cooling demand, depending on the dimensioning of the heat release component and the climate region. There are several ways to access natural heat sinks:

Earth brine heat exchangers. These are horizontally or vertically installed heat exchangers that release heat to the surrounding soil. Horizontal closed-loop piping systems are laid in the shape of straight pipes, labyrinths, or loops (Figure 16) close to the earth's surface and act as a heat exchanger between the ground and the hydraulic system of the building. They are installed in unsealed areas and require sufficient space without any large trees or shrubs to avoid pipe damage from roots. For vertical or so-called borehole heat exchangers, the heat transfer from the hydraulic system to the ground takes place via vertically laid pipes within 20 – 150 m deep boreholes. Space demand is lower, but installation costs are higher. Most commonly, earth brine heat exchangers are installed to be combined with brine/water heat pumps for heating and cooling, but can also be operated in free cooling mode without a heat pump.

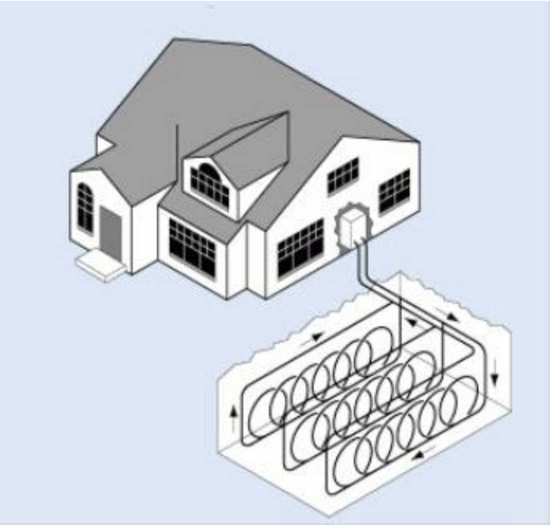

Figure 16: Horizontal closed-loop earth brine heat exchanger in a loop shape coupled with a refrigeration machine [85] (modified).

Earth air heat exchangers/earth tubes/earth tunnel cooling. These systems consist of pipes that are usually laid horizontally into the ground at a depth of approximately 3 m, where the soil displays a constant temperature close to the average annual ambient temperature of the region. Indoor or outdoor air is fanned through the pipes and thus cooled, and subsequently supplied to the building as either fresh cooled air or cooled-down recirculated air for ventilation. In comparison to systems using water or other liquid heat transport media, earth air heat exchangers require higher volume flow rates or larger surface areas to achieve the same cooling capacity. As for ground labyrinths, earth air heat exchangers should not be installed in areas with high vegetation to prevent damage from roots.

Groundwater. Groundwater can be used as a heat sink via direct open-loop systems, where the groundwater is supplied directly to the building hydraulics and discharged back into the aquifer after use. For aquifers with low groundwater productivity, closed-loop systems that do not withdraw any water from the groundwater source act as heat exchangers directly within the aquifer. Alternatively, standing column systems only cause fresh water to flow into the well reservoir at times of high cooling loads, when the return water from the cooling system is discharged outside the well.

Deep ocean/lake cooling. The minimum water temperature at the bottom of a surface water body is as low as 2 °C for the ocean and 4 °C for freshwater lakes. These systems can be designed as open- or closed-loop systems, where the water is either directly drawn from the aquifer and used for cooling and then recirculated to the ocean or pond, or an intermediate heat transport circuit is used. As ocean water leads to scaling, there usually is a closed-loop installation with a heat exchanger transferring the cold to an intermediate hydraulic circuit to prevent premature material wear. As for groundwater, the limitation of deep lake cooling is the aquifer’s rate of water gains.

Roof ponds. Here, the water in the roof pond has multiple functions: on hot and sunny days, part of the radiation hitting the roof is reflected by the water surface, part is absorbed and thus leads to heating of the water, and part is discharged via evaporation. During the night, the warm water radiates heat back to the sky to cool off. It therefore acts as a buffer between the outdoor and indoor climate, reducing the amplitude of the indoor temperature. A covered and ventilated roof pond, or a roof pond equipped with a water-to-air heat exchanger can be used to cool the ventilated air which is further used for domestic ventilation and cooling.

Depending on the temperature and type of the heat sink, the heat uptake from the building may take place via air or water as a transport medium. Cooled air is often directly used for ventilation, while cooled water may be used in chillers, thermal activation, or air handling units for cooling purposes, depending on the water temperature. Due to its higher thermal conductivity and capacity, water is a particularly effective medium for heat uptake and removal.

The use of natural heat sinks results in little or no acoustic and aesthetic disturbance and does not contribute to unwanted heat discharges in the urban environment.

3.7.2 Key Technical Properties

3.7.2.1 Earth-Coupled Heat Exchangers

System Design Indicators

Thermal conductivity of the heat sink [W/(m·K)]. This value indicates the quality of the heat sink's ability to absorb heat, with a higher value indicating quicker absorption of discarded heat. Soil thermal conductivity values typically fluctuate between approximately 0.1 and 3 W/(m K) depending on the soil type [86].
The **specific [W/m]** and **installed [kW] cooling capacity** are determined via a thermal response test [87], [88], [89]. For example, the specific cooling capacity per metre of borehole length can range from 22 – 63 W for areas in Cyprus, Germany and Japan [90]. For horizontal earth brine heat exchangers, the specific cooling capacity per metre of pipe length ranges from about 17 to 35 W [91].
Maximum allowed return temperature [°C] of the cooling medium. This is subject to legislation to ensure the ecological integrity as well as chemical stability of the used heat sink.
Earth air heat exchangers in moderate climates display a specific peak cooling capacity of about 45 W per m^2 of ground coupling area at an outdoor temperature of 32 °C [92].
Nominal power of auxiliary equipment [kW]. This gives the electricity consumption of the cooling system supplied by a natural heat sink.

The cooling power of ground source heat exchangers is thus determined by the soil temperature, specific heat capacity and conductivity, as well as the pipe diameter and length, heat transfer medium velocity and, for open-loop earth air heat exchangers, air inlet temperature. To increase the cooling capacity, the area of the heat exchanger can be shaded, wetted or painted in a light colour to decrease the soil temperature.

3.7.2.2 Water-Coupled Heat Exchangers

System Design Indicators

Water-coupled closed-loop heat exchangers provide a cooling capacity of between 35 and 117 **W per metre of pipe** length [91].
For open-loop systems, another important parameter is the **water productivity of the aquifer [m^3/day],** as well as regulations concerning the **maximum allowed water withdrawal rate [m^3/day].** For example, an open-loop cooling system in London using groundwater at a temperature of 14 °C and a withdrawal rate of 8.3 l/s (704 m^3/day) provides a cooling capacity of 279 kW [93], [94].
Maximum allowed return temperature [°C] of the cooling medium.
Nominal power of auxiliary equipment [kW].

For groundwater, the local climate, along with the soil and aquifer properties that determine the volume and temperature of the groundwater, and the groundwater reproduction rate, determine the cooling capacity of the heat sink. Using shallow groundwater aquifers is cheaper, but result in lower efficiency due to higher temperature fluctuations in the groundwater body.

To avoid efficiency losses due to short circuit flows in open-loop systems using water bodies, the withdrawal and discharge points should be situated sufficiently distant from one another.

3.7.2.3 Roof Ponds

System Design Indicators

The cooling capacity of a roof pond depends on the **water depth [m]** on the one hand, and the **thickness [m], thermal conductivity [W/(m K)], solar absorptivity [-]** as well as **reflectivity [-]** and **emissivity [-] of the roof surface** and any roof pond coverings on the other. For example, the diurnal heat gains passing through a roof pond in La Rochelle, France during the day (maximum air temperature 27.6 °C and maximum solar irradiation 511.5 W/m^2) slightly exceed the heat losses released through it during the night with a surplus of 0,01 kWh/(m^2·day). In comparison, a bare bitumen roof shows a heat surplus of 0.323 kWh/(m^2·day) and a 'cool roof' setup (cool paint coating with a thermal emissivity of 0.92 and solar absorptivity of 0.07) shows a net heat loss of 0.211 kWh/(m^2·day) [95]. Various studies have shown that roof ponds can reduce the indoor temperature by several degrees centigrade depending on the climatic conditions and roof pond configuration. For instance, an open roof pond in South Africa can reduce peak indoor temperatures from 34 °C to 28 °C [96].
Nominal power of auxiliary equipment [kW] (e.g., for water pumps or in the case of using water air heat exchangers for indoor air cooling).

Roof ponds are particularly effective in hot and arid climates, but do not perform as well in humid climates as the evaporative heat discharge contributes significantly to the cooling effect.

3.7.2.4 Further General Information

Thermal coupling of the heat sink with the building should be done as efficiently as possible, with short distances between the heat sink and the building, and appropriate heat uptake components within the building. This becomes particularly important when the cooling medium's temperature is relatively close to the indoor temperature, making radiant systems such as thermal activation more appropriate than convective systems such as fan coil units.

Compared to cooling technologies using refrigeration machines, natural heat sink systems are very efficient because only auxiliary pumps or fans are required to operate in free cooling mode. The higher installation costs of natural heat sink systems compared to air-cooled conditioning systems are offset by their greater independence from outside air temperature as well as lower energy demand.

The efficiency of a cooling system using natural heat sinks can be increased by using the heat transport medium in cascade; e.g., after domestic cooling, for industrial cooling processes, desalination plants or drinking water production.

If a refrigeration machine is used to increase the cooling power of the heat sink, the efficiency of the machine will be higher at lower heat sink temperatures.

3.7.3 Performance and Application

3.7.3.1 Resilience

Natural heat sinks are resilient to heat waves. Due to their large volume, natural heat sinks are practically inert to outdoor air temperature fluctuations and thus maintain their cooling capacity during heat waves. Cooling systems designed for free cooling are large in scale and therefore display a considerable absorptive capacity. Additionally, the heat transfer rate increases for higher cooling transport medium temperatures, meaning that during times of high heat load, heat rejection to the heat sink is more efficient. After a heat wave, the temperature of the heat sink in the area of the heat exchangers or discharge points recovers within a few days. Roof ponds are self-regulating during heat waves, as increased irradiation and temperature also increase evaporation. A sufficient water supply is a prerequisite to guarantee resilience during a heat wave. After a heat wave, roof ponds also display moderate to high recovery speeds of a few days. Natural heat sinks may also be used to feed thermal storage systems at times of normal operation to increase resilience against heat waves.

As cooling systems using natural heat sinks require electricity for auxiliary components (e.g., pumps), their cooling potential would not be available during times of power outage. The resilience of the cooling system can be increased through the local use of renewable energy sources such as photovoltaics (PV) and/or battery storage. For roof ponds, a power outage would not compromise the cooling effect as long as sufficient water is in the basin, but regular automated water refill systems would fail. The restorative capacity of natural heat sinks after a power cut, however, is moderate to high, as the excess heat dissipates within a few days.

A simulation study of a borehole heat exchanger in Sweden with a depth of 200 m, installed in soil with a thermal conductivity of 2.88 W/(m K) and an undisturbed ground temperature of 8.3 °C, found that the borehole fluid outlet temperature during the cooling period from 14 May to 22 September 2018 fluctuated between 8.6 and 11.9 °C at a mass rate of 1.5 kg/s. The borehole heat exchanger was used to supply active chilled beams in a south-facing office building under two different operating modes: 1. Intermittent operation aimed at keeping the indoor temperature constant during occupied hours. 2. Continuous operation around the clock allowed for larger room temperature fluctuation while making use of the building's thermal mass in order to reduce electricity demand during peak-load periods as well as the size of the cooling system. Operating the described cooling system in the continuous operation mode resulted in borehole outlet temperatures between 8.6 and 11.1 °C compared to the fluid temperatures mentioned before, which refer to the intermittent operation mode. Room temperatures ranged between 22.9 and 23.5 °C (intermittent) or 22.3 and 25.1 °C (continuous). The electricity consumption of the pumps and fans amounted to approximately 520 and 760 kWh for the intermittent and continuous modes, respectively, but the continuous option would allow for a shorter borehole and reduce the peak ground load by 28% [97].

Another simulation study for the southern Algerian climate showed that an earth air heat exchanger can keep the temperature of the air passing through it below 30 °C during a day with outdoor temperatures between 27 and 44 °C. The length and diameter of the heat exchanger pipe were 50 m and 30 cm, respectively. The soil temperature and thermal conductivity were 22.27 °C and 0.52 W/(m K) and the air flow velocity within the heat exchanger amounted to 2 m/s [98].

3.7.3.2 Technology Maturity

All natural heat sink cooling technologies in this profile are highly advanced, except for deep ocean cooling and roof ponds, which still require further research and testing. In particular, earth brine heat exchangers, earth air heat exchangers and groundwater have been used successfully for several decades in various climatic conditions.

3.7.3.3 Limitations

One major limitation for the use of natural heat sinks is their availability. Soil is only relatively easily available in at least moderately built-up areas, and ground and surface water bodies are not evenly distributed in all regions. Earth labyrinths and earth air heat exchangers require sufficient open space; geothermal probes require favourable geological conditions; and groundwater, and deep lake cooling are limited by the water renewal rate of the aquifer. Local water regulations limit the use of surface and groundwater and may require project approval procedures. For surface water bodies, the temperature of the discharged water should not be more than 5 - 7 °C higher than that of the water in the vicinity of the discharge point to avoid ecological damage.

Another limitation is the temperature of the available heat sink. Temperatures must be low enough to allow a heat flow from the heat transport medium to the heat sink. Furthermore, heat sinks with lower temperatures are easier to cool because the area of the heat exchangers used can be smaller and the building's cooling load can be met more easily for various outdoor conditions.

For geothermal heat sinks in cooling dominated climates, the permanent discharge of heat into the soil leads to a continuous increase in soil temperature, which in turn decreases the cooling effect of the soil. In order for the cooling potential to remain constant, adequate dimensioning of the heat exchanger and the application of appropriate cooling regimes allow the regeneration of the heat sink. If amply available, rain water may be used to cool the ground down. Excess heat loads from earth air heat exchangers can be met by additional rejection systems such as cooling towers or sky radiative cooling appliances.

If ocean water is fed directly into the building's cooling system, its scaling effect will strain the building's hydraulics, which can lead to rapid material wear. This can be avoided by using a heat exchanger and an additional hydraulic circuit to distribute the cold throughout the building.

In the case of direct use of air from an earth air heat exchanger, hygienic standards concerning the necessary air quality for ventilation are to be maintained.

Roof ponds are more effective the greater the covered roof surface is in relation to the building's wall area, making this system less eligible for multi-storey buildings. The construction of roof ponds is limited by the load-bearing capacity of the building structure and requires diligent installation of water barriers to avoid static and hygienic complications.

3.7.3.4 Application as a Retrofit Measure and in Various Climatic Conditions

For existing buildings, the use of natural heat sinks can easily be incorporated during the planning process. For existing buildings, however, the major impediment is the significant space demand for many of the natural heat sink installations. They are compatible with other cooling technologies, but may prove problematic if the required space is scarce and eligible for other uses such as roof ponds and photovoltaics.

Earth labyrinths, borehole heat exchangers and earth air heat exchangers are applicable in all climate zones. Earth air heat exchangers are best for regions with strong annual fluctuations in hot and cold temperatures. Roof ponds perform best in hot and dry climates, as most heat is released via evaporation; however, water scarcity issues should be taken into account. If sufficiently available and accessible, groundwater and surface water provide particularly efficient heat removal capacities in all climate zones.

3.7.4 Further Reading

Further information can be found in the following publications:

- Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- Information on types of geothermal heat exchangers for use with geothermal heat pumps: US Office of Energy Efficiency & Renewable Energy, *Geothermal Heat Pumps*, https://www.energy.gov/energysaver/geothermal-heat-pumps
- Sections 3.2 Ventilative cooling, 3.6 Ground source cooling, 3.7 Night sky radiative cooling in International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Sections on earth as a heat sink and water as a heat sink in: Samuel, D. G. L., Nagendra, S. M. S., Maiya, M. P., (2013) Passive Alternatives to Mechanical Air Conditioning of Building: A review, Building and Environment, 66, pp. 54–64. https://doi.org/10.1016/j.buildenv.2013.04.016

3.8 Radiant Cooling

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3.8.1 Description

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 [99], [100]. Heat transfer from indoor spaces is achieved by a combination of radiation and convection via cooled surfaces. These systems employ the high temperature cooling principle, where the temperature of the heat-transfer medium is close to the room temperature. The system conditions large indoor surfaces, usually floors, ceilings, and walls. These large, conditioned surface areas make it possible to heat or cool indoor spaces with a small temperature difference between the conditioned surfaces and the room.

Radiant cooling systems can be classified into radiant cooling panels, radiant surface systems, and thermally active building systems (TABS) [99]. Figure 17 and Figure 18 show the different types of radiant heating and cooling systems. To bring the benefits of TABS to refurbishment projects and to lightweight buildings, a new type of radiant ceiling panel has emerged. This technology combines Phase Change Materials (PCM) with radiant ceiling panels to create a system similar to TABS—i.e., PCM radiant ceiling panels. Pipes are embedded in the PCM. Water is circulated through the pipes to control the charging (melting) and discharging (freezing) behaviour of the 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 the resulting thermal indoor environment [101], [102], [103], [104], [105].

Figure 17: Example of a cooling panel.

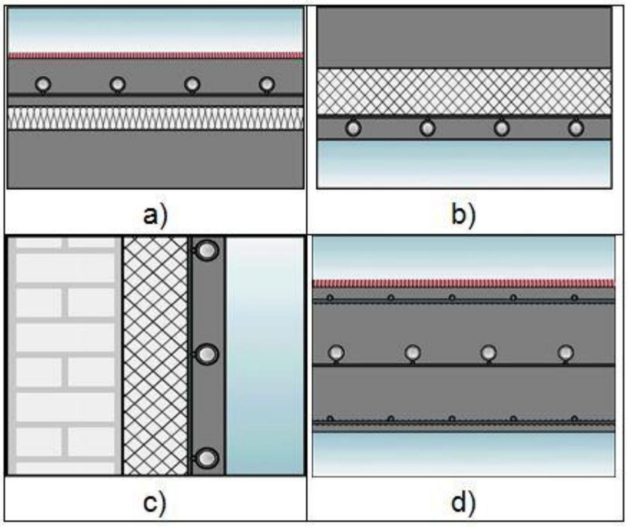

Figure 18: Cross sections of embedded radiant systems: (a) Floor, (b) Ceiling, (c) Wall, and (d) TABS.

3.8.2 Key Technical Properties

The following indicators can be used to assess the performance of radiant cooling systems [106]:

Heat Transfer coefficient [W/m²·K]. Combined convective and radiative heat transfer coefficient between the heated or cooled surface and the space (operative temperature of the space to be used).

Design heating and cooling capacity [W/m²]. Thermal output at design conditions.

Heating and cooling power [W/m²]. Heat exchange between a pipe circuit and the conditioned room.

Heating (cooling) surface area [m]. Area of surface (floor, wall, ceiling) covered by the embedded surface heating system between the pipes at the outer edges of the system.

Supply water temperatures in radiant systems are usually 16 – 23 °C for cooling. When using TABS, the average of the supply and return water temperatures will normally be 19 – 24 °C for heating and cooling, as normally a very narrow temperature range is sufficient for both heating and cooling purposes. Some TAB systems operate with constant average water temperatures throughout the year [107].

Usually, a total heat transfer coefficient is used to quickly determine the heating and cooling capacity of a radiant system, depending on the mode of operation (heating or cooling) and the conditioned surface (floor, ceiling, or wall). Total heat transfer coefficients (combined convection and radiation) are 11, 8, and 6 W/m² K for floor heating, wall heating, and ceiling heating, and are 7, 8, and 11 W/m² K for floor cooling, wall cooling, and ceiling cooling, respectively [99] under design (dimensioning) conditions, when the temperature difference between the radiant surface and the room temperature is maximum. Based on the acceptable surface temperatures (which are determined by local thermal discomfort limitations and to avoid condensation on surfaces) and assuming a room (operative) temperature of 20 °C for heating and 26 °C for cooling under design conditions, the maximum heating and cooling capacities can be estimated.

The maximum heating and cooling capacities are 99 W/m² and 42 W/m², respectively, at the floor of the occupied zone; 160 W/m² and 72 W/m² at the wall; and 42 W/m² and 99 W/m² at the ceiling. At the floor of perimeter zones, it is possible to obtain a maximum heating capacity of 165 W/m² [99] and the cooling capacity could also increase remarkably depending on the boundary conditions such as direct solar radiation on the floor.

3.8.3 Performance and Application

3.8.3.1 Building Performance

Radiant heating and cooling systems have the following advantages compared to more conventional (e.g., all-air) heating and cooling systems [100]:

- Use of low temperature heating and high temperature cooling.
- Ability to couple to natural heat sources and sinks, such as ground, lake water, or seawater.
- 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.
- Possibility of transferring peak heating and cooling loads to off-peak hours, reducing peak power demand.
- Smaller-capacity heating and cooling plants, and smaller-capacity ventilation systems (i.e., air-handling unit capacity, duct size).
- Reduced annual energy use of heating and cooling systems, including auxiliary components such as pumps and fans.
- Lower heat losses and gains during distribution from the heating or cooling plant to indoor spaces.
- Flexibility in the use and design of indoor spaces due to the lack of indoor terminal units in occupied zones, no cleaning requirements, and quiet operation.
- Uniform temperature distribution in indoor spaces, reduced risk of draft, and reduced vertical air temperature differences.
- Reduced construction costs due to (a) reduced space requirements (e.g., smaller shafts, smaller equipment rooms), (b) lowered construction heights for each floor due to reduced plenum heights (mainly due to reduced duct sizes), and (c) saved building materials.
- Possible initial and operational (such as maintenance and energy) cost savings.
- Resilience to heatwaves and power outages.

Radiant panel systems and radiant surface systems can be used in both new buildings and renovated buildings. One of the major characteristics of radiant systems is that they address only sensible loads. Therefore, they need to be coupled with ventilation systems, usually in the form of a dedicated outdoor air system (DOAS). The main function of ventilation systems is to regulate humidity (i.e., to dehumidify the air) and to provide fresh air to indoor spaces.

3.8.3.2 Resilience

Radiant systems have similar characteristics under heatwaves and power outages. The absorptive and adaptive capacities of radiant systems under heatwaves and power outages range from low to high - low for radiant ceiling panels, high for TABS, and in between those two systems for the radiant surface systems. This is because these systems have different thermal mass and 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 heatwave, the pre-cooled thermal mass will be able to absorb a certain amount of heat from the space. Without a cold source, the effect of cooling will diminish or come to a halt after a prolonged heat wave or power outage, just like any other system. The restorative and recovery capacities of radiant systems under heatwaves and power outages are high. This is because all system types can return to normal or improved operation once the heatwave is over or power is restored, and this can be done immediately [6], [108].

3.8.3.3 Limitations

Condensation should be avoided when using radiant cooling systems. For this, the supply water temperature should be kept higher than the zone dew-point temperature or dehumidification strategies should be employed [109]. Therefore, radiant cooling applications in humid climate zones require careful design and operation considerations. Studies have shown that when properly designed, controlled, and coupled with an appropriate ventilation system, radiant cooling systems can safely be applied in hot-humid climate zones without problems [110], [111], [112], [113].

TABS can only be installed during the construction of a building. This limits the use of TABS in refurbishment projects, however radiant ceilings with PCM panels have been shown to bring similar benefits to TABS [101], [102], [103], [104], [105].

3.8.3.4 Applications and Climate Conditions

Radiant cooling systems can be classified into radiant cooling panels, radiant surface systems, and thermally active building systems (TABS). Radiant heating and cooling systems can be applied in almost all climates and building types (offices, residential buildings, workshops, laboratories, food storage cellars, meeting rooms, schools, museums, airports, sports halls, and hangars).

3.8.3.5 Availability

Radiant cooling panels, radiant surface systems, and thermally active building systems (TABS) are market available. PCM radiant ceiling panels are still under development.

3.8.4 Further Reading

Further information can be found in the following publications:

- J. Babiak, B. W. Olesen, D. Petras, (2009) Low temperature heating and high temperature cooling, Brussels: REHVA - Federation of European Heating, Ventilation and Air Conditioning Associations, [Online] Available: https://www.rehva.eu/eshop/detail/no07-low-temperature-heating-and-high-temperature-cooling
- Section 3.8, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Section 4.2.7 in Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- K. Rhee, B. W. Olesen, K. Kwang Woo, (2017) Ten questions about radiant heating and cooling systems, Building and Environment, 112, pp. 367-381, doi.org/10.1016/j.buildenv.2016.11.030.
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4. Increasing Personal Comfort Apart from Space Cooling

This chapter presents resilient cooling technologies which increase personal comfort apart from space cooling. It addresses:

- Comfort Ventilation and Elevated Air Movement
- Micro-cooling and Personal Comfort Control

4.1 Comfort Ventilation and Elevated Air Movement

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4.1.1 Description

Comfort ventilation, or ventilation with elevated air movement, refers to the deliberate control and circulation of indoor or outdoor air within indoor spaces to enhance thermal comfort and simultaneously improve air quality for occupants, like most resilient ventilation solutions and concepts. This technological concept is divided into two main categories: increasing air circulation through openings and active systems. A constant flow of air is necessary.

The human body continuously loses heat to the environment in order to maintain thermal equilibrium. The nervous system's configuration causes thermal sensors in the skin to have varying degrees of sensitivity to heat and cold across the body's surface. By evaporating moisture from the surface of the skin, air passing over the epidermis has a physiologically cooling effect (convective heat transfer). In warm and neutral environments, cooling the head and upper body is very beneficial.

Variations in gender, age, body mass, clothing habits, metabolic rate, and thermal adaptation affect these comfort requirements. This technology increases the range of temperatures that are usually considered comfortable, thereby decreases the amount of energy used by mechanical air conditioning. The lower the incoming air temperature, the more effective comfort ventilation will be (see ventilative cooling technological profile). In addition, elevated air movement systems aim to create a gentle and unobtrusive breeze, replicating the natural airflow experienced outdoors (connection with the outdoors). Elevated air movement also helps to reduce the stratification of air within a space (mixing).

Local winds are rarely enough to generate the requisite indoor air velocities in most climates, complete passive comfort ventilation is unlikely. In most cases, wall-mounted, ceiling, or window (or else) fans are required to augment the wind. An electric device that employs a hub to rotate blades is a fan. Fans serve three very different purposes. The first is to exhaust hot, humid, and polluted air. The second involves bringing in outside air to either ventilate for comfort or cool down a structure at night. When interior air is cooler than outdoor air, the third purpose is to move the air throughout the room. When indoor air is cooler and/or less humid than outdoor air, ceiling or table fans should be utilized, and windows should be closed. The ceiling fans can be turned on in reverse in the winter to direct warm air downward (an anti-stratification technique). This technological profile describes automated fans that are controlled centrally or cooperatively. Types of fans include energy star fans, standard fans, low profile fans, dual motor fans, wet and damp fans, DC fans, remote controlled fans, commercial fans, outdoor-coastal fans, fans with other systems (i.e., lights), reverse mode fans, and industrial-agricultural fans.

4.1.2 Key Technical Properties

Below is a list of key technical properties that are relevant when designing or purchasing the described resilient cooling technology:

Cooling effect of moving air [°C/°F]. Air passing has a physiological cooling effect (convective heat transfer) by evaporating moisture from the skin's surface. Under summer comfort conditions, with indoor operative temperatures over 25 °C, artificially increased air velocity can be used to compensate for increased air temperatures according to Table 7. Low-velocity air movement, typically less than 0.3 m/s, guarantees the avoidance of drafts and discomfort (air speed over 0.8 m/s moves normal office paper from a desk). ISO and ASHRAE organizations also provide reference numbers very similar to those presented here. Table 8 shows the number of degrees that the temperature would have to drop to create the same cooling effect as the given air velocity.

Table 7: Indoor operative temperature correction ($\Delta\Theta_o$) applicable for buildings equipped with fans providing building occupants with personal control over air speed at occupant level [114]:

Average Air Speed (Va) 0.6 m/s	Average Air Speed (Va) 0.9 m/s	Average Air Speed (Va) 1.2 m/s
1.2°C	1.8°C	2.2°C

Table 8: Air velocity and thermal comfort [115]:

Air velocity (m/s)	Equivalent temperature reduction (°C)	Effect on comfort
0.05	0.0	Stagnant air, slightly uncomfortable
0.20	1.1	Barely noticeable but comfortable
0.25	1.3	Design velocity, for air outlets that are near occupants
0.40	1.9	Noticeable and comfortable
0.80	2.8	Very noticeable but acceptable in certain high-activity areas if air is warm
1.00	3.3	Upper limit for air conditioned spaces. Good air velocity for natural ventilation in hot and dry climates
2.00	3.9	Good air velocity for natural ventilation in hot and humid climates
4.00	5.0	Considered a gentle breeze when felt outdoors

Corrective Power [°C/°F or K]. It is the ability of a system, expressed in degrees, to “correct” thermal conditions toward the comfort zone, measured as the difference between two temperatures at which equal thermal sensation is achieved - one temperature in the comfort zone with no system, and one with the system in use, with all other environmental factors held constant.

Physical cooling capacity of ventilation. Considerable amounts of heat can be removed from rooms with high air flow rates when the outdoor air is colder than the indoor air (especially at night; see ventilative cooling technological profile).

Raising the air conditioning cooling setpoint or potential to eliminate the need for AC [°C/°F]. Energy waste is intensified by narrow temperature set points. Efficient fans are used to elevate the air conditioning temperature setpoint in buildings. Elevating the cooling setpoint from a typical 23 °C (73 °F) to 26 °C (79 °F) saves approximately 30% of the cooling energy without increasing the discomfort percentage (see micro-cooling and personal comfort control technological profile). Fans consume negligible power compared to HVAC energy use. An extra benefit is the decrease in energy consumption during peak energy demand periods. There is a possibility of reduced-size cooling systems or a system that runs part-time during periods beneficial to the electricity grid and supply sources. It is also possible that the cooling system will not be required, which would result in a significant reduction in the cost (installation and maintenance).

Energy-savings metric [%]. HVAC energy required with fans, divided by HVAC energy without fans, expressed as a percentage (%).

Corrective power energy efficacy [-]. This is the ratio between corrective power and the electrical consumption of the fan.

Cooling-fan efficiency index [-]. This is the ratio between the $\Delta T_{cooling}$ effect and electrical consumption of the fan.

Time to comfort [hr]. This might be accomplished during the next few minutes of the operation.

Proportion of net openable area of a natural ventilation system as a function of the floor or wall area [%]. The floor area must have at least 20% openable windows for comfort ventilation, with openings roughly distributed between leeward and windward walls (cross ventilation). Ideal windows are those that are at eye level for everyone in the room. This elevates the windowsill 30 to 60 cm above the floor for seated or reclined individuals. A design that passes air over the heads of humans is also inadequate.

Fan information [-]:

- coverage (occupied floor area; location, hotspots, height)
- shape-geometry (weight, length, width, impeller diameter, design of blade tips-aerofoil, number of blades, blade angle)
- motor type and power (operating voltage, flow field, aerodynamics, min and max speed (revolutions per minute), speed controller, efficiency, service factor; [W])
- noise reduction (aerodynamic, electromagnetic, and mechanical noise; BPF)
- material mechanical properties (density (Kg/m3), Young’s modulus (GPa), Poisson’s ratio)
- material type (i.e., glass or fibre forced polymer, steel, aluminium, wood, PVC)
- and others (i.e., control, protection-safety, cleaning-repairing possibility, lubrication, interface between blade and rotor, or mount-hub)

Supplementary key technical properties are presented in 4.2 Micro-cooling and Personal Comfort Control.

While efficiency drives the manufacturing process, aesthetic considerations dominate the design of blades. Fans with aerofoil blades circulate more air more efficiently while using less electricity, whereas flat-bladed ceiling fans are inefficient (typical wattage around 6 – 30 W (÷1.5 m diameter)). Large, slowly rotating ceiling fans are far more effective than small, quickly rotating ones.

4.1.3 Performance and Application

4.1.3.1 Building Performance and Climate Conditions

The described technology is a versatile solution that can enhance air circulation and improve indoor comfort in various regions worldwide. Its applicability extends beyond specific climatic zones, offering advantages across different environmental conditions, including temperature and humidity variations (Figure 19). By referring to the ASHRAE weather map [32], we can identify potential areas where this technology can be particularly beneficial. Exemplary KPIs for a single-family home in Los Angeles, California, U.S. for CORDEX 2050 weather conditions are presented in Table 9.

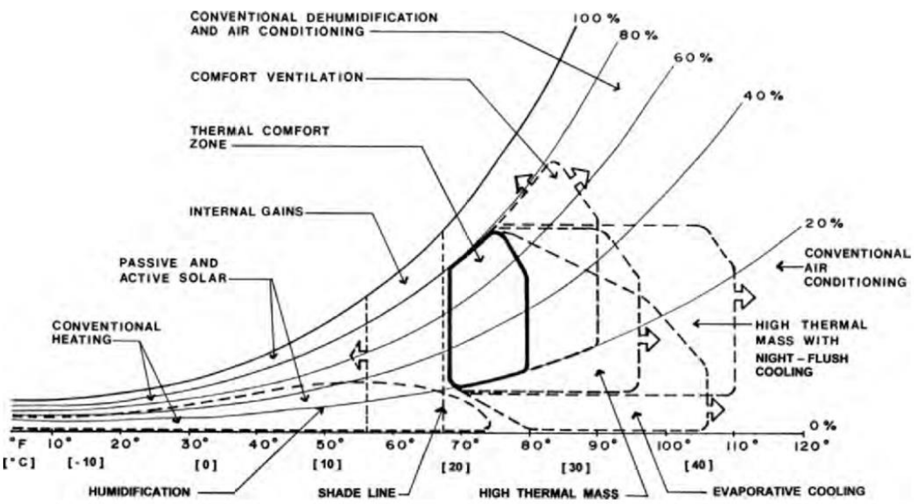

Figure 19: Comfort ventilation strategy as a function of ambient conditions [116].

Table 9: Key Performance Indicators (KPIs), based on [3], of HVAC-related energy usage and heat stress for a single-family home in Los Angeles, California, U.S. for CORDEX 2050 weather conditions and changes in KPIs from the application of ceiling fan [39]:

KPI	Baseline	Reduction from elevated air movement 0.4 m/s[f]	Reduction from elevated air movement 0.8 m/s[g]	Reduction from elevated air movement 1.2 m/s[h]	Reduction from elevated air movement 1.6 m/s[i]
Daily heat stress[a] [°C·h]	101	28%	39%	44%	47%
Annual HVAC electricity need intensity[b] [kWh/m²]	40	21%	31%	36%	39%
Annual HVAC heating need intensity[c] [kWh/m²]	27	3%	4%	5%	5%
Annual HVAC primary energy intensity[d] [kWh/m²]	113	16%	24%	28%	30%
Annual HVAC carbon emission intensity[e] [$kgCO_{2e}/m^2$]	17,1	14%	22%	25%	27%

[a] Daily degree hours of exceedance against a standard effective temperature (SET) of 30 °C during a heatwave without AC.

[b] Annual electricity need per conditioned floor area related to HVAC usage.

[c] Annual gas need per conditioned floor area related to HVAC usage.

[d] Annual primary energy usage per conditioned floor area related to HVAC energy need with primary energy factor for electricity: 2.05 and gas: 1.09 based on 2021 eGRID database for California State average [22].

[e] Annual carbon emission per conditioned floor area related to HVAC energy need with CO_{2e} emission factor for electricity: 272 g/kWh and gas: 225 g/kWh based on 2021 eGRID database for California State average [22].

[f] Raise the cooling set point temperature 2.0 °C from 24.9 °C to 26.9 °C and increase air speed near human skin to 0.4 m/s.

[h] Raise the cooling set point temperature 3.1 °C from 24.9 °C to 28.0 °C and increase air speed near human skin to 0.8 m/s.

[g] Raise the cooling set point temperature 3.6 °C from 24.9 °C to 28.5 °C and increase air speed near human skin to 1.2 m/s.

[i] Raise the cooling set point temperature 4.0 °C from 24.9 °C to 28.9 °C and increase air speed near human skin to 1.6 m/s.

In warm and humid climates, such as tropical regions (i.e., zones 1 and 2; humid subcategories of other zones), fans are crucial for providing relief from high temperatures. These areas often experience hot and moist weather throughout the year, necessitating the use of air conditioning and dehumidifiers. However, fans can complement these systems by promoting better air movement and creating a perceived cooling effect for occupants. By using fans alongside air conditioning, individuals can raise their thermostats, resulting in reduced energy consumption and lower utility bills without compromising comfort.

In temperate climates with varying seasons (i.e., zones 4 to 6), fans offer year-round benefits. During the summer, fans improve air circulation, providing a refreshing breeze and reducing reliance on air conditioning systems. In winter, when heating systems are in use, fans can be reversed to gently push warm air downward from the ceiling, distributing heat more evenly throughout the space. This redistribution of warm air not only improves thermal comfort but also leads to energy savings by reducing the need for excessive heating.

In arid and desert regions (i.e., zone 3; dry subcategories of other zones), fans contribute to occupant comfort by creating a cooling effect through increased air movement. These areas often face high temperatures and dry climates, where traditional cooling systems may be inadequate or uneconomical. By combining fans with natural ventilation strategies, such as opening windows during cooler periods, occupants can enhance airflow, minimize stagnant air, and create a more comfortable environment without relying solely on energy-intensive cooling equipment.

Even in moderate climates with balanced seasonal variations, fans provide benefits (i.e., marine zones). They enhance overall comfort levels in different buildings, reducing the reliance on active cooling systems. By using fans strategically, occupants can create a pleasant environment during warmer months and facilitate air circulation during cooler periods, promoting natural ventilation and minimizing the need for artificial air conditioning.

4.1.3.2 Resilience

Long-term climate change and heat waves have a significant impact on comfort ventilation from openings, but power outages do not (low absorptive capacity). Using this technology in advance of a heatwave is also not possible (connection with occupancy). On the other hand, active systems show a high degree of adaptability in the face of heat waves, which means that during periods of exceptionally high outdoor temperatures, the various performance modes can actively meet increased comfort expectations. This comes at the price of higher electricity costs. After a heat wave, fans can rapidly resume normal operation (restorative capacity and recovery speed are high, as long as the system has not been physically damaged). Active systems are inoperable during power outages because they require electrical power if they are not connected to backup systems (i.e., batteries and generators) or renewable energy sources (or DC systems). When photovoltaic (PV) electricity generation is at its peak, cooling demands are also at their pinnacle. They are therefore extremely vulnerable in this regard. The desired indoor temperature or comfort sensation can be rapidly restored after a power outage. Due to the previously mentioned low power outage resilience and electricity demand considerations, it is recommended that fans be used in conjunction with other cooling technologies to increase resilience. Priority should be given to passive cooling technologies, such as shading and others, in order to reduce the cooling demand as much as possible before resorting to active cooling technologies.

4.1.3.3 Limitations

The implementation of comfort ventilation has challenges stemming from the lack of exact information to accurately predict the required cooling load, as well as the integration of energy performance calculations, indicators, and control schemes. Furthermore, the effectiveness of ventilation through windows is contingent upon the occupant's behavior, which is influenced by various factors such as lifestyle, psychological state, physiological needs, and accessibility to window openings. Consequently, accurately predicting the extent to which natural ventilation can be successfully implemented in practice proves to be a challenging task.

The presence of high levels of outdoor noise in urban areas poses a significant obstacle to the implementation of ventilation techniques that rely on natural driving forces. Therefore, it is necessary to develop methods for accurately estimating noise levels in urban canyons. This is crucial in order to evaluate the potential of utilizing ventilation strategies effectively, as well as to assess the risk of occupants closing windows to mitigate noise, thereby compromising the effectiveness of the cooling approach.

Key outdoor pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon dioxide (CO_2), ozone (O_3) and suspended particle matter (PM) are typically monitored continuously in urban areas of significant size. These pollutants are commonly recognized as significant obstacles to the implementation of ventilation strategies. The determination of the ratio between indoor and outdoor pollutants is crucial for evaluating the viability of employing natural ventilative cooling in an urban setting.

The practice of manually or automatically opening windows in ground floor residences is partially deemed undesirable due to safety concerns. The clarification of burglary, weather, and injury protection is necessary in specific instances.

4.1.3.4 Application and Availability

The technology is applied to all kinds of building types (new or renovated) and sizes and refers mainly to lightweight construction. A moderate amount of insulation is still required. It is important to note that the effectiveness of fans and comfort ventilation in different regions depends on factors such as building design, zoning, layout, size, internal height and opening configurations. Proper opening and fan placement and selection, including considerations of power and other specifications, are crucial for optimizing performance and ensuring efficient air circulation. Several studies have shown that this setpoint increases save about 10% of total annual cooling HVAC energy per °C elevation, which is approaching 20% to 30% of total energy use in developed countries and growing continuously. The technology can be used in combination with other technologies very effectively (integration with HVAC and passive systems, intelligent control, and automation).

In recent years, fans have made great strides in their energy efficiency, performance, aesthetics, and acceptance by designers, practitioners, and occupants (technology readiness level 5 - 9; availability could change from country to country). Such fans are available and are being actively and competitively marketed. ASHRAE Standard 216 [117] is a recently finalized test method that promotes the use of ceiling fans in building design. It comprises fan layout data tables and design tools. Next steps include widespread adoption of the technology in building control (holistic integration).

4.1.4 Further Reading

Further information can be found in the following publications:

- S. Attia, et al., (2021) Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. Energy and Buildings, Volume 239, 110869, https://doi.org/10.1016/j.enbuild.2021.110869
- ASHRAE Handbook – Fundamentals, 2021.
- Givoni, B., (1998) Climate Considerations in Building and Urban Design, Man, Climate and Architecture, 2nd ed., ISBN: 978-0-471-29177-0
- IEA EBC, Ventilative Cooling of Buildings, Sourcebook (Annex 62), 2018.
- International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Lechner, N., (2015) Heating, Cooling, Lighting: Sustainable Design Methods for Architects, John Wiley & Sons, Hoboken, 23
- R. Wandre et al. 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1259 012025.
- Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.

4.2 Micro-cooling and Personal Comfort Control

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4.2.1 Description

A personal comfort system (PCS), also known as a personalised environmental control system (PECS), is a device under the control of the occupant that is used to condition the individual or its immediate environment (microenvironment) without affecting the environment of other occupants. PCS can be equipped with heating, cooling, and even ventilation (fresh air) functions. As a resilient cooling system, the main function of interest in PCS is cooling.

PCS devices offer both comfort and energy benefits. Because they are personalized, these devices allow occupants to control their thermal microenvironments and thereby satisfy their individual comfort requirements. Due to their low energy use, PCS devices are inherently suitable for resilience applications and adaptable for use during energy emergencies. As the room (total volume) temperature may extend above 28 °C [114] during a heatwave, PCS may offer relief and safety at lower energy expense. PCS may also provide comfort immediately after an extreme event (e.g., heatwave), creating habitable conditions at an early stage. Furthermore, if capable of generating the same level of comfort and productivity for an extended room temperature above 26 °C [114] during the cooling season, further energy savings may be achieved reducing thus the stress on the energy system. A similar effect may be obtained for lower room temperatures during the heating season if the PCS is equipped with a heating element.

Cooling PCS devices may involve the following technologies:

- Vertical-axis ceiling fans and horizontal-axis wall fans (such fixed fans differ from pure PCS devices in that they may be operated under imposed central control or under group or individual control)
- Small desktop-scale fans or stand fans
- Furniture-integrated fan jets
- Devices combining fans with misting/evaporative cooling
- Cooled chairs, with convective/conductive cooled heat absorbing surfaces
- Cooled desktop surfaces
- Workstation micro-air-conditioning units including personalized ventilation, some including phase change material storage
- Radiant panels (these are currently used less for PCS than for room heat load extraction)
- Conductive wearables
- Fan-ventilated clothing ensembles
- Variable clothing insulation: flexible dress codes, variable porosity fabrics.

4.2.2 Key Technical Properties

According to a literature review [118], the following indicators can be used to evaluate the resiliency and performance of PCS:

Power use [W]. Power input.

Manikin-based Whole-body Equivalent Temperature difference (ΔT_{eq}) [K]. PCS heating/cooling effect quantified with a thermal manikin. The indicator represents the difference between the room temperature and the equivalent temperature of the non-uniform environment generated by the effect of the PCS [119]. May not reflect the overall effect on thermal sensation generated by thermoregulatory responses such as blood circulation in extremities and evaporative cooling may not be considered [118].

Corrective power (CP) [K]. The degree to which a PCS system may "correct" the ambient temperature toward neutrality, defined as difference between two ambient temperatures at which equal thermal sensation is achieved (no PCS) and one with PCS in use [120].

Corrective energy and power (CEP) [W/K]. Ratio between power use and corrective power [121].

Coefficient of performance (COP) [-]. Ratio between whole-body heat loss and the system power use [122].

Ventilation effectiveness (ε_V) [-]. Difference in tracer gas concentration at the exhaust room air with the concentration at the inhalation zone [123].

Personal exposure effectiveness (ε_P) [-]. Difference in tracer gas concentration at the inhaled air with and without PV and the supply air from the PV [123].

As PCS vary in structure and functionality and there are no standardized guidelines available, the ranges for these indicators are still under evaluation. The power use of PCS is critical in order to assess the expected energy use and possible energy savings compared to alternative systems. The power use of PCS should be as low as possible so that its energy use does not exceed the energy use incurred by employing the total volume system instead.

The CP and ΔT_{eq} are similar indicators showing the correcting capability of a PCS. The former is based on subjective thermal sensation measurements and represents the difference between two ambient temperatures at which the same thermal sensation is achieved. The latter is based on manikin measurements and shows the expected difference in heat loss when using PCS. Their absolute value should be significantly higher than the power use, which should lead to the lowest CEP (ratio between the power use and corrective power). Moreover, the COP should be as high as possible for cooling, i.e., the highest possible heat loss for the least power use.

If PCS are equipped with clean air supply (fresh outside air) or with an air cleaner, additional indicators are of interest, namely ε_V and ε_P. The former represents the effectiveness of removing internally produced contaminants and must be higher than the one achieved with the alternative ventilation system, e.g., mixing-ventilation (ε_V up to 1) or displacement ventilation (ε_V up to 1.4) [124]. The ε_P is a further refined ventilation effectiveness indicator for PCS showing the percentage of personalised air in inhaled air, for which the highest possible value is preferred.

4.2.3 Performance and Application

4.2.3.1 Building Performance

PCS can improve thermal comfort. A system equipped with clean air supply can furthermore improve indoor air quality and reduce the risk of airborne infection [125]. Furthermore, such devices can yield HVAC system energy savings if the room temperature range can be relaxed in either the hot or cold direction according to the PCS effect. This can lead to a total HVAC energy use reduction of approximately 10% per K room temperature setpoint relaxation [126], [127]. PCS are envisioned not only as the single HVAC system, but also as add-ons to the HVAC systems installed. They are compatible with any other total-volume conditioning strategy (e.g., mixing-ventilation, displacement, underfloor, radiant systems), but the interaction, i.e., control, is partly case dependent and requires further investigation.

4.2.3.2 Resilience

PCS have no absorptive capacity under heatwaves or power outages, as they are not part of the building envelope or structure. Their adaptive capacity is high during heatwaves, as the cooling output can be adjusted, but is limited by their maximum capacity. Assuming no batteries or emergency power generators are installed, a low adaptive capacity is expected during power outages, as only certain devices will be able to keep on functioning (such as conductive wearables, fan-ventilated clothing ensembles or phase change material assisted PCS). PCS devices have high restorative and recovery capacities under heatwaves and power outage events, as the systems will be functioning normally once the heatwave or power outage is over. Moreover, as PCS condition the microenvironment, action can be taken immediately thus ensuring high recovery capability.

The resilience and performance of PCS has yet to be quantified. However, if an extreme event occurs, the resilience and performance of the system can be evaluated by adjusting according to PCS capabilities, e.g., using CP or ΔT_{eq}. For instance, if the PCS has a CP of ±2 K and the resulting indoor environment temperature without PCS is 28 °C, then the evaluation can be made relative to an indoor environment temperature of 26 °C. CP values up to 3 (cooling by frontal air jets) and 5 (ceiling fans and cooling by chairs) were identified in the literature for cooling [120]. Range of values for the specific primary energy consumption were not provided, however the power use for cooling was found to be up to 80 W [118].

4.2.3.3 Application and Climate Conditions

PCS are applicable in all climate zones and buildings (including retrofit). However, PCS functionality may differ depending on the building use (e.g., office building, residential, etc.) and the occupants, e.g., elderly people may require advanced PCS with increased flexibility and higher cooling capabilities. By conditioning the individual or the immediate environment, these devices can overcome inter-personal differences.

4.2.3.4 Limitations

The thermal environment correction will depend on the PCS heating/cooling capacity, but also on occupant use. Without fresh air supply, the ventilation effectiveness of the PCS depends on the air cleaner's performance.

4.2.3.5 Availability

As PCS vary in structure and functionality, e.g., multifunctional or restricted to either heating, cooling, or ventilation functions only. Even though there are commercially available products, the technology is not as mature as some of the other technologies, e.g., compression refrigeration.

4.2.4 Further Reading

Further information on PCS can be found in the following publications:

- Section 4, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Section 4.3 in: Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
- IEA EBC – Annex 87 – Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems, https://annex87.iea-ebc.org/
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- Kim, J., Bauman, F., Raftery, P., Arens, E., Zhang, H., Fierro, G., Andersen, M., Culler, D., (2019) Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers, Building and Environment, 148, pp.348-360, https://doi.org/10.1016/j.buildenv.2018.11.012
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5. Removing Latent Heat from Indoor Environment

5.1 Dehumidification

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5.1.1 Description

The removal of latent heat from indoor environments through dehumidification is an essential and important method, especially in hot and humid climates, to reduce the cooling load and to increase human comfort. In hot and humid climates, conventional air conditioning systems alone might not be able to provide desired thermal comfort conditions. Cooling requirements in such climates should distinguish between sensible cooling capacity (temperature control) and latent cooling (humidity). The dehumidification process takes place when moisture, water vapor or humidity is removed from the air, keeping its dry bulb temperature constant. On the psychrometric chart the dehumidification process is represented by a straight vertical line, which starts at the initial value of relative humidity, extending downwards and ending at the final value of the relative humidity.

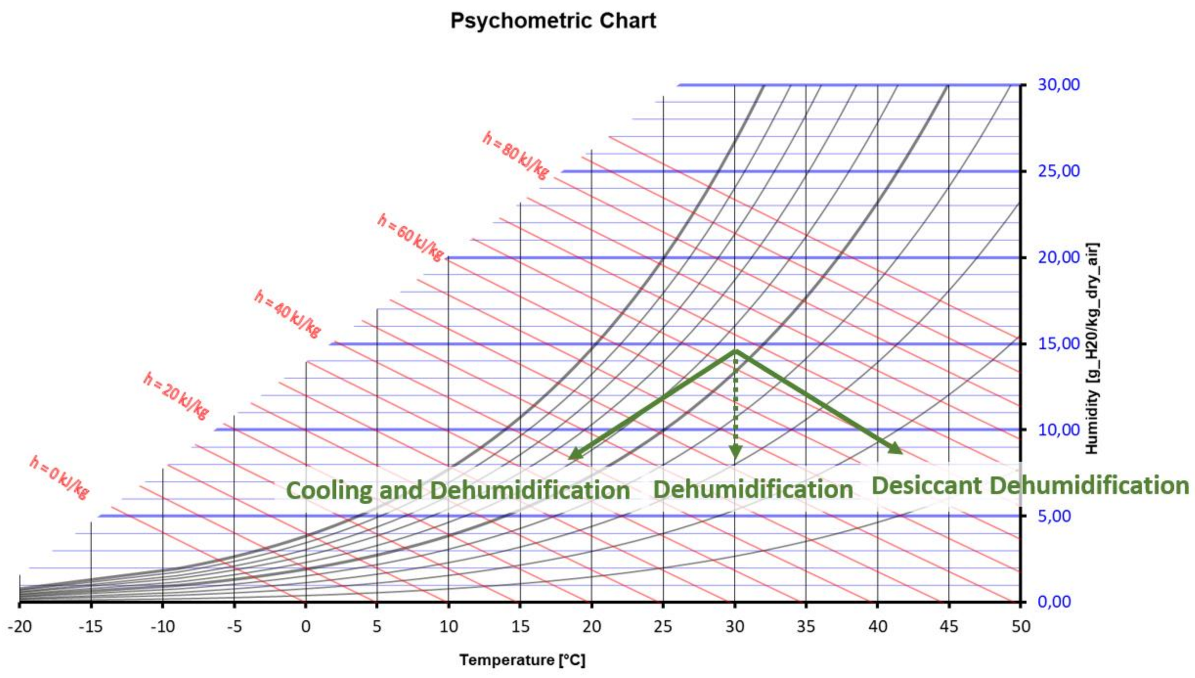

Figure 20: Psychrometric chart of dehumidification processes.

Dehumidification is normally accompanied by cooling or heating of the air. This effect is used in a number of air conditioning applications.

There are two major physical principles of removing latent heat from indoor environments, depending on the dehumidification method used.

Refrigeration dehumidification utilizes conventional vapor compression cycles to dehumidify the humid air through cool-reheat processes, as shown in Figure 21. The humid air is dehumidified when it flows over a surface (Evaporator) with a temperature lower than the dew point of the humid air. The condensed water is collected and the dry air is reheated in the condenser. Afterwards the air is fed into the room. The latent load of moisture content is reduced by lowering the temperature of the air.

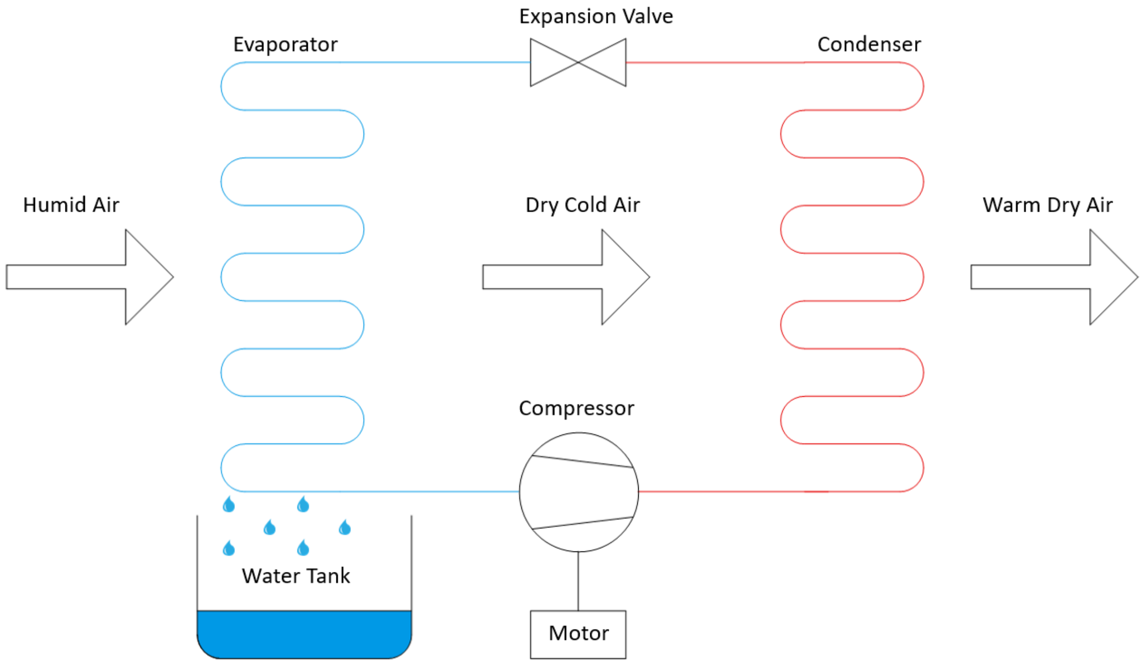

Figure 21: Working principle of refrigeration dehumidification.

Desiccant dehumidification dehumidifies air by lowering the vapor pressure of desiccant surfaces that absorb/adsorb the moisture from the passing humid air. If the vapor pressure of the desiccant surface is lower than that of the humid air, moisture would transfer from the air to the desiccant material until saturated or until equilibrium conditions are reached. The desiccant can be regenerated by removing the moisture with warm air. Figure 22 shows a simplified desiccant dehumidification cycle.

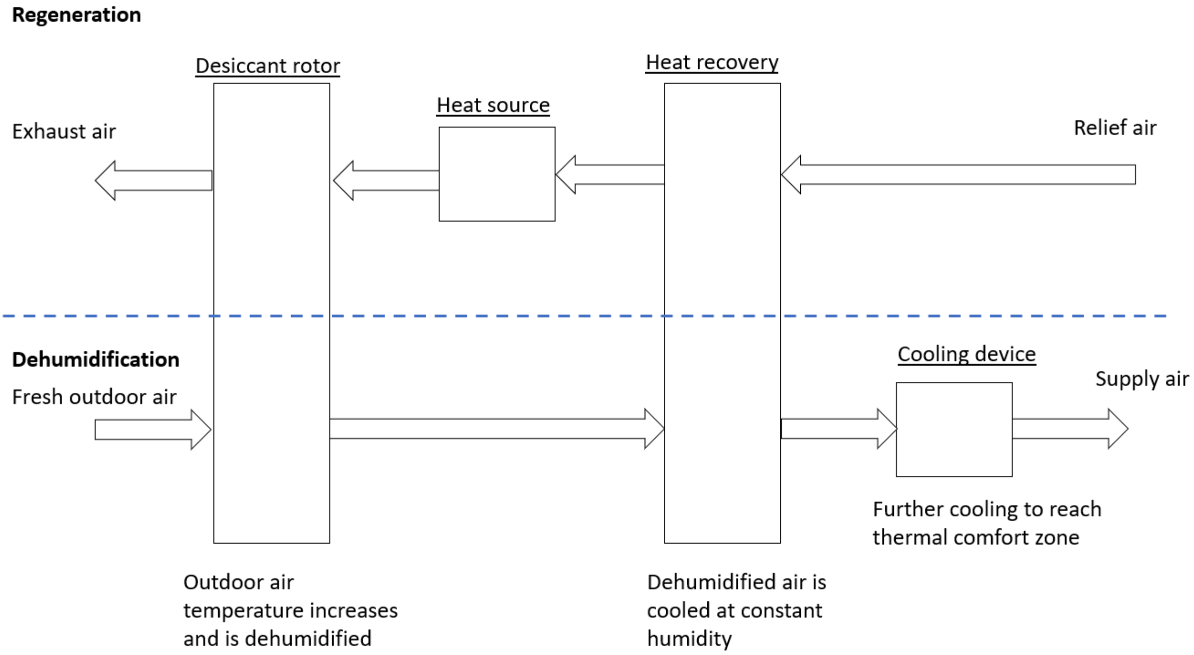

Figure 22: Simplified schematic representation of desiccant dehumidification.

There are two types of desiccant materials, solid and liquid. **Solid desiccants** use adsorption processes and **liquid desiccants** use chemical and physical processes to absorb moisture. Compared to solid desiccant systems, liquid systems offer greater flexibility and control of moisture removal, as well as lower heating and cooling requirements for the regenerator and absorber, and therefore have attracted more attention.

As shown in Figure 20, desiccant dehumidification alone will increase the dry bulb temperature. To achieve a cooling effect, the remaining steps of a desiccant cooling system are required.

Further dehumidification strategies are:

Ventilation dehumidification utilizes dry outdoor air to replace indoor humid air. However, the dehumidification capacity, control accuracy, and dehumidification efficiency depend highly on the relative humidity of the outdoor air. This method is therefore only suitable for regions with relatively dry outdoor air.

Thermo-electric dehumidification uses the thermoelectric effect (Peltier effect) to convert electricity into a temperature difference across a Peltier module. The module includes two heat sinks, a cold side heat sink and a hot side heat sink. Humid air, driven by the fan, flows over the cold side heat sink and the air is dehumidified. The dehumidified air then passes through the hot side heat sink to be reheated before being delivered to indoor environments. Compared to refrigeration dehumidification, thermo-electric dehumidification does not require a compressor and a refrigerant. However, the dehumidification capacity is limited and the control of the relative humidity of the indoor air is not as accurate as with desiccant and refrigeration dehumidification.

5.1.2 Key Technical Properties

For desiccant dehumidification systems, the characteristics of its **working medium** are a key technical property. Good desiccants are characterized by a large saturation absorption capacity, low viscosity, high heat transfer and stability. They must also be non-corrosive, odorless, non-toxic, non-flammable and ideally low cost.

Key Technical Properties which are important for all dehumidification principles are:

Cooling capacity [W, kW]. The most important aspect when designing a cooling system is the required cooling capacity, which depends on the circumstances. It is defined as the total (i.e., sensible and latent) energy exchange between the air and solution streams.

Moisture removal rate [g_{H20}/s]. It is defined as the mass of moisture exchanged between the air and solution streams per unit time. Dehumidifier performance is evaluated on the basis of moisture removal rates and effectiveness.

Humidity or moisture effectiveness [-]. This is the ratio between the actual change in humidity ratio of the air across the dehumidifier and the maximum possible change in humidity ratio of the air [128]. Humidity ratio might also be referred to as specific humidity.

Relative humidity [g_{H20}/m^3_{Air}] of input and output air and **temperature** [°F, °C] of input and output air. Due to aspects concerning human health, temperature and humidity must be controlled at all times to avoid the growth of fungi and bacteria. The air temperature might drop below the set value to achieve the desired humidity level, and a reheat coil is therefore required to increase the sensible temperature of the air back to its set value.

Sensible heat ratio [-]. It is defined as the ratio between the sensible load and the total load (sensible + latent load). Especially in hot and humid climates, the designed sensible heat ratio can be well below 0.75. In such cases, conventional air conditioning systems or refrigeration dehumidification cannot provide the desired thermal comfort conditions. These systems perform better if the ratio is above 0.75 [129].

Furthermore, there are performance indicators such as the **coefficient of performance (COP)** [-] and its subtypes, electrical coefficient of performance and thermal coefficient of performance. The COP describes the ratio between the cooling capacity and the total consumed energy and, depending on the system, can be related to the electrical or thermal energy consumed.

In addition, the use of a refrigerant would have a negative impact on global warming and ozone depletion.

5.1.3 Performance and Application

5.1.3.1 Building Performance

In hot and humid climates however supplemental dehumidification energy must also be considered, not just space cooling energy. Simulations show that stand-alone dehumidification with heat recovery can save 29 - 42 % of primary energy, depending on the system. However, it is difficult to give exact figures because dehumidifying and cooling cannot be considered separately but combined as a system, simply because both are required in certain climates [130], [131].

5.1.3.2 Resilience

Dehumidification technologies absorb the impacts of heatwaves by decreasing the humidity of indoor air, which improves the comfort level and relieves part of the pressure on other cooling systems. Desiccant dehumidification, refrigeration dehumidification, thermoelectric dehumidification, and mechanical ventilation dehumidification all require electricity and are therefore not very robust to power outages. Natural ventilation dehumidification could operate during a power outage, but its capacity to remove latent heat depends on building characteristics, local climate, and occupant behaviour.

Although dehumidification technologies could improve the thermal comfort level during a heatwave or recovery the thermal condition after a heatwave, their cooling capacity is limited by the fact that they only address the latent heat in the indoor environment. This means that the cooling capacity cannot be increased as much as may be required and dehumidification technologies may be used as a support or in combination with other resilient cooling technologies.

Due to its dependence on the power supply as well as the limited scalability of the cooling capacity, this technology should not be implemented in isolation. Combinations with passive cooling technologies are recommended in any case and should always be treated as the first choice. Since a substantial amount of sensible heat can always be assumed in the building, consideration must also be given to the removal of this heat. It may be necessary to have a second, active cooling technology.

In order to increase the power outage resilience, the combination with local power generation from a PV system would be useful. Desiccant dehumidification systems integrated with renewable and sustainable heat sources such as solar energy and industrial waste heat have been widely investigated and rapidly developed in recent decades.

5.1.3.3 Limitations

Desiccant dehumidification requires relatively high regeneration temperatures (90 – 260 °C for solid desiccants; 60 – 90 °C for liquid desiccants). As a result, a large amount of thermal energy is required and the practical application of these systems is limited. Low-tech or environment friendly energy solutions are therefore difficult to implement. Ideally, low-grade thermal energy is used, such as waste heat or solar energy [132].

Operation causes noise and waste heat emissions, in addition attention must be paid to possible condensation in the indoor environment. The use of low-grade heat from the sun and/or industry could reduce the heat pollution to the environment and avoid/minimize the consumption of fossil energy to drive the desiccant systems.

5.1.3.4 Application and Climate

All of these technologies are well developed and commercial products are available in the market in the form of either large dehumidification plants or small household dehumidifiers. Both individual consumers and building contractors are quite free to purchase dehumidification products, although the desiccant dehumidification plants are usually purchased by building contractors. Dehumidification technologies can be used in new construction as well as in retrofits.

Some of the major applications of these dehumidification technologies are in residential buildings, office buildings, supermarkets, cinemas, hospitals, hotels, indoor swimming pools, and pharmaceutical manufacturing plants [133]. Refrigeration dehumidification has been widely implemented, especially in residential and small office buildings. Since moisture can come from both indoor sources, such as people and wet surfaces, and outdoor sources, such as humid outdoor air, there is a high demand for, and therefore potential application of, air dehumidification in buildings with high moisture emissions and in climates with high outdoor humidity.

Removing latent heat from indoor environments through dehumidification is an essential and important method, especially in hot and humid climates (ASHRAE Climate Zones 1A and 2A [32]), to reduce the cooling load and to increase the human comfort. Desiccant refrigeration and thermo-electric dehumidification technologies work in principle in areas with humidity above comfort level, while ventilation dehumidification technology works in areas with dry outdoor air. For example, temperate marine climate and temperate continental climates, including Northern Europe, do not require dehumidification for most conditions, whereas subtropical monsoon climates and tropical rainy climates including Southeast Asia, do require certainly dehumidification for most of the year.

In principle, dehumidification cooling can be paired with any other resilient cooling technology that can be operated in hot and humid climates, as well. In fact, this is even recommended because of the physical working principle of dehumidification cooling.

5.1.3.5 Availability

All dehumidification technologies are well developed, and commercial products are available in the form of either large dehumidification systems or small household dehumidifiers.

5.1.4 Further Reading

Further information can be found in the following publications:

- Chapter 5, Remove latent heat from indoor environments, International Energy Agency, Resilient Cooling of Buildings State of the Art Review (EBC Annex 80)
- Zhang C. et al., (2021) Resilient cooling strategies–A critical review and qualitative assessment, Energy and Buildings 251, 111312, doi.org/10.1016/j.enbuild.2021.
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- D. Pietruschka, U. Eicker, M. Huber, J. Schumacher, (2006) Experimental performance analysis and modelling of liquid desiccant cooling systems for air conditioning in residential buildings, International Journal of Refrigeration, Volume 29, Issue 1, Pages 110-124, https://doi.org/10.1016/j.ijrefrig.2005.05.012.

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